

Monitoring river health in the wet–dry tropics: strategic considerations, community participation and indicators

TRaCK

Tropical Rivers and Coastal Knowledge

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TRaCK brings together leading tropical river researchers and managers from Charles Darwin University, Griffith University, the University of Western Australia, the Commonwealth Scientific and Industrial Research Organisation, James Cook University, the Australian National University, Geoscience Australia, the Environmental Research Institute of the Supervising Scientist, the Australian Institute of Marine Science, the North Australia Indigenous Land and Sea Management Alliance, and the governments of Queensland, the Northern Territory and Western Australia.

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Acronyms and abbreviations

ANZECC	Australian and New Zealand Environment Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
AusRivAS	Australian River Assessment System
BACI	Before–After Control/Impact
ER	Ecosystem Respiration
FARWH	Framework for the Assessment of River and Wetland Health
GIS	Geographic Information System
GPP	Gross Primary Production
MODIS	Moderate-resolution Imaging Spectro-radiometer
NAILSMA	North Australia Indigenous Land and Sea Management Alliance
P/R	Gross primary production to ecosystem respiration ratio
PSR	Pressure–Stressor–Response (framework)
RNA	Ribo-Nucleic Acid
SEAP	Stream and Estuaries Assessment Program
SIGNAL	Stream Invertebrate Grade Number Average Level
TRaCK	Tropical Rivers and Coastal Knowledge
TRARC	Tropical Rapid Assessment of Riparian Condition
TRIAP	Tropical Rivers Inventory and Assessment Project
WEP	Waterways Education Program
WOC	Working on Country [Program]

Foreword

At a national level, research into monitoring river health was initiated in the early 1990s by the Australian Government with the National River Health Initiative program, which produced most notably the Australian River Assessment System (AusRivAS) macroinvertebrate models (eg Smith et al. 1999). This nationwide data base contributed to the 2001 audit of river health (Norris et al. 2001), which however only included a small portion of the wet–dry tropics. The audit was followed by more specific tropical river research between 2006 and 2008 with the Tropical Rivers Inventory and Assessment Project (TRIAP), which developed an integrated information base for the assessment of river status (see Finlayson and Lukacs 2008).

The Tropical Rivers and Coastal Knowledge (TRaCK) consortium undertook research between 2005 and 2010 that spanned a range of topics relating to cultural, environmental and economic aspects of tropical rivers. TRaCK's primary objective was to provide knowledge to governments, communities and industry for the sustainable use of rivers in the wet–dry tropics. The program was followed by a year consisting of six 'synthesis and adoption' topics, which included monitoring river health. This report is based on the findings of two workshops and contributions of TRaCK partners.

On 16 August 2011, a workshop was held in Brisbane to identify the implications of TRaCK research for river health monitoring in the wet–dry tropics. The workshop was attended mainly by researchers and government agency TRaCK partners. The attendees were Michele Burford, Mark Kennard, Simone Langhans, Francis Pantus and Tim Jardine from Griffith University; Simon Townsend with affiliations to Charles Darwin University and the Northern Territory Department of Land Resource Management; Rebecca Dobbs from the University of Western Australia; Chris Humphrey and Simon Nally from the Australian Government Department of Sustainability, Environment, Water, Population and Communities; Satish Choy, Niall Connolly and Pru Fleming from the Queensland Government; Mike Braimbridge from the Western Australian Department of Water; and Rod Kennett and Erica McCreedy from the North Australian Indigenous Land and Sea Management Alliance (NAILSMA).

The workshop was organised by Kathy Carter (Griffith University) and Amy Kimber (Charles Darwin University).

Following the August workshop, another workshop was held on 1 September 2011 at Mary River Park (Northern Territory), as part of a NAILSMA I-Tracker forum. The workshop was attended by about 60 people, mostly Indigenous land managers and representatives of these groups. TRaCK researchers who led the monitoring component of the workshop were Michael Douglas from Charles Darwin University and Emma Woodward from the CSIRO.

Executive summary

River health is in generally good condition in the Australian wet–dry tropics compared to the more developed parts of Australia. The health of rivers is nevertheless modified by anthropogenic activities due to diffuse catchment pressures; notably grazing, feral animals and fire, and more localised pressures from mining and agriculture. Residents of the wet–dry tropics have high expectations that the rivers will remain healthy, and view any degradation, even if minor on a national scale, as being significant and the possible start of long-term degradation.

Monitoring river health in the wet–dry tropics faces significant challenges. The vast area, small population base and limited all-weather road infrastructure impose resource and logistical challenges. The high seasonality of rainfall also imposes constraints on monitoring. In the wet season most rivers are inaccessible. In the dry season many rivers cease flowing while others reduce to a series of disconnected pools or waterholes. Some rivers and streams are groundwater-fed and flow year-round.

River health monitoring can be considered a societal activity, founded on principles of collaboration, communication, scientific credibility, transparency, community participation, education, and—importantly—relevance to management. The Framework for the Assessment of River and Wetland Health provides a comprehensive outline for surveillance-type river health monitoring, underpinned by the pressure–stressor–(ecological) response framework that seeks to link anthropogenic pressures to river health.

The key objective for long-term monitoring espoused in this report is the early detection of anthropogenic effects that may potentially degrade river health. This concurs with the approach of the Australian and New Zealand Environment Conservation Council and the Agriculture and Resource Management Council of Australia and New Zealand (ANZECC-ARMCANZ 2000). This approach is especially significant in the wet-dry tropics to provide warning of river health degradation and thereby avoid the social and economic costs of restoration. In many parts of Australia monitoring is directed to assessing river health responses to restoration activities. Early detection however requires adequate resources, which are severely limited in the north, and a sound knowledge of the desired reference condition so that natural inter-annual variability can be distinguished from anthropogenic impacts. To address the resource constraint, a two-tiered approach to monitoring is proposed. This approach acknowledges that not everything, everywhere, can be monitored. The first tier would report on the pressures at a catchment-wide scale and make use of GIS and other spatial data, while the second tier would be undertaken at a much smaller scale, or case study level, to detect early degradation. Second-tier results could be extrapolated to the larger catchment if a relationship between pressure and river health is established.

The wet–dry season transition period is proposed as the best time to sample macroinvertebrate communities, a widely-used indicator for monitoring and assessing river health. This is the period of highest species diversity, and is also when wastewater discharges may have their highest impact. Monitoring river health using water quality, whole-of-river metabolism, phytoplankton, macroinvertebrates, ecogenomics and fish as indicators is discussed in this report, along with the use of time-lapse photography to monitor animal visitation to waterholes, aquatic plant cover, and erosion.

Monitoring by community groups and landholders can contribute to and complement surveillance-type river health monitoring. It can contribute to monitoring by providing data (eg water quality), and complement surveillance monitoring by focusing effort on local management issues beyond the resources of catchment-wide surveillance monitoring. Case studies of river health monitoring by Indigenous communities highlight the advantages of cross-cultural exchange of information and the importance of building on established social networks. An assessment of the capacity and willingness for community-led monitoring is important. Trials of indicators tested by community groups found photo-point monitoring to be the most successful method. While community-based monitoring is driven by the community, there is an important role for scientists in assisting groups to select appropriate indicators and methods for measuring and monitoring change.

Monitoring river health is an essential element of the adaptive management cycle, and can provide early warning of river health degradation. The logistical, resource and capacity constraints of monitoring, and the unique environment, necessitate the development of a monitoring system tailored to the wet–dry tropics.

1 Strategic considerations for river health monitoring

1.1 Introduction

Monitoring is one component in the adaptive management cycle (Figure 1). The evaluation of monitoring improves understanding for better planning and policy development, which leads to management actions. Underpinning river health management are objectives to maintain or restore the environmental values or beneficial uses of a river system. Most monitoring is driven by state and national government policy and legislation, and undertaken by mainly state agencies. However, industry, natural resource and catchment management boards, as well as the local government, community groups, landholders and Indigenous groups also conduct monitoring.

Monitoring can fall into three broad categories: surveillance, compliance and performance monitoring. Surveillance monitoring refers to broad scale monitoring that aims to assess river health at a large scale, typically catchment based. Compliance monitoring is undertaken as a legal requirement, typically associated with a licence; for example, to extract water for human and agricultural uses or discharge wastewater to a river. Performance monitoring provides information about a specific management action, such as riparian restoration along a nominated stream reach.

This report focuses on the surveillance monitoring of river health, where health refers to the river's ecological integrity (see Norris and Thoms 1999). To be effective, surveillance monitoring needs to be undertaken over long periods, with a decadal perspective to address long term climate patterns including climate change, as well as potential lags in anthropogenic impacts on river health.

We discuss strategic considerations to river health monitoring, based largely on the research of Risby et al. (2009) and Dixon et al. (2011), community participation and potential indicators. Community-based river health monitoring, including that undertaken by Indigenous ranger groups, can complement surveillance monitoring by government agencies. We describe a participatory river monitoring program trialled by four Indigenous groups.

Very few catchments in the wet–dry tropics undergo surveillance monitoring of river health. In the Northern Territory, river water quality and macroinvertebrate communities are monitored in the Darwin Harbour catchment (eg Fortune et al. 2009), and in Alligator Rivers Region streams (eg Supervising Scientist 2011). In the Daly catchment, monitoring has been sporadic, comprising several one-off, short-term surveys (Schult & Townsend 2012).

Figure 1 The adaptive management cycle showing monitoring and evaluation. Source: Queensland Department of Science, Information, Technology, Innovation and the Arts.

In the northwest part of Western Australia, annual monitoring of fish, macroinvertebrates, vegetation and water quality is done in the Ord Region to support the Ord River allocation plan. The Western Australian Department of Water currently maintains and operates 26 hydrometric gauging stations and 32 rainfall gauges across the Ord and Fitzroy river catchments. These stations provide data on water level, flow and irregular water quality measurements. A small number of Indigenous ranger groups are currently initiating monitoring programs to assess the implications of management actions for river health. Elsewhere in the Kimberley, specific monitoring of aquatic health using indicators such as macroinvertebrates and fish are only of short term duration and largely ad hoc. However, a number of long-term studies have been undertaken on key species (eg Fitzsimmons et al. 2009).

Compliance monitoring can potentially contribute to surveillance monitoring. In the Northern Territory, compliance monitoring is mainly undertaken by the mining industry, with at least five issued licences that require river health monitoring. In Western Australia, compliance monitoring is done for water abstraction and wastewater discharge by the mining and agricultural sectors, notably the Argyle Diamond Mine and the Ord River Irrigation Area.

In northern Queensland, surface water and groundwater quantity and quality are assessed regularly and reported periodically (eg DERM 2011a, McNeil & Raymond 2011). Other indicators, such as macroinvertebrates, were previously monitored (eg Conrick et al. 2001, DNRW 2006) but more comprehensive monitoring based on the pressure–stressor–response framework and risk assessment is currently used (DERM 2011b,c). In addition, environmental flow assessments based on ecological assets that have critical links to flow are carried out in water planning areas (eg DERM 2011d). Compliance monitoring is also undertaken by the mining industry.

1.2 The wet–dry tropical environment: climate, river systems and people

The wet–dry tropics region of Australia is vast. It represents 15% of the total land mass, or 1.2 million square kilometres, and for the purposes of the Tropical Rivers and Coastal Knowledge (TRaCK) program comprised catchments that drain into the Coral Sea, Gulf of Carpentaria and the Timor Sea (Figure 2). TRaCK research focused on the Fitzroy, Ord, Daly, Flinders and Mitchell River catchments, and Darwin Harbour. The Queensland Government also undertook research in the Burdekin catchment, which drains into the eastern seaboard, and lies outside the TRaCK research area but has a wet-dry tropical climate.

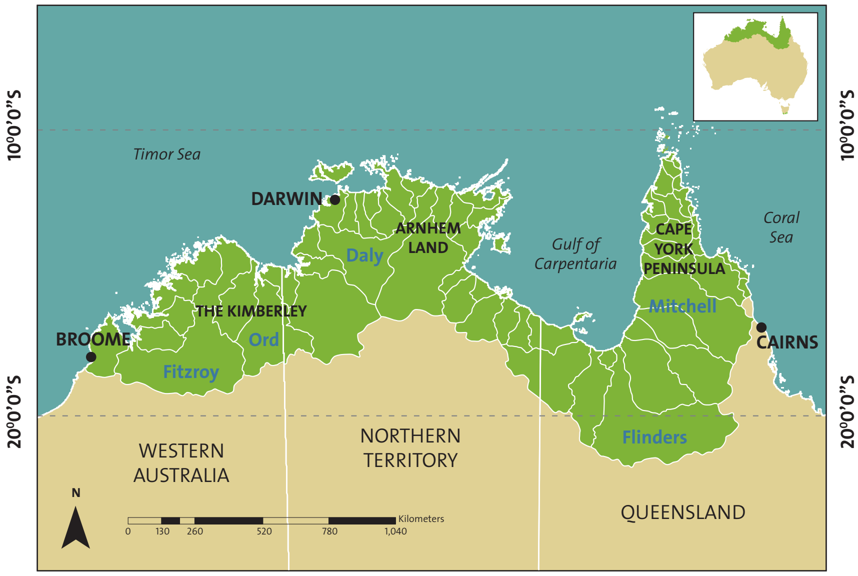


Figure 2 The wet-dry tropics. The TRaCK research area comprised catchments with rivers that flow into the Gulf of Carpentaria and the Timor Sea. Rivers that flow into the Coral Sea were not part of the TRaCK research area.

