MONSOONAL NORTH
NRM CLUSTER

CLIMATE CHANGE IN AUSTRALIA
IMPACTS & ADAPTATION INFORMATION FOR AUSTRALIA'S NRM REGIONS

Vulnerability and risk assessment of northern Australian catchments and biodiversity

Paul Close, Renee Bartolo, Neil Pettit, Doug Ward & Mark Kennard

Citation

Close, P., Bartolo, R., Pettit, N. & Ward, D. & Kennard, M. (2015). Vulnerability and risk assessment of northern Australian catchments and biodiversity. Climate Change Adaptation across Australia's Monsoonal North – Northern Monsoon NRM Cluster, Griffith University, Nathan.

Copyright

Disclaimer

An Australian Government Initiative
CSIRO
Territory Natural Resource Management
TRaCK Tropical Rivers and Coastal Knowledge
Cape York Natural Resource Management Ltd
The University of Western Australia
James Cook University Australia
Southern Gulf Catchments
Northern Gulf Resource Management Group
Rangelands NRM Western Australia
NQ Dry Tropics
NAILSMA North Australian Indigenous Land and Sea Management Alliance
Charles Darwin University
Griffith University

Contents

List of Figures

1. Introduction

Northern Australia hosts a range of high value estuaries, rivers, lakes and wetlands. These ecosystems have intrinsic and cultural value, and provide clean water, food and recreational activities for people. They also support high biodiversity and many species of plants and animals that are found nowhere else. It is important that these valuable assets be sustainably managed and protected so that they provide ongoing value to both human activities and ecological requirements. Climate related changes in rainfall, run off and sea level, together with future development, particularly the expansion of agricultural, urban and industrial land use, represent significant risks to these high-value ecosystems (Pusey and Kennard, 2009; Close et al., 2012). Associated risks are likely to include; increased variability and severity of floods and droughts; increased water temperatures; seawater intrusion into lowland freshwater wetlands, and; increased fragmentation of aquatic habitats (Pusey and Kennard, 2009).

In recent years, aquatic ecosystems across northern Australia have been the focus of substantial research and monitoring leading to a more comprehensive understanding of biodiversity values, ecological and socio-cultural assets and integrated knowledge of how tropical aquatic ecosystems function at a variety of scales, ranging from the entire landscape to individual wetlands, and river pools. This has been made possible through programs such as the *Commonwealth Environmental Research Facility*, *National Environmental Research Program*, *Northern Australia Water Futures Assessment* and now the *Natural Resource Management Climate Change Impacts and Adaptation Research Program*. With few exceptions, these programs included geographic scopes stretching more than 3,000 km, from Broome in the west to Cairns in the east, including three drainage divisions: Timor Sea; Gulf of Carpentaria and North-East Coast, north of Cairns and three management jurisdiction (WA, NT and QLD).

In 2012, knowledge of northern Australia's aquatic ecosystems and biodiversity was synthesised by a large, multidisciplinary project: *Assessing the likely impacts of development on aquatic ecological assets in northern Australia* (Close et al., 2012). The geographical area considered by the project included three drainage divisions (Timor Sea, Gulf of Carpentaria and the part of the North-east Coast Drainage Division, north of Cairns) and 64 river basins. This project synthesised knowledge on: i) ecology and hydrology; ii) human impacts and their relationship to future development and climate change risks; iii) ecological water requirements, ecosystem function and habitat use by key biota, and; iv) relationships between ecological, social and cultural values. It also recommended management strategies and monitoring frameworks to report on environmental change and identified specific knowledge needs and future investment priorities. The project provided water planners and managers with additional information on the possible impacts of future development and climate change scenarios on aquatic ecosystems in northern Australia that could be utilised in decision making for water management.

This project, *Climate Change Adaptation across Australia's Monsoonal North* delivers improved knowledge, tools and management options to regional NRM organisations in the Monsoonal North Cluster enabling them to better adapt to the challenges posed by a changing climate. It focuses on both direct impacts such as increased temperature and sea level rise, and indirect impacts such as changes in pest species distribution, altered fire regimes and habitat loss. The Project will deliver tailored maps, spatial datasets, modelling and scenario evaluation tools that meet the specific requirements of individual NRM organisations.