Rainfall within the wet-dry tropics is highly seasonal, with annual rainfall higher along the coastline (1200-1500 mm) than inland areas (300–400 mm). Most rain falls during the wet season months of December to March. The two transition periods (October–November and April–May) are characterised by convective storms, while rainfall is negligible during the dry season (June–September).

This highly seasonal pattern of rainfall produces predictable seasonal patterns of river flow (Kennard et al. 2010). High flows and floods occur during the wet season, though water levels and the extent of flooding varies between years. Dry season flow depends on the extent of groundwater supply, and may extend through the dry season or cease shortly after the last storms of the wet–dry transition period. During the dry season, many rivers reduce to a series of disconnected pools. This highly seasonal flow regime underpins the river's ecology (Douglas et al. 2005, Warfe et al. 2011). Most rivers are unregulated, although notable exceptions are impoundments on the Ord, Leichhardt and Darwin rivers. Groundwater supplies water for irrigation, stock and potable domestic purposes, with the potential to significantly reduce dry season flow.

The wet–dry tropical region's population is low (approximately 240 000 people), with an average density of about 0.1 persons/km$^{2.}$ This is low compared to the more developed parts of Australia (eg Victoria has 23 people/km^2). Most of the population resides in Darwin and its hinterland (120 000 people), Mt Isa (22 000 people), Broome (16 000 people), Katherine (10 000 people) and Kununurra (7500 people). The remainder of the population live in small communities, many of them Indigenous. There are large areas of the wet–dry tropics that are regarded as 'very remote' according to the Accessibility/Remoteness Index of Australia (DoHA 2001). Despite this remoteness, the region supports substantial industry (eg mining, grazing, fishing, tourism) and heritage values (eg Indigenous art, dinosaur fossils).

The landscape of the wet–dry tropics is highly weathered, of low relief, and dominated by savanna grassland and woodlands. Low-intensity cattle grazing is the main land use, while Indigenous and conservation uses are the next most common uses. More intensive land uses, such as agriculture and mining, represent less than 2% of the land area (Woinarski et al. 2007). Intensive agriculture is currently concentrated in parts of the Ord and Daly river catchments, and will extend to the Keep River catchment through the Ord River Irrigation Scheme Stage 2 development. Intensive agriculture tends to be on a small scale in the Gulf of Carpentaria catchments; for example, sugar cane crops in the upper Mitchell River catchment. Fire is a significant landscape-scale management issue, with fires more frequent and more intense than the traditional Indigenous management of the land (Russell-Smith et al. 2003).

Pusey et al. (2011) has recently reviewed threats to river health in the wet–dry tropics (Figure 3), which were:

- grazing
- altered fire regimes
- feral animals
- weeds
- cropping and agriculture
- tourism and recreational activities
- industrial, mining and urban impacts
- altered flow regimes
- physical infrastructure (eg barriers to fish movement)
- climate change.

Despite these threats, river health in the wet–dry tropics is generally good compared to the rivers in southern Australia (Pusey et al. 2011). However, there is degradation due to diffuse impacts (eg feral animals, grazing, irrigation) and point sources (eg wastewater discharge from mines).

Cattle track network under the riparian canopy

Riparian weed *Passiflora foetida* smothering saplings

Cattle access to the stream edge

Past cattle bank and stream access

Stream edge trampled by cattle

Stream edge trampled by pigs

Figure 3 Cattle, feral animal and weed disturbance to the riparian zone and stream channel

Photos: I Dixon

1.3 Challenges for river health monitoring in the wet–dry tropics

The vast land area, scant road network and climatic extremes of the wet–dry tropics, combined with the small population, pose logistical challenges to monitoring. Long distances need to be travelled to undertake fieldwork, which imposes a time and financial cost. The road network is not extensive, with only major roads generally sealed. This restricts vehicular access to watercourses, especially low order streams. In the wet season, unsealed roads can become impassable, and sealed roads can be periodically flooded. In the dry season, when vehicular access becomes possible, many rivers and streams cease flowing and become dry riverbeds or a series of disconnected pools that dry out.

River health monitoring has tended to occur during the dry season when vehicular access is possible, and been biased towards large, high-order rivers such as the Daly, Mitchell, Fitzroy and Ord rivers. A perennial flow regime dominates the high order rivers of the Daly catchment, but represents a small proportion of the total drainage network (Figure 4). Small, lower order streams have not been monitored in proportion to their contribution to the total length of the drainage system.

There is some evidence that perennial small streams are more vulnerable to cattle and feral animal impacts than larger rivers (Dixon et al. 2011); hence, their omission in monitoring programs may produce misleading assessments. Vehicle access to such streams, even in the dry season, can be difficult and time consuming, especially in the absence of bush tracks. Moreover, to select flowing sample sites an understanding of stream flow regimes (perennial or seasonal flow) is required but often lacking and not necessarily accurately represented on topographic maps.

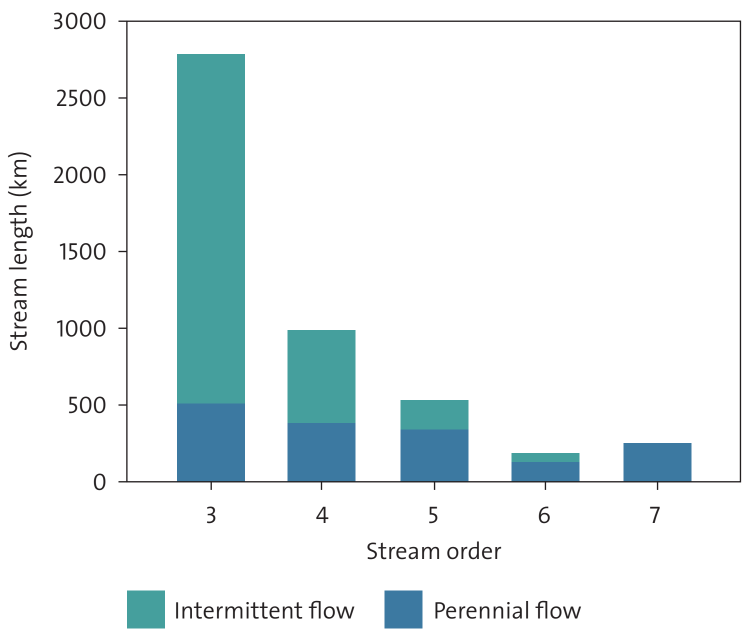


Figure 4 Daly catchment perennial and intermittent flow stream lengths. Stream order and length were obtained from a National Land and Water Resource GIS (Dixon et al. 2011), which omitted 1st and 2nd order streams. The perennial flow category was based on GIS classification, Tickell (2008) and data supplied by the Department of Land Resource Management.

1.4 Monitoring objective

Clearly stated objectives and hypotheses are the basis of river health monitoring programs by providing an articulated purpose. In the wet–dry tropics, long term monitoring for the early detection of river health degradation, as advocated in national guidelines for river health assessments (ANZECC–ARMCANZ 2000), is recommended. This primary objective seeks to detect degradation before it becomes ecologically significant, thereby avoiding undesirable social impacts, and costly river and catchment restoration. Importantly, residents of the wet–dry tropics have high expectations that their rivers will remain healthy and view any degradation, even if minor on a national scale, as being significant and the possible start of long-term degradation. Additionally, for Indigenous people, the environmental values of a healthy river are inseparable from cultural values and underpin a wide range of cultural activities.

A secondary objective that is closely aligned with the main objective is to monitor for the incremental degradation of river health. This objective provides a spatial and temporal context to the primary objective. River health degradation on a catchment scale typically results from the cumulative impact of multiple pressures (fire, grazing, feral animals, point sources and weeds) operating at a range of spatial and temporal scales. Single anthropogenic disturbances are rare with the possible exception of pollution from acid mine drainage.

The adoption of an early detection objective, however, has design and resource implications. To detect small degradations in river health with reasonable confidence, replication is required to overcome natural spatial and temporal variability. Using more replicate sites or sampling occasions increases the likelihood of detecting true river health degradation, although with diminishing returns at 'high' sample size.

In statistical terms, replication increases the power to detect an effect, which minimises type I and II error rates.[1] Increasing replication, however, requires more resources.

The early detection of river health degradation also requires the selection of indicators responsive to possibly low levels of anthropogenic pressure. Indicator choice should be based on a sound conceptual understanding of the relationship between pressures and the environment, and ideally supported by experimental evidence that provides an insight into the threshold and rate of indicator response to a pressure.

[1] A type I error incorrectly classifies a site as impaired. A type II error incorrectly classifies a site as unimpaired.

1.5 Monitoring principles

River health monitoring should be more than the collection of site-specific data to meet the legal and policy obligations of governments and other organisations. Rather, monitoring can be viewed as a societal activity, where governments typically play leadership and facilitation roles. This more comprehensive view is underwritten by the following desirable qualities of a monitoring program, referred to as principles:

- **Collaboration.** Monitoring is undertaken by governments, industry, landowners and communities, and should aim to be a collective activity and, whenever possible, make use of all monitoring data to contribute to river health assessment. Collaboration requires human resources, and includes data management.
- **Communication.** All stakeholders and the community have an interest in river health, and want to know the health of rivers in their catchment. Communication needs to be tailored for a range of audiences, from technical reports to plain English summaries, such as report cards.
- **Scientific credibility.** Monitoring must be conducted in a scientifically rigorous manner. It should be underpinned by a sound understanding of river ecology based on a program of research that includes the impact of anthropogenic pressures. A credible monitoring program comprises articulated objectives and hypotheses, the selection of responsive indicators, adequate design, and data analysis and interpretation. Peer review should be sought at all times.
- **Transparency.** To facilitate credibility with all stakeholders and the community, and promote a collective approach to river health assessment, monitoring should be transparent. Information about river health monitoring—including, for example raw data—should be made publicly available. Transparency provides a basis to build trust between monitoring organisations, stakeholders and the wider community.
- **Community participation and education.** The community is often keen to participate in, and contribute to, monitoring programs. Community-derived data do not need to feed directly into the scientific design of a program, and may address local river health issues not addressed by a scientifically designed program. Community monitoring, nevertheless, should be reported and be part of the collaboration. Community participation offers opportunities for river health monitoring in the remote parts of the wet–dry tropics that would be too costly to otherwise undertake. Participation can be valuable in itself by facilitating education, thereby informing the public and land managers about river health management issues, and building capacity and social networks.
- **Relevant to management.** River health monitoring is a component of the adaptive management cycle and needs to be relevant to management. The pressure–stressor–response (PSR) framework, discussed below, seeks to link the anthropogenic pressures—the primary focus of management actions—to river health.
- **Resource efficient.** The resources for river health, especially in the wet–dry tropics, are significantly limited, and should be allocated to provide the most valuable information for the cost incurred.

1.6 Pressure–stressor–response framework for monitoring

The pressure–stressor–response (PSR) framework provides a conceptually comprehensive and potentially diagnostic approach to surveillance monitoring (Figure 5). The framework seeks to link the following:

- anthropogenic pressures on the environment (also referred to as threats)
- the biophysical stressors that collectively drive river ecology
- ecological attributes.

The framework is based on a conceptual understanding of the effect pressures have on riverine ecological health.

Figure 5 provides a simplistic example of the PSR framework. In the first example, clearing native vegetation constitutes a pressure—it increases the catchment's vulnerability to erosion. During the wet season, run-off can transport sediment to the river, increasing the concentrations of suspended sediment and reducing the amount of light available for photosynthesis by algae in the water column and plants on the riverbed, hence reducing the amount of plant biomass. The second example links groundwater extraction for irrigation to reduced dry season flows, and the habitat area for invertebrates and fish. Rarely, however, is there a simple link between a pressure, stressor and ecological response, except perhaps in the case of toxic pollutants. Instead, there is typically more than one pressure, which affects multiple stressors to potentially produce a range of ecological responses.

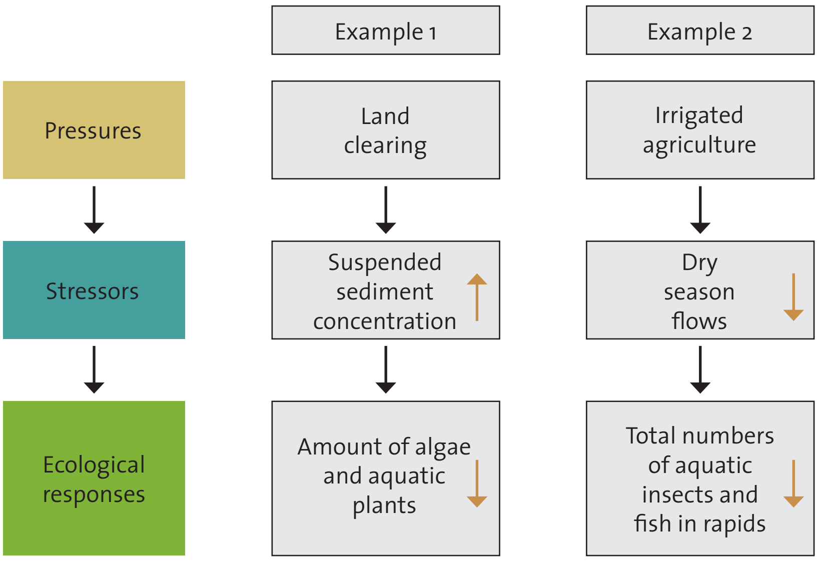


Figure 5 Two simple examples that show the link between pressure, stressor and ecological response. Source: Northern Territory Department of Land Resource Management.

The PSR framework underpins the Framework for the Assessment of River and Wetland Health (FARWH), discussed next, and is embedded within the Queensland integrated monitoring framework (DERM 2010, 2011c).

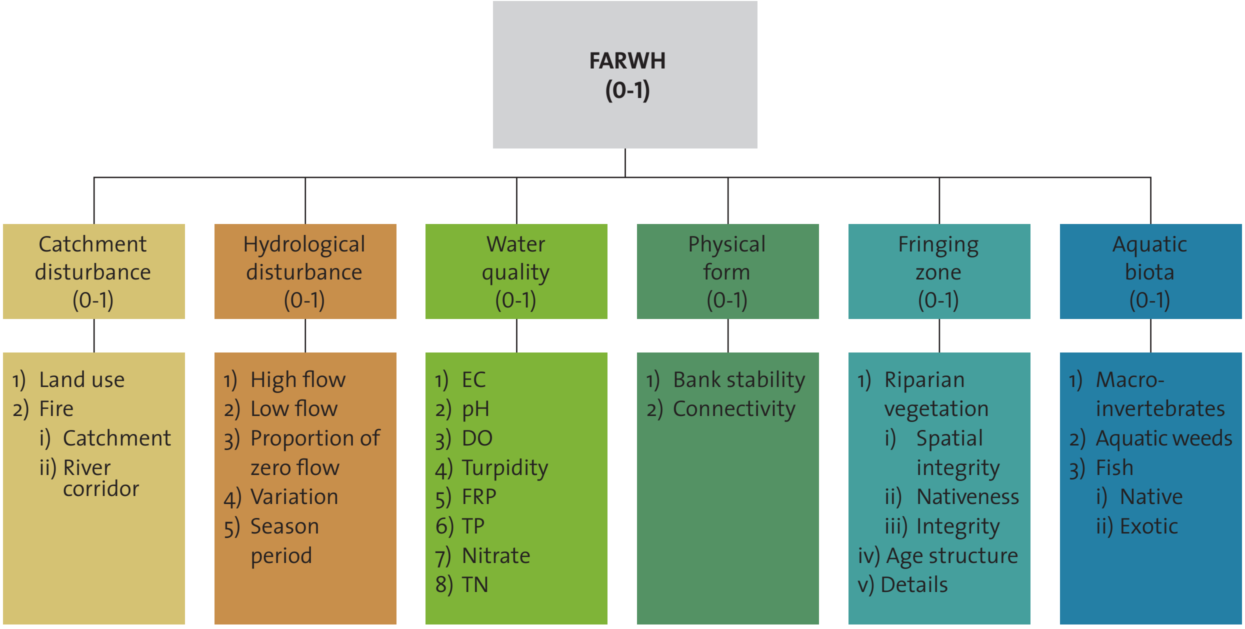
1.7 The Framework for the Assessment of River and Wetland Health (FARWH)

The FARWH was trialled in the wet–dry tropics by TRaCK and the Queensland Government (Dixon et al. 2011, the Queensland Government 2011e), and was supported by the National Water Commission (NWC 2011).

The FARWH provides a comprehensive approach to river health monitoring, and concurs with the PSR framework. It comprises six themes (Figure 6): (1) catchment disturbance, (2) hydrology, (3) water quality, (4) physical form, (5) fringing zone, and (6) aquatic biota.

Each theme is scored between 0 and 1, where 0 indicates an extremely impacted or degraded condition, and 1 is a reference condition. Each theme can comprise several subindices that combine to a score between 0 and 1, which are then integrated across themes to provide a single river health score for a catchment. Sample sites are ideally selected to represent the drainage system over a range of stream orders, and the natural (eg geological) and anthropogenic (eg land use) influences. The value of the FARWH lies in its conceptual basis and the detailed information that underlies the scores, which can be lost through the numerical aggregation and integration process.

The FARWH does not prescribe indicators for each theme or sub-theme. This provides flexibility for catchment or region specific pressures, stressors and ecological response indicators to be selected. For example, the area burnt by fires was included in the wet–dry tropical FARWH catchment disturbance index, but is not included in other frameworks.



DO = dissolved oxygen; EC = electrical conductivity; FRP = filterable reactive phosphorus; TN = total nitrogen; TP = total phosphorus

Figure 6 Framework for the Assessment of River and Wetland Health (FARWH).

The most significant findings from the wet–dry tropical trials of the FARWH are listed below (see DERM 2011e, Dixon et al. 2011):

- The Flow Stress Ranking, developed for the Victorian river health program, can be applied (Figure 7) with minor adaption to accommodate wet and dry seasons.
- Grab or spot water samples are likely to miss short-term pollution events. For example, plumes of highly turbid water were only detected with continuous logged monitoring when cattle regularly disturbed a stream in the afternoon; grab samples in the morning missed these events. Continuous monitoring is preferable to grab samples, and is also best for the diel-dependent (variable over the day) variables (dissolved oxygen, temperature and pH).
- The Tropical Rapid Assessment of Riparian Condition (TRARC) required reference site data to be applied to the FARWH fringing zone theme. TRARC sub-indices were not correlated to independent measures of cattle and feral animal impacts, although this may reflect the localised nature of these impacts compared to the 200 m riparian reach surveyed. A subset of TRARC sub-indices, using raw data rather than categories, may improve the sensitivity of riparian condition assessments.
- Most fringing (riparian) zone vegetation in the Western Australian, Northern Territory and Queensland wet–dry tropics has not been cleared. The condition of this zone can, however, be degraded by weeds, fire and grazing, which are not detected by remote sensing methods.
- Macroinverebrate Australian River Assessment System (AusRivAS) and fish observed/expected scores were weakly related (r^2 ~10–15%) to the intensity of cattle impacts in the Daly and Fitzroy rivers.
- Diel-dissolved oxygen and temperature measurements to monitor river metabolism (photosynthesis and respiration) in streams sometimes produced 'unusual' dissolved oxygen curves with a night-time maximum that were attributed to the influence of large, probably thermally stratified pools upstream, and precluded the calculation of whole-of-river metabolism. The computation of metabolism in small streams with relatively large pools is problematic.
- Reference condition for the wet–dry tropics has not been extensively monitored, nor has it been well defined. This limited the application of the FARWH.
- When working over large and remote areas, both spatial and temporal logistic and resourcing issues resulted in an insufficient number of test and reference sample sites to obtain adequate statistical power (eg Burdekin River catchment). This led to a lack of confidence in certain indicators, particularly those under the 'water quality' theme.
- High levels of natural temporal variability in geographic areas, such as the Burdekin River catchment, provide a constraint to meaningful condition assessments based on the snapshot approach. To address statistical issues when reporting at different spatial scales or using different sample sizes, it is suggested that different power/confidence levels are used for analysis (appropriate to the spatial scale or sample size). Risk assessment could be used to establish the power/confidence level that reflects the priorities within and between catchments.
- Remote sensing and GIS can improve assessments over large areas.

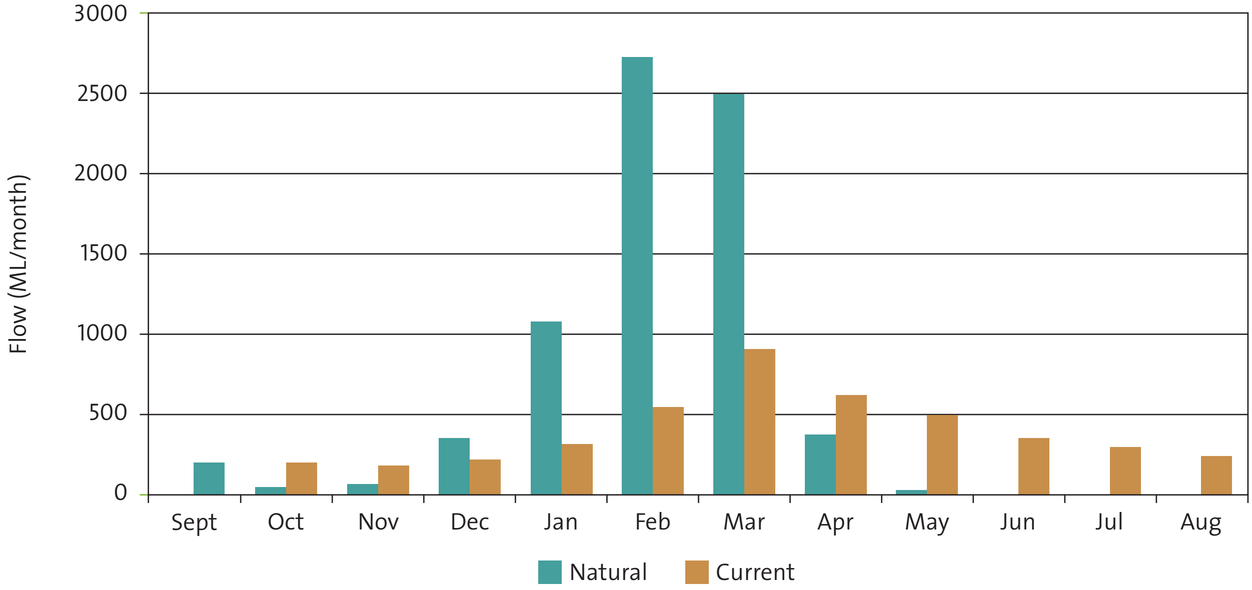


Figure 7 Monthly average flows for the Ord River, downstream of the Argyle Dam and the Dunham River confluence, 1974–2005. These data were used to calculate the Flow Stress Ranking for the Framework for the Assessment of River and Wetland Health 'hydrological disturbance' theme. Source: Dixon et al. (2011).

1.8 A two-tiered approach to monitoring

A major recommendation of the wet–dry tropical FARWH trial was a two-tiered approach to monitoring (Dixon et al. 2011; Figure 8). The first tier monitors pressure on a catchment-wide scale. The second tier monitors stressors and ecological response on a smaller scale to evaluate river health of high management and conservation priority, including reference sites. This approach is similar to Queensland's Stream and Estuaries Assessment Program (SEAP), which uses a risk assessment to identify broad scale pressures, and then monitors stressors and ecological responses of the priority pressures (DERM 2011b).