Consultations on priority issues and projects culminated in a workshop held in Darwin in July 2013, at which series of potential projects to address the priority issues identified by NRM planners were identified. Nine projects were selected to address NRM priorities across the north monsoonal regions:

Project 1 – Climatic Knowledge Synthesis
Project 2 – Indigenous knowledge of climate change to improve adaptation planning
Project 3 – Decision Making and Planning for Natural Resource Management

Project 4 – Vulnerability and risk assessment of northern Australian catchments and biodiversity
Project 5 – Scaling Biodiversity Data
Project 6 – Climate change impacts on pest plants
Project 7 – Social Resilience of Agricultural Landscapes
Project 8 – Carbon Sequestration
Project 9 – Interactive Stressors

This document is intended to provide background information to accompany Project 4. Project 4 has developed and integrated spatially-explicit models for assessing risks to ecological assets by building on recent work conducted through the Northern Australia Water Futures Assessment (Close et al., 2012) and the earlier Tropical Rivers Inventory and Assessment Project (Bartolo et al., 2008).

The Project aimed to present a broad-scale assessment of risks and vulnerabilities for all of northern Australia's coastal river catchments by refining and synthesizing existing semi-quantitative Relative Risk Models (RRMs). This information is presented in the Northern Australian Aquatic Assets Geodatabase (Ward et al., 2015). The Geodatabase has been developed to assist in the quantification and communication of risks associated with threats to aquatic ecological assets across northern Australia. It comprises a base level set of spatial layers on aquatic features (rivers, lakes, swamps, estuaries, springs) and context layers (catchments, land use, protected areas, terrain, vegetation, roads and places) associated with the aquatic features. It also includes a catchment based assessment of relative risk scores associated with threats arising from factors such as flow alteration, sea level rise and climate change. Because a great deal of spatial data is now freely available for download, the Geodatabase is not comprehensive but has been designed as a base level set of data on aquatic features upon which users can incorporate additional data sets if desired.

This document provides supporting information for the project Geodatabase. It includes a brief synthesis of knowledge on aquatic ecosystems of the region and an overview of the approach used to develop risk profiles for drainage basins.

2. A Synthesis of current knowledge

2.1 Regional characteristics

Climate, landscape and groundwater connections vary across northern Australia creating a diversity of river systems, including those that flow year-round, and others that cease to flow for varying lengths of time during the dry season. Northern Australia is generally characterised by low relief landscapes. River flows in the central to western regions are typically constrained in rocky channels, flanked by a succession of relatively small, discontinuous floodplains. In comparison, rivers draining to the Gulf of Carpentaria flow through extensive alluvial floodplains for much of their length. To the east of the Great Dividing Range (i.e. the northern North-East Coast Drainage Division) steep coastal escarpments abut a narrow coastal plain and the rivers tend to be much shorter and steeper than those found elsewhere in northern Australia.

The region's climate is characterised by highly seasonal, summer-dominated rainfall, high temperatures and high evaporation rates. Mean annual rainfall is highly variable (range 400 – 4000 $mm.year^{-1}$) across northern Australia. While more than 60% of Australia's runoff is generated in northern Australia, the region experiences rainfall and runoff that varies strongly, both annually and seasonally. Most precipitation occurs in the wet season (November to March) near the coast, and declines with increasing distance inland where evaporation rates are also higher.

A number of groundwater basins occur across northern Australia, and interact with some surface water systems by contributing groundwater to perennial flows. Stream flow in northern Australia is considerably more seasonal and has a higher inter-annual variability than other world rivers of the same climate type and a large proportion of the study area is considered to be water limited over the dry season months (April and October). There are few river reaches that flow year-round and those that do have high cultural, social and ecological value and are generally sustained by localised groundwater discharge. Although there are notable exceptions, few rivers in the region are regulated and levels of catchment disturbance remain relatively low.