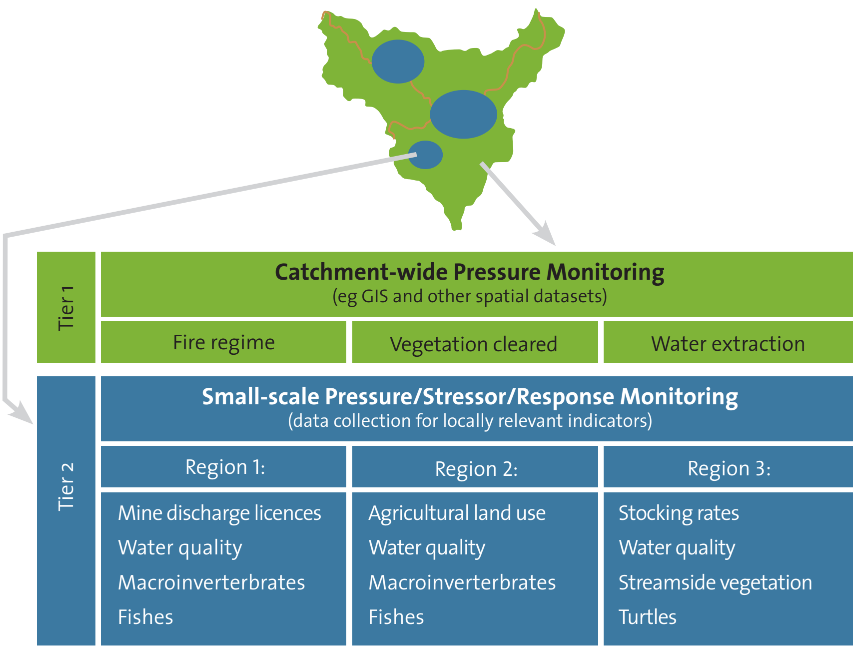


Figure 8 Two-tiered approach to river health monitoring (GIS).
Source: Northern Territory Department of Land Resource Management

To obtain a catchment river health assessment, second-tier findings or scores can be extrapolated to the broader catchment based on knowledge of the relationships between the pressure, stressor and ecological response themes. This extrapolation would be based on relationships between tier 1 pressures and tier 2 themes, and may be quantitative or even qualitative. The latter qualitative approach was applied to the Daly River catchment (Dixon et al. 2011), which was classified into developed and undeveloped regions defined by the extent of sub-catchment native vegetation cleared. Quantitative approaches have not been researched in the wet-dry tropics.

The recommendation for a two-tiered approach is an acknowledgment of the mismatch between catchment size and the resources available for river health monitoring, and the need for the efficient expenditure of monitoring budgets. It acknowledges that not everything can be monitored everywhere.

Tier 1 is envisaged to use mainly GIS or spatially explicit catchment-wide datasets. The tropical FARWH applied land-use and satellite-derived fire data (Figure 9), but could include the area of native vegetation cleared as a surrogate for catchment development.

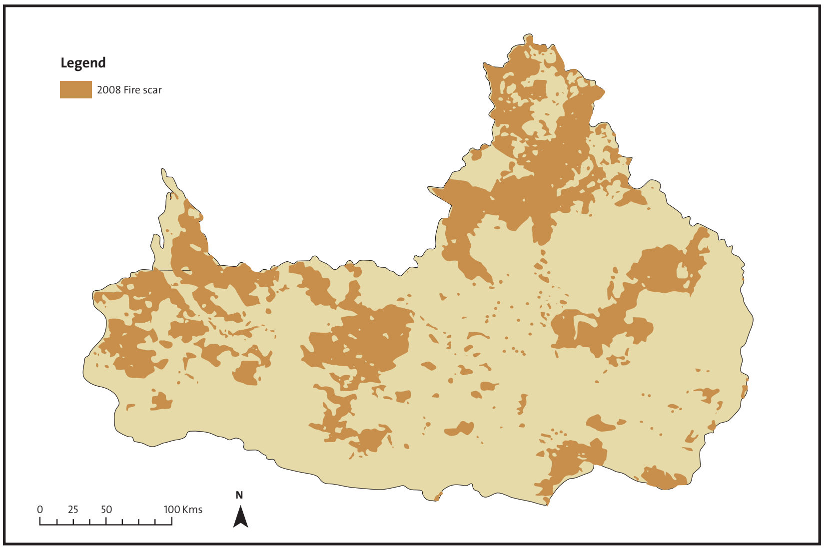
Tier 1 could also include the hydrology theme when hydrographic data are available. However, we caution against the use of Tier 1 monitoring for the fringing zone theme based on the proportion and area of cleared vegetation because most of the zone's vegetation has not been cleared and would be better assessed on below canopy criteria, though this has practical constraints.

Tier 2 comprises small-scale, case study–type monitoring to assess the impact of a pressure on the ecological condition of a river or stream. This tier could include an experimental design such as the before–after control-impact (BACI) or sites representing a gradient of anthropogenic pressure. An example of a well designed, detailed study to elucidate the response of river health indicators to catchment pressures is provided by Arthington et al. (2007) for the wet tropics.

The resources for monitoring could be assigned according to an explicit assessment of the risk of river health degradation, based on tier 1 data and an understanding of the relationships between pressure and river health. Point-source impacts on river health are often monitored through government-licensed discharges and could contribute to tier 2 monitoring. Reference sites need to be monitored as part of tier 2 monitoring.

Where resources and skills are severely limited, the most efficient and informative monitoring may comprise only tier 1 monitoring at a sub-catchment scale, and rely on the knowledge that reduced pressure will reduce degradation of river health. For example, resources may be better allocated to monitoring pig populations (pressure indicator) and their response to eradication measures, rather than monitoring a single stressor (eg pig physical disturbance along river reaches) or the aquatic biota.

The wet-dry tropical FARWH recommendation for a two-tiered approach to monitoring concur in principle with the recommendations for the national FARWH implementation (NWC 2011), although the latter includes the fringing zone and hydrological stressors as tier 1 components.



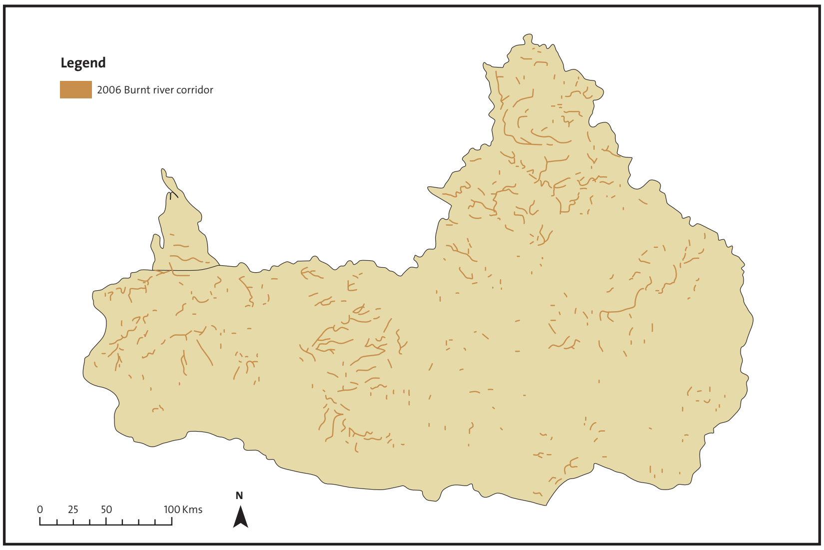


Figure 9 Fires are now more frequent and intense in the wet–dry tropics (top). Catchment (middle) and river corridor (500 m widths; bottom) fire scars identified by the moderate-resolution imaging spectroradiometer (MODIS) for the Fitzroy River catchment (2008). Source: Dixon et al. (2011).

1.9 Temporal variability

Temporal variability is important and needs to be considered when designing monitoring programs for river health in the wet–dry tropics. Natural changes in ecosystems associated with high seasonal and interannual variability in climate and river flow can confound the interpretation of monitoring results if these changes are not well understood.

Seasonal variability

Researchers have investigated the responses of stream macroinvertebrate communities during different phases of the hydrograph in wet-dry tropical, seasonally flowing streams, notably within Kakadu National Park (Garcia et al. 2011; Humphrey & Douglas, unpublished data). An aspect of seasonal changes in community structure was demonstrated by calculating dissimilarity indices for the communities resident at two different sites in the same stream. These dissimilarity values are plotted over the hydrograph conceptually in Figure 10. Periods in the hydrograph where paired site (upstream–downstream) dissimilarity are low indicate that the communities are relatively similar to one another in the types of taxa and relative abundances of taxa.

Periods of 'high' dissimilarity, shown in Figure 10, indicate either (a) moderate and consistent flow or spate-related disturbance for periods of flow connectivity (wet season); or (b) stochastic colonisation and other processes (eg different fish predation) occurring independently in pre-flow and late dry season pools. During recessional flow as major flows recede, disturbance effects dissipate and habitat between adjacent sites tends to become similar. In response, diversity and abundances (number of taxa per sample) increase (Figure 11), and community structure becomes increasingly similar between paired sites. These changes towards increasing similarity in community structure over the recessional flow period are reflected in the decreasing between-site dissimilarity (Figure 10). High similarity in community structure (or low paired-site dissimilarity) is also evident at initial pool creation associated with early wet-season pool formation as a result of low diversity (Figure 11b) and common substrate-derived microcrustacean fauna.

The relevance of changing similarity in indicator assemblages over the annual hydrograph for monitoring is that stream health assessments are based on the comparison of community structures at the time of sampling at test sites with those from a reference condition (reference sites are sampled simultaneously and/or are compared to baseline data). If annual monitoring is not standardised to the same or similar hydrological conditions, natural shifts in community structure among sites may be incorrectly attributed to human-related disturbance, which may seriously confound monitoring results. If standardisation of annual sampling times is not possible or if monitoring requires regular sampling during different seasons, then a full understanding of ecological/community dynamics that govern inter-site community similarity for all relevant stream assemblages, not just macroinvertebrates, is essential. Flow or flow-related variables that are closely related to community dissimilarities may then be modelled to account for natural temporal variability using statistical covariance methods. This would then enable the use of variants of classical hypothesis testing for impact detection and assessment (eg statistical tests of data gathered using BACI designs).

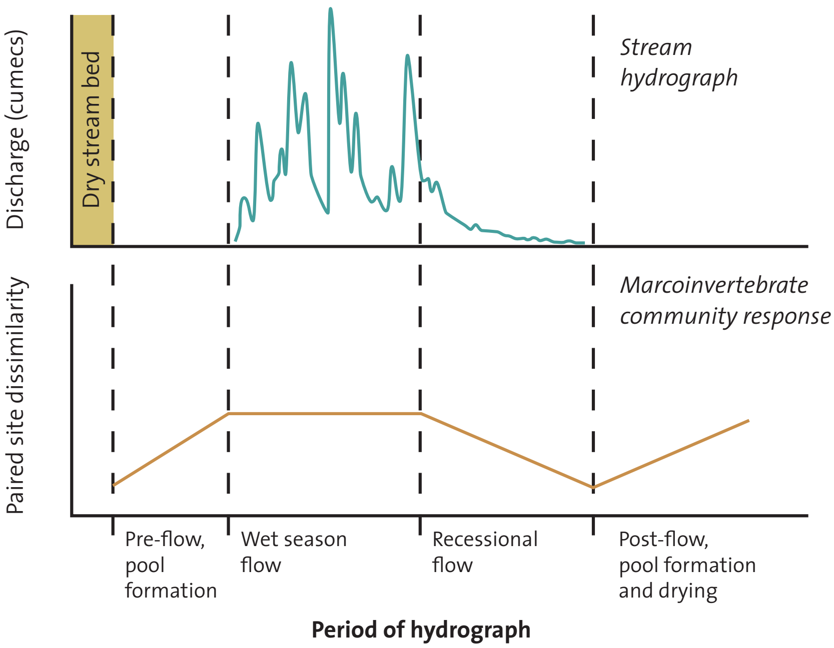


Figure 10 Behaviour of paired-site (upstream–downstream) Bray–Curtis dissimilarity measures for different phases of the hydrograph in northern seasonally flowing streams that cease to flow during the latter part of the dry season. Source: Humphrey & Douglas (unpublished data).

The observations of increasing abundance and diversity of macroinvertebrates in a section of stream of permanent flow, as shown in Figure 11(c), are relevant to riffle habitat. These stream sections are effectively scoured during the wet season then become increasingly colonised by taxa with a preference for flow as the dry season progresses (Dostine & Humphrey 2011). In similar streams, Leigh (2011) examined seasonal (early and late dry season) patterns of macroinvertebrate community structure in edge and sand habitats. For edge habitat, converse patterns were observed to those from riffle habitat. Thus, as recessional flow declines to become undetectable in the late dry season and even cease, macroinvertebrate communities in both habitats tend to become less diverse at the family level, with fewer taxa that prefer flow.

Interannual variability

Garcia et al. (2011) have described interannual variation in the composition of invertebrate communities. This description was a summary of Humphrey et al. (2000), who examined and analysed long-term datasets from across Australia, including three from streams in the wet–dry tropics, to determine the degree of interannual variability evident in stream macroinvertebrate communities. Indices were derived to quantify persistence or constancy—that is, the tendency for community composition (presence/absence) or structure (relative abundance) to remain relatively unchanged between years. Using community structure data, persistence in Australian streams was generally found to be low. For wet-dry tropical Australia, Dostine and Humphrey (2011) showed how a gradual reduction in the base (dry season) flow of a perennially flowing section of a stream, during several consecutive years of below-average rainfall, could lead to a sudden switch from high abundances of flow-dependent taxa to the near extinction of several of these taxa. This switch persisted well after the years of low flow and when rainfall and flow had returned to average or above average conditions.