The Kimberley region of Western Australia is remote and waterways in the region have typically low levels of disturbance. The region is rich in natural resources and mining activities represent a significant potential for increased water resource use, increased infrastructure and concentration of populations.

The Northern Territory includes a diverse range of waterways in both remote and developed catchments. Groundwater discharge is an important feature of some catchments, maintaining river flow throughout the dry season. Demands on Northern Territory water resources from mining, pastoral diversification and tourism represent significant threats. Climate change, particularly sea level rise, also threatens the lower reaches of many river basins.

In north western Queensland, rivers flowing to the Gulf of Carpentaria are seasonally connected (during the wet season) via the Gulf Plains, an ecologically important floodplain system which spans the entire coastal region. Most aquatic habitats are intermittent, despite significant groundwater influence. Primary industries in the catchments include pastoralism and mining and increased development of the water resource to support expansion of the mining industry represents a significant potential risk.

Waterways across northern Australia are generally in good condition. Naturally seasonal flow patterns maintain a diverse range of aquatic ecosystems that support high biodiversity. Floodwaters during the wet season are influential, distributing sediments and nutrients that support a range of ecosystems, including floodplains that are some of the most productive ecosystems on earth and estuaries that support significant fishing industries. Water dependent plants and animals in northern Australia are diverse and many are found nowhere else. The region also has a long history of Aboriginal occupation, particularly associated with waterways, and culturally important sites are numerous. Biodiversity and cultural assets in Northern Australia are closely linked and have adapted to the unique landscape, climate and river flows. Changes to river flows, landscapes and aquatic habitats due to climate change and development demands are likely to impact the unique biodiversity values of the region.

2.2 Climate and development impacts on hydrology

Groundwater provides an important contribution to many northern Australian waterways from maintaining permanently watered wetlands, to maintaining year-round river flows. Groundwater recharge occurs during the wet season via a combination of diffuse infiltration of rainfall, floodplain inundation and leakage from streams and rivers. Estimates of recharge rates range from <1 mm yr-1 to >200 mm yr-1; with the lowest rates in the most arid regions (e.g. much of the Flinders-Leichhardt region) and the highest rates generally associated with wet-tropic climates and more permeable soils.

Predicted changes in annual groundwater recharge due to climate change vary from +39% to -5%. The impacts of climate change on groundwater dependent ecosystems will be more immediate in those which are fed by shallow, local, unconfined aquifers (e.g. the Flinders-Leichhardt, Mitchell and Kimberley regions) and, conversely, delayed in systems fed by deep, regional aquifers (e.g. the Daly and Fitzroy regions). In some areas with significant levels of current groundwater extraction (e.g. the Darwin Rural Area), groundwater levels are likely to continue to decline despite increases in diffuse recharge, and these declines may threaten a number of groundwater dependent ecosystems in the area.

Development impacts on groundwater have been estimated in very few locations. The greatest impact from development is expected in catchments with a high degree of groundwater-surface water connectivity, such as the Daly River. Development is most likely to have significant impacts in parts of aquifers that are furthest from the rivers.

During the dry season, river flows recede rapidly and the majority of surface water features cease to flow, and may either dry completely or form a chain of disconnected waterholes. There are, however, several iconic perennial rivers such as the Daly River and Roper River (NT), the Fitzroy River (WA) and many of the rivers on Cape York peninsula (QLD) that rely on significant groundwater input through the dry season.

Stream flow in northern rivers is extremely seasonal with the vast majority (> 90%) of annual flow occurring during the wet season (November to April). Aquatic ecosystems dependent on these flows are well-adapted, responding to both wet season high flows and the long dry season low flows. The predicted changes to the high and low flow characteristics of most northern rivers under future climate scenarios are quite large and likely to have significant consequences to aquatic biota. Under 'dry climate change scenarios' some areas are likely to experience considerable increases in the duration of low and zero flows, which may have major ecological impacts. Combining climate change with development pressures will likely exacerbate changes to low flow conditions. Similarly, under 'dry climate change scenarios' flood frequency can be reduced greatly and this may have impacts on provision of habitat and breeding grounds. Under wet climate change conditions, flooding may become much more frequent and this could have both positive and negative impacts depending on the flow requirements of different species.