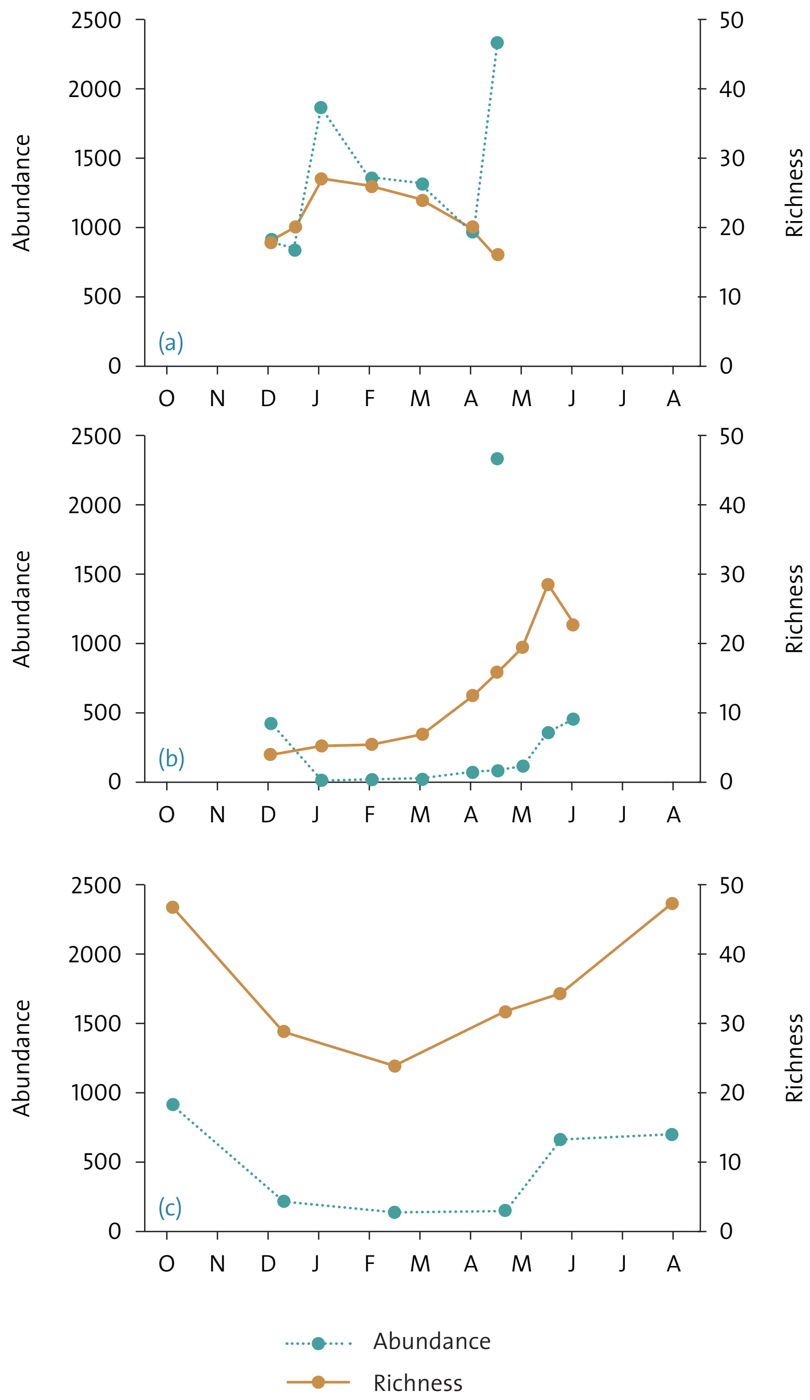


Figure 11 Seasonal patterns of stream macroinvertebrate richness and abundance for (a) a seasonally flowing stream with the hyporheic zone contact; (b) a seasonally flowing stream without hyporheic zone contact; and (c) a permanently flowing stream. Source: Garcia et al. (2011; Figure 5.2).

Using community compositional (presence/absence) data, several observations were made (Humphrey et al. 2000):

- As interannual flow variation (as measured by the coefficient of variation for annual flow) decreases, persistence in macroinvertebrate community composition increases. Since interannual variation in flow for most streams in the wet–dry tropics is among the lowest observed in Australia, this indicates that compositional persistence of macroinvertebrate communities in this region is relatively high.
- Persistence was higher in streams (or portions of streams) of permanent flow than in streams of seasonal flow that dry out for a portion of the year. Stochastic processes associated with macroinvertebrate recolonisation of seasonally flowing streams were presumed to explain the greater interannual variability in community composition observed in these streams.
- Although no significant correlations were observed between persistence and latitude, there was a tendency for macroinvertebrate communities of permanent streams in temperate Australia to be more persistent than those in permanent streams in tropical regions. The shorter life cycles of tropical invertebrates (due to warmer water temperatures and because short cycles are selected for in regions with high seasonal extremes in discharge) were thought to contribute to the reduced persistence of communities in permanent streams of the Australian tropics.
- Cyclonic disturbance, and extreme flood and drought were the main factors causing low persistence of macroinvertebrate communities in Australian streams. Although none of the wet–dry tropical streams represented in the analysis by Humphrey et al. (2000) had been subjected to these (extreme) events for the record of data analysis, cyclonic disturbance and floods are features of the hydrological record of many of these streams and interannual shifts in macroinvertebrate composition can be expected to occur as a consequence.

The Humphrey et al. (2000) research was commissioned under the National River Health Program to assess the implications of temporal variability on the development of AusRivAS predictive (bioassessment) models. In particular, an important assumption of predictive modelling is that macroinvertebrate community composition is reasonably constant over time. Despite the temporal variability found in the composition of macroinvertebrate communities in streams of the wet–dry tropics, the level of variability was considered low enough for successful model development.

2 Indicators

The following section draws upon research conducted by TRaCK, as well as conclusions from several years of research and monitoring by TRaCK partners. It is not intended to be a review of all possible indicators for rivers and streams in the wet-dry tropics.

2.1 River metabolism

Richard Hunt, consultant,
and Simon Townsend,
Charles Darwin University

River metabolism refers collectively to gross primary production and ecosystem respiration in rivers (Odum 1956), and underpins the trophic structure and biomass of aquatic ecosystems. River metabolism has been identified as one of five fundamental ecosystem processes (Giller et al. 2004). When calculated from diurnal measurements of dissolved oxygen concentrations and temperature, gross primary production (GPP) and respiration refer to the total amount of carbon fixed by photosynthesis and the oxidation of organic carbon by molecular oxygen, respectively. River metabolism responds to a wide range of stressors that include nutrient, chemical, and sediment pollution; flow alteration; the condition of the riparian vegetation; channelization; and aquatic plant management (Young et al. 2008). Metabolism can be measured using benthic chambers or the open-channel method (Bott 1996). Benthic-chamber measurements are habitat or substratum specific, whereas the open-channel method integrates metabolism over a river reach and takes into account larger scale and spatially variable processes. Open-channel river metabolism was investigated in the middle reaches of the Daly River over the dry season (Webster et al. 2005, Robson et al. 2010, Townsend et al. 2011), and contrasting tropical freshwater systems in Far North Queensland (Hunt et al. 2012).

Rates of photosynthesis and respiration in the Daly River and three high-order tributaries were similar between sites, and approximately doubled over the dry season. In the clear waters of the Daly River, primary producer biomass, notably benthic algae, is most likely to be limited by nutrients (Ganf and Rea 2007, Townsend et al. 2008, Robson et al. 2010). Thus, photosynthesis is responsive to primary producer biomass, and indirectly responsive to nutrient concentrations and trophic state. Nutrient pollution by nitrogen and phosphorus of the Daly River would be expected to increase primary producer biomass and produce higher rates of photosynthesis. Respiration in the Daly River is closely coupled to photosynthesis, and is potentially responsive to other anthropogenic impacts and nutrient pollution (see Young et al. 2008).

In the Mitchell River, water resource development is restricted to small areas in the upper catchment. A natural flow regime persists through most of the river system. During the dry season high light availability, clear water and stable perennial base flows can potentially support high levels of aquatic primary production. During wet season flows and floods, inputs of terrestrially derived organic matter can later drive high rates of respiration in the river channel during the dry season. Despite the low nutrient availability, gross primary production was predominantly regulated by light and increased lower in the catchment. The river was heterotrophic and ecosystem respiration (ER) was regulated by temperature but was markedly higher at the strongly heterotrophic downstream reach, suggesting that a greater quantity and quality of organic material accumulated lower in the catchment (Hunt et al. 2012).

The effect of discharge on river metabolism was investigated using time series analysis in the regulated Barron River, which experiences high variation of depth and velocity during the dry season as a result of water released from a large in-stream impoundment. Variation of GPP was predominantly explained by discharge (~60%) while turbidity and radiation were also explanatory factors (~20% combined). ER was regulated by a combination of temperature and flow (adjusted $r^2 = 0.57$) and the river, which was consistently heterotrophic, shifted towards lower primary production to ecosystem respiration (PP/ER) ratio during periods of higher discharge (Hunt and Menke, unpublished data).

Nutrients can have a strong regulatory effect on the accumulation of primary producer biomass, particularly when other controlling factors such as light are not limiting. River metabolism in a constructed wetland (Hunt, unpublished data) which received high nitrogen and phosphorus inputs from agricultural runoff and aquaculture effluent was strongly autotrophic (PP/ER = 1.6) and contrasted with the normally heterotrophic status in the river systems. Within the inlet channel to the wetland, where the water surface area and residency times for suspended algae were greatly reduced, respiration was very high and the system was strongly heterotrophic (PP/ER = 0.25).

The advantage of open channel river metabolism measurements, over the direct measurement of primary producer biomass, is its considerably greater efficiency of field, sample analytical and calculation effort. A comprehensive survey of plant biomass for a 5 km reach could take four to five days, and needs to be followed by sample preparation and laboratory analysis. In contrast, river metabolism is determined from dissolved oxygen and temperature data logged by a water quality probe deployed for several days, and also provides information about respiration processes.

Limitations and constraints to river metabolism monitoring, however, include the need for a water quality probe that can log data, and use of an appropriate algorithm that best estimates the oxygen reaeration coefficient. Also, the method is only applicable to homogenous reaches of rivers and streams, without significant groundwater inflow over the study reach. Where a reach includes large pools, relative to runs, the method cannot be readily applied because the diurnal oxygen curve is not solely a function of photosynthesis and respiration, but confounded by pool hydrodynamics, which can result in diurnal curves with a night-time dissolved oxygen concentration maxima (Dixon et al. 2011).

The application of river metabolism in unimpacted systems can be used as a baseline measure of the fundamental processes that support river ecosystems and provide a comparison to systems affected by disturbance. Photosynthesis and respiration are responsive to stressors and indirectly to catchment pressures. The rapid response of river metabolism to stressors, which can be measured at a daily time scale, provides a powerful indicator of river function changes over short time frames and longer periods. By quantifying the response of metabolism to variation of light, nutrients, temperature and discharge, time series models can be used to estimate how different environmental stressors affect these regulatory factors, and to predict their impact on ecosystem functioning.

2.2 Phytoplankton and benthic algae

Simon Townsend,
Charles Darwin University

Phytoplankton (microscopic algae) suspended in a river generally originate from the riverbed or grow within the water column (pelagic), although a small number of algal species are capable of growth in both environments. The biomass of pelagic phytoplankton in fast-flowing rivers is commonly constrained by the continual advective losses downstream. Otherwise, light and nutrients limit phytoplankton biomass, sometimes interacting with river bathymetry and flow.

The composition and growth of phytoplankton has been investigated in the Daly River (Townsend et al. 2012). Most phytoplankton were pelagic, with a single species dominant. Loads of chlorophyll *a* biomass, and sometimes the dominant alga, increased downstream, suggesting net biomass growth. Overall, the biomass of pelagic phytoplankton species was most likely to be limited by nutrients, rather than advection, except possibly along specific reaches.

Consequently, phytoplankton concentrations in the Daly River are likely to be responsive to nutrient pollution. When using phytoplankton to monitor an ecological response to nutrient pollution, chlorophyll *a* concentrations are a simple indicator of phytoplankton biomass, but should be accompanied by the enumeration and biomass computation of phytoplankton species to assess the domination of pelagic species over riverbed species.

Benthic algae also respond to nutrient pollution, however, this depends on the current speed. In the Daly River, a field experiment showed that the response of benthic algal biomass on pavers increased linearly with current speed (Townsend et al.). When nutrients were added, more algae grew (relative to a control) in the faster currents than slower ones. This implies the response of benthic algae to nutrient pollution will not be uniform. Alterations to current speed through river regulation and flow modification will also have implications for current-mediated nutrient uptake by benthic algae and by inference algal biomass (Townsend and Padovan 2009). The spatial and temporal variability of benthic algae may be high (eg Townsend and Padovan 2005) and require too many resources to be a resource-efficient indicator, unless these factors can be standardised and undertaken on a small scale. Monitoring river metabolism is an alternative.

2.3 Water quality

Michele Burford, Australian Rivers Institute, Griffith University

Evaporation drives the water quality of waterholes

Many rivers in the wet–dry tropics cease flowing during the extended dry season to become a series of disconnected waterholes. This includes the Flinders River system in the southern Gulf of Carpentaria (Queensland). These waterholes persist throughout the dry season, providing refuges for plants and animals. Studies of the Flinders River system have shown that water quality in these waterholes changes over the dry season, with parameters such as nutrients and chlorophyll *a* increasing in concentration due to evaporative concentration (Faggotter et al. 2010). Water quality is dependent on the initial dry season quality, rate of evaporation and waterhole average depth. Turbidity due to clays and other colloidal material which remain suspended can also increase over the dry season due to waterhole evaporative concentration, as shown by Townsend (2002). The effect of evaporative concentration on water quality is inversely related to the average depth of a water hole, and needs to be taken into account when interpreting water quality monitoring data.

Nutrient bioassays

Four key factors typically affect phytoplankton growth: hydrodynamics, light, grazers and nutrients. The macronutrients nitrogen and phosphorus are essential for phytoplankton growth, but in excess can result in blooms and reduce ecosystem health. Therefore, understanding the role of nutrients in promoting phytoplankton growth is a critical component to understanding the effect of anthropogenic and climatic impacts.

The traditional method for this assessment is to measure nutrient concentrations in the water, and use both the concentrations and ratio of nutrients to assess whether the waterbody is likely to be limited by nitrogen or phosphorus, or both. However, it is difficult to assess when nutrient concentrations are limiting to growth, as other factors can limit growth such as the rate that nutrients are being cycled, the growth rate and physiological state of the phytoplankton, and the contribution of other limiting factors such as light. Therefore, a complementary method of assessment is to conduct phytoplankton bioassays. This involves adding nitrogen, phosphorus, and nitrogen + phosphorus to water samples, incubating them for a set period with sufficient light, then measuring growth, photosynthesis or biomass accumulation. By comparing these treatments with a control, with no nutrient added, it is possible to assess whether phytoplankton respond to nutrient addition, and to which nutrients. Knowledge of the limiting nutrient(s) will help direct management to reduce nutrient enrichment, as nitrogen and phosphorus differ in their behaviour in the environment.

Bioassays conducted in the waterholes of the Flinders River system in the southern Gulf of Carpentaria, and the middle reaches of the Daly River have shown that phytoplankton were limited by both nitrogen and phosphorus (Faggotter et al. 2010, Robson et al. 2010). This suggests that managing phytoplankton bloom issues requires controlling inputs of both these nutrients.

2.4 Freshwater fish

Mark Kennard, Australian Rivers Institute, Griffith University

Fish are widely advocated as useful indicators of ecosystem health (eg Fausch et al. 1990, Harris 1995, Karr and Chu 1999), because:

- they are almost ubiquitous components of aquatic ecosystems
- they are relatively long-lived and mobile, and therefore reflect conditions over broad spatial and temporal scales
- local assemblages generally include a range of fish species representing a variety of trophic levels and therefore integrate effects from lower trophic levels
- fish are at the top of the aquatic food web (with the exclusion of crocodiles) and are consumed by humans, making them important for assessing contamination
- environmental and life history requirements are comparatively well understood
- they are relatively easy to collect, identify and subsequently release unharmed.

The documented responses of fish to a diverse range of anthropogenic disturbances suggest that fish may be sensitive indicators of the net effect of human impacts on aquatic ecosystems. Fish also provide an easily interpretable endpoint of environmental degradation and can be used as a justification for remedial action, given their ecological, social and economic importance.

Fish can be used as indicators of ecosystem health by assessing toxicant bioaccumulation, fish condition and incidence of fish kills, trends in recreational or commercial fish catches; or by using summary indicators describing fish assemblage structure and function, and comparison with least disturbed (reference) conditions.

There are, however, a number of challenges with the use of fish as indicators, including:

- the difficulty in separating natural versus disturbance-induced variation (which requires an accurate definition of the expected or reference condition)
- responses to anthropogenic disturbance are not well established or validated
- the possibility of poor diagnostic potential, because fish are likely to reflect the result of an integrated effect of a range of disturbance sources (except for extreme or obvious disturbances, such as toxicants or barriers to migration), due to relatively high mobility and longevity.

The central goal of bioassessment is to decide whether a site exposed to anthropogenic stress is impaired while minimising type I errors (incorrectly classifying a site as impaired) and type II errors (incorrectly classifying a site as unimpaired). The development of a fish-based monitoring program should satisfy several key requirements before it can be applied for ecosystem health assessment in a given river or region (Kennard 2005). These requirements include (but are not limited to):

- the ability to collect raw biological data in a standardised fashion and with sufficient accuracy and precision such that it truly represents the locality in question and is directly comparable with other locations
- assessment of the natural ranges in spatial and temporal variation of the biological attributes in question, and the drivers of this variation
- the ability to accurately define the reference condition for biological attributes expected in the absence of anthropogenic stress based on relationships between natural environmental drivers and biotic patterns, such that human disturbance-induced changes can be quantified using biological indicators
- the sensitivity and demonstrated ability of the chosen indicators to reflect or respond to human disturbance.

A systematic evaluation of these key requirements has recently been undertaken for the Daly River catchment (see Dixon et al. 2010) using data collected from past TRaCK research (Chan et al. 2011, Stewart-Koster et al. 2011) and new data from a large number of sites subject to varying intensities of disturbance due primarily to cattle grazing, feral animal activity and the associated local riparian, in-stream habitat and water quality degradation.

The study revealed that fish assemblages sampled by electrofishing with at least 10 five-minute electrofishing 'shots' provided accurate and precise estimates of local fish assemblage attributes with a high degree of statistical power to discriminate between sites.

A set of candidate ecosystem health indicators was selected based on fish assemblage composition, species' relative abundances and ecological trait composition (fish species morphology, habitat use, reproduction, movement and trophic requirements). Evaluation of natural variation in these fish assemblage attributes in response to natural environmental gradients (using predictive models developed and validated using a set of minimally disturbed reference sites) revealed that the reference condition could be reliably defined for only fish assemblage composition. The results of the study also indicated that disturbed streams and rivers in the Daly River catchment were likely to display some differences in native fish assemblage composition from that expected by comparison with similar areas not subject to disturbance (using the predictive model). Deviations in fish assemblage composition from expected natural conditions can therefore potentially be used as summary indicators of degraded ecosystem health and be used for identifying areas that may require management intervention. However, their utility in diagnosing sources of disturbance or the mechanisms by which they influence fish is debatable and requires further examination.

2.5 Macroinvertebrates

Chris Humphrey, Environmental Research Institute of the Supervising Scientist, Australian Government Department of Sustainability, Environment, Water, Population and Communities

Stream macroinvertebrates remain the most logical and popular choice for monitoring of stream health in Australia, including the wet–dry tropics, because of their inherent virtues and adoption under National River Health Initiatives as the flagship indicator group for this purpose (see ANZECC-ARMCANZ 2000). As a consequence, national protocols have been developed (ie the AusRivAS predictive modelling approach to stream health assessments), underpinned by substantial research and the development of a significant skill base across Australia. By comparison, the limited expertise in Australia in phytoplankton, and especially zooplankton, biology has placed severe constraints on the general utility of these groups for routine stream health assessments.

Macroinvertebrates are used in monitoring programs for biodiversity assessments (see ANZECC-ARMCANZ 2000), with the measured responses being regarded as surrogates of ecosystem-level change. Macroinvertebrates may be used to assess broad-scale land use changes or disturbances associated with point-source disturbances.

The first attempt at a synthesis of information on macroinvertebrate communities from wetlands and waterways within Australia's wet–dry tropics was undertaken by Humphrey et al. (2008) as a component of the Tropical Rivers Inventory and Assessment Project (TRIAP; Finlayson and Lukacs 2008). For this, the team examined two aspects:

- broad-scale river health assessments: an analysis of AusRivAS family-level data from wet–dry tropical Australia (Western Australia, Northern Territory and Queensland datasets)

- macroinvertebrate inventory records for assessments at specific sites and/or for conservation and biodiversity importance.

For the first component, AusRivAS bioassessment data were assessed in two ways for TRIAP:

- evaluating the potential to derive wet–dry tropical AusRivAS models, with possible improved precision and resolution, with the artifices of jurisdictional boundaries removed as current models had been developed for each state and territory, or regions therein
- seeking links between macroinvertebrate data and corresponding environmental data, including hydrology, habitat, geomorphic classification and water quality datasets of the respective stream sites.

In relation to the potential to derive unified wet–dry tropical AusRivAS models, the analysis of Humphrey et al. (2008) was not particularly encouraging. The combined Western Australia, Northern Territory and Queensland datasets showed a separation in multivariate ordination space that was consistent with differences in sample processing methods adopted by the different state and territory agencies. Thus, any identified separation of macroinvertebrate communities based upon environmental variables could be confounded by artefacts introduced in sample processing methodology.

Relationships were sought between macroinvertebrate data and corresponding environmental data for Western Australia, Northern Territory and Queensland AusRivAS datasets. Distinct zoogeographic separation of macroinvertebrate communities was evident within northern Western Australia and within Queensland to distinguish gulf-flowing streams from inland-flowing streams. At a smaller scale, within the Daly River catchment, a distinct biological pattern was revealed and found to be associated mainly with stream water chemistry and local hydrological conditions.

Some association between macroinvertebrate communities and water quality (namely, conductivity) was also evident in Kimberley streams, but these relationships were rather weak and are consistent with past analyses (Kay et al. 1999), suggesting a lack of major geographic and climatic barriers that would otherwise promote such zoogeographical separation.

For the second study component listed above, the task of extracting and compiling macroinvertebrate species-level data from northern Australian streams was impractical. Instead, extensive consultation was used to compile metadata descriptions of the macroinvertebrate species-level data available for sourcing and compiling, should this need to be identified, prioritised and adequately resourced. A number of government agency staff and other specialists contributed to this task. These metadata descriptions are contained in Humphrey et al. (2008). Compilation of these metadata highlighted the need for further work on inventory and taxonomy, but also database management to allow for cross-regional comparisons.

Other synthesis and review studies for macroinvertebrates of wet–dry tropical streams of northern Australia were conducted by Finlayson et al. (2006) and Garcia et al. (2011). Seasonal and inter-annual variability of wet–dry tropical stream macroinvertebrates are also described in Section 1.9 of this report.

Some general comments about the role and utility of macroinvertebrate communities for monitoring and assessing the health of seasonal and temporary waterbodies in the wet–dry tropics remain. The experience of researchers and government agency staff suggests that there is a general resilience of macroinvertebrate communities in these systems. The life cycles of species in stream systems that dry out are adapted to seasonal drying and the species are typically cosmopolitan, vagile and/or include seasonal dormancy in their life histories. Those that persist in pools by the late dry season are quite tolerant of poor water quality, including low dissolved oxygen regimes, and aerial breathing forms are well represented. The stream faunas present in upland sites with rocky substrates include many flow-dependent taxa, and a number of these forms have proven to be sensitive to water quality and flow variations (eg the mayfly family, Leptophlebiidae).

It is a common observation that, by recessional flow periods in the early dry season (and in the absence of acid mine drainage and persistent salinity issues), fauna have recovered from wet season disturbance events (natural or anthropogenic), most likely reflecting the short life cycles of most northern species, the high vagility of many species, and the generally intact landscapes of the north such that potential recolonisation sources are relatively plentiful and never too far away.

Stream health assessments using macroinvertebrate community data in tropical Australia may be better informed through an improved understanding of distributions, life histories and habitat profiles of resident species. Research, data compilations and reviews could prove invaluable in the following areas:

- an improved understanding of the functional feeding group categories for northern species
- habitat profiles of resident species (distributions, environmental requirements - see Suter et al. 2006)
- the potential to use species traits of life history, dispersion, reproduction and general physiology to provide greater resolution in stream health assessments (compared with conventional taxonomic approaches)
- the potential for development of biotic indices for northern streams (eg northern SIGNAL - see Chessman et al. 1997)
- the synthesis and management of databases for species distributions (eg Australian Biological Resources Study Fauna Online, Australian National Insect Collection Database, Australian Natural Heritage Assessment Tool).