2.3 Aquatic habitats in an ephemeral landscape

In-stream pools form critical refuges for many aquatic biota during the long dry season when many rivers cease to flow. Both the magnitude of dry season flow and the relative contribution of groundwater over this period influences the number, extent and persistence of river pools. There are reasonably good relationships between pool number, total pool area and flow, but the relationships vary among rivers presumably due to variations in the contribution of groundwater over the dry season. The preceding wet season affects the rate at which pools form in the early dry season, whereas the number, extent and persistence of river pools late in the dry season is presumably influenced by the relative contribution of groundwater. The number of river pools initially increases during the dry season as water levels decrease and larger pools disconnect to form multiple river pools. By the end of the dry season, pool number decreases due to the disappearance of small pools, which cannot be sustained by groundwater flow.

2.4 River floods and wetland connectivity

Flood flows during the wet season connect off-stream floodplain wetlands with the main channels of floodplain river systems, and these 'flood pulses' are thought to be the major determinant of the high biodiversity of floodplains. Only limited quantitative information is available on the dynamics of this connectivity from modelling undertaken in the Fitzroy River (WA). The duration of wetland connectivity varies in relation to the distance from and topography between the main river channel, and floodplain waterholes. Some wetlands connect in relatively small and frequent floods and others only connect in much larger, less frequent floods. Wetlands in the lower part of the floodplain tend to have greater connectivity because of the longer duration of inundation in this area.

2.5 Important biological and ecological thresholds.

Conceptual relationships and critical thresholds of habitat use by key fauna, as well as thresholds for vital ecosystem processes were identified based on review, synthesis and analysis of current data and knowledge (see Close et al., 2012).

2.5.1 Habitat Connectivity

Rivers are highly connected ecosystems and the distribution, reproductive biology and movement characteristics of freshwater fauna reflect this. Changes in habitat connectivity between estuaries and their upstream river and floodplain habitats may significantly interfere with breeding and recruitment, impacting populations along the entire river length and resulting in flow-on effects to commercial and recreational fishing industries. Salt water intrusion, increasing water temperatures and changes to river flows associated with climate change are likely to alter the distribution, abundance and suitability of habitats in many tropical rivers.

2.5.2 Water Temperature

Water temperature is arguably the most important water quality parameter, directly influencing habitat suitability as well as modifying a wide variety of physical, chemical and biological processes. The maximum recorded water temperature from northern Australia is 44°C, although mean daily water temperatures rarely exceed 33°C. The maximum thermal tolerance fish and crustacea is approximately 39°C, with the tolerance of individual taxa ranging from 33°C - 42°C. In general the thermal tolerance of species was greater than the water temperatures usually found in northern Australian waters, however, given the over-riding effect of even short-term elevated temperatures in determining environmental outcomes, this does not preclude temperature being a major driving force in tropical aquatic communities.

2.5.3 Ecosystem productivity

Australian tropical floodplains are generally considered highly productive ecosystems with seasonal flooding supplying fresh water and nutrient rich sediments to river channels, floodplains and estuaries. Seasonal changes in water levels and associated increases in aquatic and floodplain primary production usually produce a corresponding shift in the nature of the dominant primary producers. Regional variation in hydrological regimes, particularly the degree of flood plain inundation, strongly influences the nature of primary productivity. Many of the drivers and triggers for primary productivity in northern Australian aquatic ecosystems are system specific. Nonetheless, the magnitude, duration, rate of rise and timing of peak flows are likely to be key drivers of riverine, floodplain and estuarine productivity.