2.6 Ecogenomics

Chris Humphrey, Environmental Research Institute of the Supervising Scientist, Australian Government Department of Sustainability, Environment, Water, Population and Communities

The field of genomics is a new area of biological assessment. It offers potentially cost-effective identification of all organisms, including microorganisms and meiofauna, within biological assemblages through techniques that target a single or multiple gene(s) of interest that are present in all organisms of interest in the sample (ecogenomics). The field of functional genomics uses analyses of an organism's ribonucleic acid (RNA) to identify changes in gene expression, thereby providing information on the mode of action of contaminants or other environmental stressors on individual organisms (contaminant-specific biomarkers of exposure and effects). Ecogenomics will potentially overcome the major limitations of assemblage group assessments, including phytoplankton, zooplankton and other microorganisms referred to above (ie taxonomic specialist shortages). While this area of biological assessment has not been studied as part of TRaCK, it is incorporated in the National Environmental Research Program, and future investigative studies will be conducted in the Alligator Rivers Region on this topic.

2.7 Time-lapse photography

Tim Jardine and Jeff Shellberg, Australian Rivers Institute, Griffith University

The remoteness of the northern Australian landscape and the strong hydrologic seasonality restrict year-round access to many important river and wetland sites. Time-lapse photography offers the potential to overcome some of these limitations by providing information at hourly or daily intervals throughout seasons when access is difficult or impossible. Two examples of the utility of time-lapse cameras are provided below: one is for identifying animal pressure on waterholes and subsequent ecological response (Figure 12), and the other is for measuring gully erosion retreat rates and hydrological processes (Figure 13).

Example 1: Waterhole animal use and ecological response

Animal pressures on waterholes (feral pigs, cattle) and the ecological response (aquatic plant cover) to seasonal changes and pressures were identified using time-lapse cameras (Moultrie Gamespy, EBSCO Industries Inc, Alabaster, 2848 x 2136 pixels, ~6 MP) that were mounted on trees at nine permanent floodplain waterholes in the lower Mitchell River, Queensland. At three of the sites, both time-lapse and motion-detect cameras were installed to compare the relative merits of the two types. Along with a series of other measurements not described here, transects into the riparian zone and the waterhole were used to assess cattle activity and aquatic plant cover and compared with information obtained from the cameras.

Time-lapse cameras were superior to motion-detect cameras because they provided standardised measures of pressure on waterholes (cattle presence). The total number of cattle photographed at a site was strongly correlated with a secondary measure of cattle activity: the number of cow pats counted on transects (Figure 13). The photos showed that, as the dry season progressed and water became less available on the landscape, the frequency of visitation to these permanent waterholes by cattle increased. Shallow waterholes with high cattle activity had high nutrient concentrations and turbidity at the end of the dry season, while deeper waterholes visited less often by cattle had lower nutrient concentrations and less turbid water.

Photos from time-lapse cameras also provided the necessary resolution to estimate the cover of aquatic plants and observe many of the dominant species present, including weeds (eg water hyacinth). Per cent cover estimated from the photos by a viewer with no knowledge of the sites (an overseas colleague) was highly correlated with transect measurements, and independent measurements using the photos by two of the project team members were also highly correlated. From this, the seasonal changes in aquatic plant cover could be estimated throughout wet periods when the sites were inaccessible. They showed that cover typically declines towards the end of the dry season, followed by rapid regrowth after the first flood event of the wet season. This highlights the need to consider seasonal dynamics in the assessment of river or waterhole condition.

For animal assessments, the major limitation of the time-lapse cameras was that they considerably underestimated pig activity. High-intensity, nocturnal pig intrusions to waterholes that were short in duration were often captured by motion-detect cameras, but these animals were rarely captured by time-lapse cameras. This can be addressed by reducing the frequency of image collection from hourly to daily (depending on the goals of the monitoring). However, extra battery capacity is required to collect hourly images over many months.

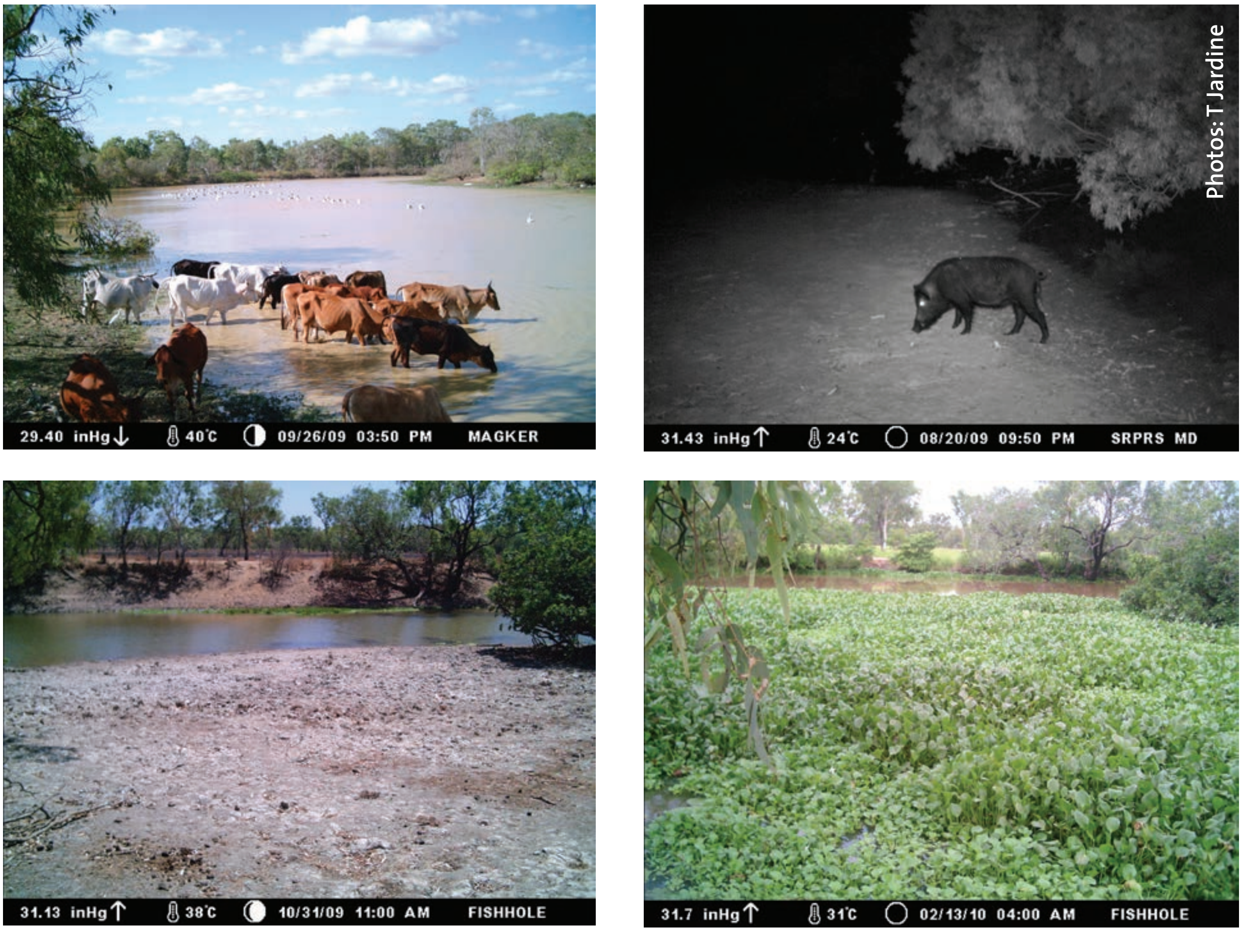


Figure 12 Time-lapse photographs of (top) cattle and pig visitation, and (bottom) a dry season waterhole, later covered by aquatic plants in the wet season.

Another limitation of time-lapse cameras in general is the difficulty of maintaining the cameras in the harsh conditions encountered in northern Australia (rainfall, humidity, heat and ultraviolet light exposure). This can be partially overcome by sealing joints on the outer surface of the camera and adding protective covers, as discussed below.

Time-lapse cameras offer the potential to assess the positive and negative impacts of cattle on waterholes (Jansen and Robertson 2001, Marty 2005), as well as seasonal changes in plant cover and weeds, and to do so at times of the year when access to sites is otherwise impossible (see Figure 12).

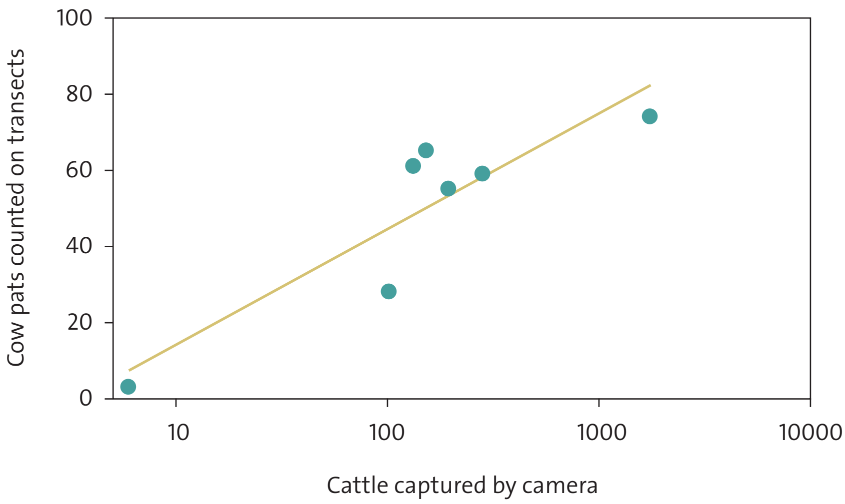


Figure 13 Correlation (r=0.89, p=0.007) between cattle photographed and cow pats counted on transects.

Example 2: Gully erosion retreat rates and hydrological processes

Gully erosion retreat rates were measured using time-lapse cameras (Moultrie Gamespy, EBSCO Industries Inc., Alabaster, AL, 2848 x 2136 pixels, ~6 MP) that were mounted on stable trees at three alluvial gully sites along the Mitchell River Fluvial Megafan, Queensland (Shellberg et al. 2012). Oblique daily photographs were internally rectified to each other in a GIS using ground control points. The gully scarp edge was digitised daily after intervals of observable change. Due to the oblique angle, only a relative change in gully area at the scarp edge could be measured, which was calculated as the percentage of daily change divided by the total change over the period of record. To estimate actual planform change, the percentage of daily change divided by the total change was multiplied against the horizontal area change measured during annual GPS surveys using a differential global positioning system (GPS) (Trimble with Omnistar HP; see Brooks et al. 2009). These erosion index data were then compared against daily rainfall metrics, river/gully water surface stages, and photographic observations of hydrological processes.

Daily time-lapse photography demonstrated that annual scarp retreat was the cumulative sum of both subtle and major incremental failures of discrete soil blocks or smaller flakes (Figure 14), and was driven by multiple water sources and erosion mechanisms.

Observed water sources for erosion came from the combination of direct rainfall, diffuse infiltration-excess water dripping over the scarp face, infiltration-excess runoff plunging off the scarp face, and backwater into and full inundation of the scarp face from river floodwater. The 24-hour rainfall total was the best predictor of daily scarp area change for all sites (r2 > 0.60) and likely represents a proxy measure for a whole suite of measured and unmeasured variables influencing gully scarp retreat. The incursion of river backwater and overbank flooding into alluvial gullies episodically overwhelmed typical rainfall-runoff processes and caused major scarp retreat at frequently inundated sites.

Several initial electrical corrosion problems were encountered with the time-lapse cameras due to harsh moisture conditions during the four-month wet season deployments. However, these problems were fixed by using silicone along every joint of the camera housing to ensure a watertight seal. Future deployments could use improved weatherproof housings, however this will increase costs relative to the price of the cameras.

The oblique time-lapse photography proved to be valuable for qualifying basic hydrogeomorphic processes in remote locations, and for quantifying daily scarp retreat and relative planform area change in conjunction with annual GPS measurements. More intricate camera setups could be used in the future, such as vertical views (ie for towers or trees) or horizontal views of the gully face using multiple cameras. While oblique photographs from non-photogrammetric cameras are not ideal due to potential sources of quantitative error, they are extremely cost effective and more practical than obtaining low-altitude, large-scale aerial photographs at the daily scale to measure scarp retreat. Overall, time-lapse photography is a valuable tool for managers and scientists for short and long-term monitoring of hydrogeomorphic and ecological processes.