2.5.4 Hydrological regimes

Impacts of climate change and development on natural hydrological regimes are many, varied, persistent, interactive and difficult to reverse. Development impacts often have clear and direct effects on the timing and rates of rise and fall of water flow. Devegetation and water regulation alter the frequency, duration, and rates of rising and falling flow. They can also alter groundwater rates of recharge and discharge, and duration of base flow. There are few examples in northern Australia where naturally intermittent or ephemeral streams have become perennial due to water regulation. With increasing water resource development, and the expansion of mining activities, these effects may become more widespread in the future. The most significant impact of water supplementation of naturally intermittent waterways appears to be the proliferation and spread of aquatic weeds and macrophytes. It is likely that the presence of permanent water and deeper pools will facilitate the movement of estuarine fish species further upstream. The presence of these species would likely impact resident aquatic fauna, both indirectly through their effect on local food sources, and directly through predation and competition, resulting in changes to assemblage structure.

2.5.5 Invasive plant species

Globally, aquatic ecosystems are considered to be highly vulnerable to invasion by alien plants. Weeds have been found to have negative impacts on the environment, the economy and Indigenous cultural values. In northern Australia, five species are listed as Weeds of National Significance (WoNS) because their impacts on natural and agricultural systems are so severe: giant sensitive tree, olive hymenachne, cabomba, salvinia and rubber vine. Other weeds that have serious impacts on northern Australia's aquatic ecosystems, include para grass, water lettuce and gamba grass. Increased CO_2 levels and temperatures associated with climate change are likely to increase the growth and geographical distribution of invasive weed species. Other impacts of climate change may limit the spread of weeds in some habitats, for example, rising sea levels will reduce the availability of freshwater habitats for some weed species.

2.6 Key Hydro-ecological linkages

Based on the synthesis provided above the following relationships were identified between seasonal flow characteristics and key ecological values.

2.6.1 Dry season

- Base flow, cease to flow, and groundwater levels are the key flow components of the dry season.
- The duration and timing of disconnection, the rate and variability of winter base flow and the persistence and level of groundwater discharge have the greatest impact on ecological values.
- Flow components support a wide range of biological values, and maintain ecological integrity and vital ecosystem processes such as reproduction and migration.

2.6.2 Dry-wet season transition

- The onset of flows and the timing of floods at the commencement of the wet season are the key flow components during this transition.
- The duration, timing and magnitude of flow have the greatest impact on ecological values.

- Values associated with longitudinal connectivity are important during this transition, with dominant processes including cues for reproduction, and the alleviation of stresses related to the late dry.

2.6.3 Wet season

- Flood events, peak and total annual flow, and groundwater recharge are the key flow components of the wet season.
- The duration, magnitude and extent of flood inundation, as well as the timing and volume of total wet season flow, and the rate of groundwater recharge, have the greatest impact on ecological values.
- Flow components support a wide range of biological values and extensive aquatic and terrestrial primary productivity. Dominant processes include habitat maintenance, nutrient supply and connectivity: allowing for successful migration/reproduction and appropriate genetic exchange.

2.6.4 Wet-dry season transition

- High flow recession and groundwater dynamics are the key flow components during this transition.
- The magnitude, duration and timing of groundwater discharge affects primary productivity values, whilst the recession of flood and peak flows and groundwater levels affects the persistence of aquatic fauna, which may become stranded on the floodplain or in unviable habitats if flows recede too quickly.

2.6.5 Any season

- Variability, base flow and mean annual flow are key flow components throughout all seasons.
- Variability in seasonal wetting and drying, and in flow parameters such as rates of rise, magnitude and constancy impact ecological values such as species diversity, productivity and habitat structure.
- Base flow perenniality, and the magnitude of mean annual flow increases fish biodiversity due to increased connectivity and productivity.

3. A Synthesis of current knowledge

Relative Risk Modelling (RRM) is a robust methodology that incorporates spatial variability at a large scale to examine the interaction of multiple threats to habitats, and their effects (impacts) on identified 'assessment endpoints'. Relative risk estimates are determined for the specific regional catchments under assessment. The assessment process allows comparison of risk estimates among sub-regions, sources, habitats and endpoints to identify: the sub-regions where most risk occurs; the sources contributing the most risk; the habitats where most risk occurs; and the ecological assets most at risk in the study area.

The risk assessment was undertaken using a semi-quantitative approach (see Figure for summary). The semi-quantitative, multiple threat-asset approach identified relative risks to regions, catchments and assessment endpoints.