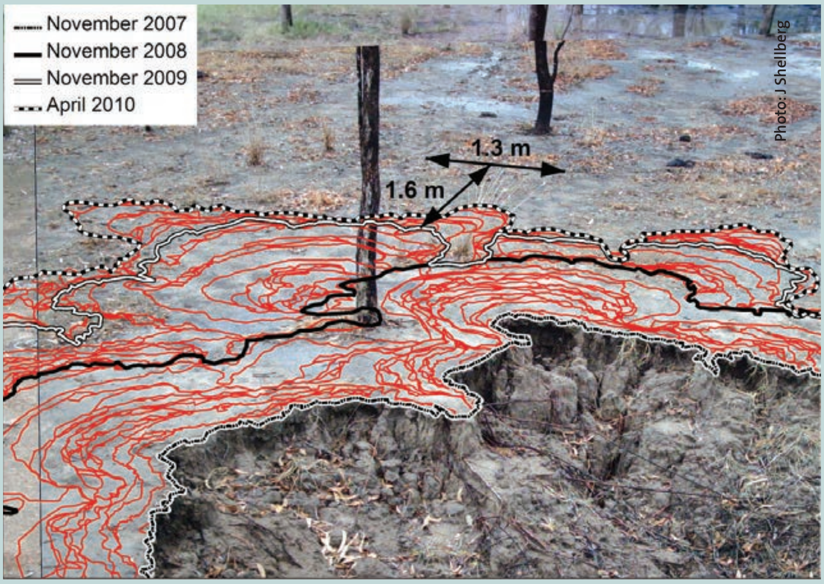


Figure 14 Incremental change in gully location from daily photographs at site KWGC2 between 2007 and 2010, Mitchell River Fluvial Megafan.

3 Community monitoring

3.1 A Kimberley case study

Rebecca Dobbs, Centre of Excellence in Natural Resource Management, University of Western Australia

Natural resource management can benefit from collaboration with local communities in research, monitoring, identification of values and the development of management procedures, priorities and strategies. In particular, monitoring is an important process for evaluating the effectiveness of management actions and a key component in any adaptive management framework. In the Kimberley region of northern Western Australia, remoteness combined with limited resources and community capacity has the potential to restrict onground management and monitoring of rivers and their catchments.

To address these issues, a waterways education program (WEP) was developed and has been implemented over the past three years (Dobbs & Cossart 2010). The Kimberley WEP relies on partnerships between government, research and community groups involved in regional natural resource management, with adequate regional capacity and community involvement considered a fundamental management requirement.

The Department of Water (Kununurra) and the University of Western Australia (TRaCK) jointly initiated the program, partnering with communities and Indigenous rangers employed through the Working on Country (WOC) Program to manage the cultural and environmental values of their land and sea estates (eg weed control, fire management, feral animal control).

The Kimberly WEP focuses on strengthening local community knowledge and participation in natural resource management, with an emphasis on providing remediation actions and monitoring techniques for rivers and wetlands. Delivery involves hands-on field sampling of a range of indicators, including macroinvertebrates ('bugs'), fish, water quality and vegetation, providing an interactive demonstration of western science techniques and their application for river monitoring (Figures 15 and 16). This collaboration allows rangers to combine up-to-date research with their onground knowledge to identify issues of concern in their management area. After initial training, the WEP offers further training for targeted onground monitoring and remediation, supporting rangers to monitor and ultimately manage their local waterways.

Providing capacity building for waterway management from a community, government agency and research organisation perspective is an important step towards better management outcomes for waterways in the Kimberley. The WEP has led to the establishment of a number of ongoing monitoring programs, including those focused on issues of fish parasites and long-term monitoring in Lake Gregory by Paruku Rangers (Dobbs et al. 2011a), and monitoring of feral pig impacts by Wunngurr Rangers in the Willigan area (Dobbs et al. 2011b).

Lessons from the Kimberley WEP can be applied to other programs and highlight how an education program can assist with community monitoring through its ground-up approach. Important features contributing to the program's success include:

- an appreciation for the value of information exchange between western science and Indigenous knowledge
- building on existing programs, relationships and initiatives, which reduces development costs and increases the time spent onground, while also ensuring that with changes in funding opportunities, the program maintains longevity

Photos: R Dobbs

Figure 15 Monitoring by Kimberley Wuungurr Rangers (fish) and Paruku Rangers (water quality).

- flexibility to allow participants to achieve different objectives, including language, mentorship and accreditation for TAFE courses (also ensuring increased uptake and longevity of the program)
- the provision of embedded scientists and managers (facilitating community access to research and management – an important strategy in a large, remote region).

The Kimberley WEP has adapted and trialled various monitoring techniques, tailoring them specifically to community and Indigenous ranger use in the tropics (Dobbs and Cossart 2010). These methods include a modified version of the Tropical Rapid Appraisal of Riparian Condition (TRARC), which is currently being trialled for its use in assessing riparian vegetation and weed impacts. Trials have also shown that quantitative estimates are difficult to obtain with consistency, and semi-quantitative methods (eg photo points and line-intercept methods) have been effective in identifying feral animal, weed and erosion impacts. These results support other TRaCK research trialling community monitoring techniques (Featherston et al. 2011a,b; Finn et al. 2011a,b).

A number of limitations and challenges from community monitoring in the tropics have been overcome, although there are also issues yet to be addressed. To address data management issues, monitoring programs have been adapted into Cybertracker sequences for use on hand-held computers. TRaCK is also currently working closely with the North Australia Indigenous Land and Sea Management Alliance (NAILSMA) to combine monitoring techniques with new technology and build into the NAILSMA I-Tracker program, which will help standardise ranger monitoring techniques used across northern Australia. More work is needed to develop and trial suitable indicators that rangers can collect, interpret and sample while also being sensitive to disturbances.

Despite these challenges, the WEP has helped communities to increase their capacity to manage waterways and to strengthen their ownership of environmental issues, while also building researchers' capacity to incorporate Indigenous knowledge into projects.

Secondary benefits highlight that the focus of community monitoring programs should not always be on providing scientific data to feed into western science. The Kimberley program has facilitated the development of new partnerships with a large number of stakeholders (including government and non-government agencies, land councils, language centres, Indigenous Protected Areas and schools). By integrating a cross-agency program of water planning, research and management, the program provides an important vehicle for participants to interact and be involved in activities undertaken by researchers. Government agencies involved in the WEP subsequently employed ranger groups during TRaCK trials of the Framework for Assessment of River and Wetland Health (FARWH).

Photos: R Dobbs

Figure 16 Monitoring by Paruku Rangers using hand-held computers and Cybertracker software.

3.2 Trial Indigenous participatory monitoring program

Emma Woodward, Tropical Ecosystems Research Centre, Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Figure 17 Gooniyandi monitoring participants testing water quality.

Monitoring programs

Researchers Marcus Finn and Pippa Featherston (CSIRO) from the TRaCK project 'Indigenous socio-economic values and river flows' collaborated with Indigenous communities in the Fitzroy (WA) and Daly River (NT) catchments to develop and trial a 12-month participatory monitoring program for flow regime changes and wild resource use.

Four Aboriginal land management groups participated in the trial monitoring: the Wagiman-Guwardagun Rangers and Malak Malak Rangers from the Daly River (NT), and the Gooniyandi Rangers and a family group from Parkul Springs/Bidijul from the Fitzroy River (WA). The trials commenced with each group identifying key sites for monitoring based on perceived threats to values at these sites, suitable indicators to monitor outcomes for water management plans, and monitoring techniques that each group wished to trial. The monitoring methods were also selected for their ease of implementation. The methods tested included:

- establishment of permanent photo points and canopy cover photos
- measurement of water quality
- catch rates and recording of fishing trips
- using transects to assess landscape changes.

A range of water quality measurements were taken at a number of sites. The use of water quality as an indicator reflected the groups' perception that it was a legitimate indicator of aquatic health from a western science perspective. A manual water quality kit was used, but limited training in the kit's use meant that it was difficult for groups to use without assistance (Figure 17). More consistent results could be obtained by using a more automated water quality testing unit that did not require in-field mixing of chemical reagents.

Recording and measuring of fishing catches was tested by two of the four monitoring groups. This technique, while popular, proved problematic due to the limited time available. Fishing, and the subsequent measuring of catch, tended to be done on an opportunistic basis.

The use of transects for assessing weeds and disturbance by cattle and feral animals (Figure 18) was successful in some communities but not in others. The physical ability of a group determined the success of this method. The technique was tested and quickly discarded by one group, whose rangers were quite senior and physically challenged by walking across rough terrain.

Permanent photo points proved to be a quick, consistent and easy-to-replicate way of collecting information on water levels, aquatic and riparian vegetation changes (including weed growth), disturbance by cattle and feral animals, and in some cases, the characteristics of cultural sites. Although the results of the permanent photo points were not quantitative measurements, the photos gave the Indigenous research participants the opportunity to view temporal changes at a single point in time. Obvious impacts that could be assessed included feral pig damage to billabongs (Figure 19). Permanent photo points were by far the most accepted technique of recording information, and the easiest to implement.

Most of the groups did not have easy access to computers or the relevant training required for data storage, analysis, report writing and publication. This meant that future participatory monitoring programs should consider an individual group's requirements for supervision, support, and championing by an organisation with access to necessary skills and equipment.

Figure 18 (left) Ranger using a tape measure to assess the incidence of animal damage along a billabong edge.

Figure 19 (below) Extensive feral pig damage along the edge of a billabong (Daly River).

A monitoring program that involves Indigenous ranger groups – whether these groups are funded or informal – should prioritise an assessment of the groups' capacity at the beginning of the monitoring program. A successful monitoring program will need to ensure that monitoring support and training is clearly identified and funded as part of the program, particularly where the group identifies limitations in their ability to engage in and carry out activities.

TRaCK Indigenous workshop
Lessons learned through the TRaCK participatory monitoring program were shared with Indigenous land management groups at the NAILSMA I-Tracker Forum held at Mary River Park (NT) in September 2011. A specific session, the 'TRaCK Water Forum', was held to discuss water monitoring with participants and to seek feedback about the groups' own concerns for water health and management (Figure 20).
The following questions were asked:

- What are the top five water health threats (in your management area)? Highlight the top one or two threats.
- What part of the river system is your top threat affecting (eg billabong, main channel, floodplain)?

After these initial questions, individual groups were then asked the following questions:

- What are you monitoring now? What is in your management plan?
- What you would like to monitor?

Figure 20 Identification of common issues at the September 2011 workshop.

The common threats across the region were identified as being feral animals (several species), weeds (several species), sediment and erosion (from different sources, including mining and from road development) and mining (which is seen as an increasing threat).

Across all groups, many river and wetland habitats were represented as being under threat. Examples of threats and habitats threatened for two of the regions are shown in Table 1.

All Indigenous land and sea management groups that participated in the workshop are already undertaking some form of monitoring on Country, but many, if not all groups, are keen to strengthen this component of their management plan. The group identified some impediments to undertaking current and future monitoring, and made the following commentary:

- The difficulties associated with accessing advice on, and the provision of appropriate monitoring equipment, and the ability to get it to remote areas. More technical support would address this.
- The difficulty of accessing Country to monitor.
- The lack of a framework of 'issues' across the north. For example, in Cape York, the issues that require monitoring should perhaps be identified first, before a dedicated person(s) is appointed to provide the training requirements.
- The cost of sending samples away ($3000–$4000 for more expensive tests). Also, consultants are needed to interpret results.
- The lack of a 'one-stop shop' and assistance with designing a monitoring program.
- The inability to detect change because a lack of capacity may be setting up a false sense of security.
- Inadequate Caring for our Country funding—every year, projects miss out.
- Issues relating to the validity of compliance monitoring—there is a perception that it could be a waste of time.
- The lack of baseline information. For example, how many megalitres flow out? How much sediment should be in the river?
- Opportunities for Indigenous employment have improved, but Indigenous people should not just be seen as a labour force; they need to be partners in the research and in designing and understanding the monitoring programs.

Further information about the trials can be obtained from Featherston et al. (2011a,b), Finn et al. (2011a,b) and Jackson et al. (2011).

Group/region	Top threats	'River' habitats threatened by the top threats
Cape York (Central East Coast River System)	Pigs and cattle; tourism; mining; legislation; climate change; erosion	Wetlands, floodplains, estuaries, catchments
West Cape York (Napranum, Mapoon, Lockhart)	Mining and groundwater quality; pigs and weeds (control measures and environmental health); agricultural industry (sediment, chemical pollution, run off); climate change; water usage); groundwater quality (domestic use)	Mining effects: waterholes (construction); river mouth blocked by sediments; seagrass and mangroves on estuaries and coast, river channel (water take) Weeds: floodplains; creek channel and sea (pesticide and sediment control); estuarine and coastal systems Groundwater: domestic use, extra or added pressure on existing water systems through increased mining

Table 1 Threats identified by the September 2011 workshop participants.

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