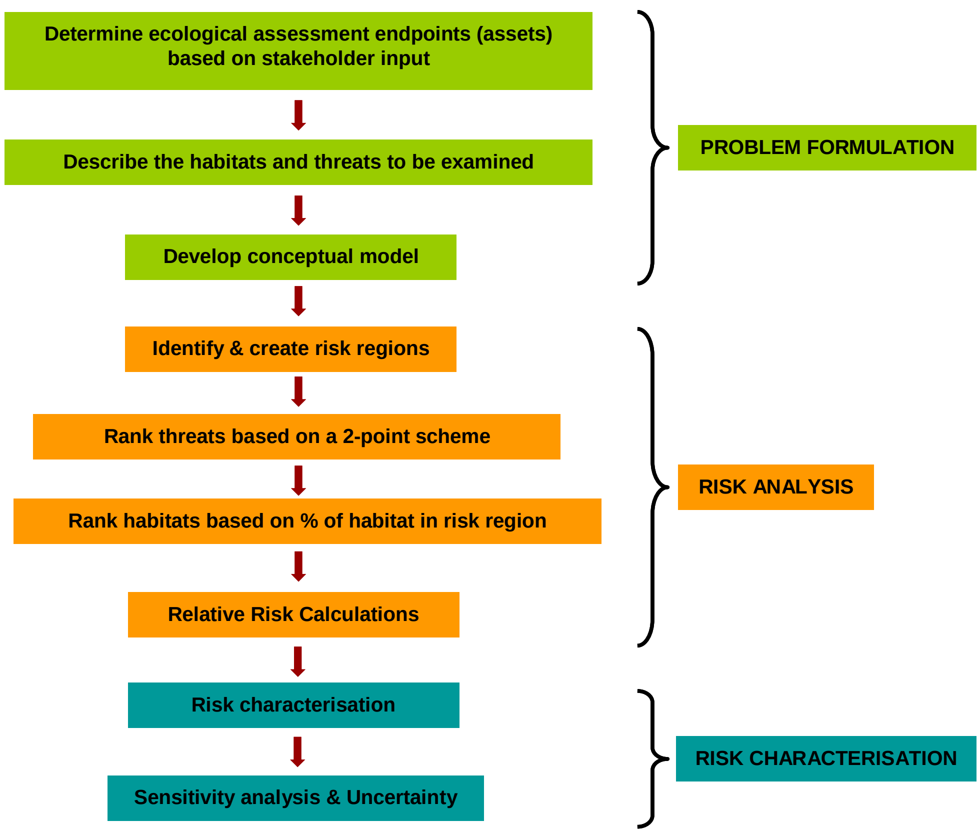


Figure 1. Methodology for developing relative risk models

The **ecological assessment endpoints** included in the RRMs were; maintenance of flow regime; water quality to meet or exceed a specified standard; maintenance of extent and health of riparian vegetation; and maintenance of biodiversity. **Habitats** directly related to tropical rivers included waterways, riparian vegetation wetlands and areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt within the landward zone of the coastline. Thirteen **Threats** incorporated into the RRMs included multiple parameters associated with land use, sea level rise, mining and river disturbance (see Close et al. 2012 for details).

Risk hypotheses were illustrated in a conceptual model for the specified threats and habitats. The resultant conceptual model for northern Australia, shown in Figure 2, formed the basis for undertaking risk calculations within the RRMs. The risk hypotheses are evident through the links between threats, habitats and assessment endpoints, while the interactions are defined by the exposure and effects pathways.

The risk hypotheses related to ecological values only. Figure 2 shows the risk hypotheses associated with multiple land uses, sea level rise, and river disturbance with respect to their potential to alter hydrology, change in-stream ecological processes, produce a change in groundwater level, result in an influx of contaminants, change riparian vegetation structure, and reduce habitat for flora and fauna in both riparian and wetland habitats.

Risk assessments were undertaken for each of sixty two (62) risk regions (Figure 3). A two point scale (ie. 0, 2, 4, 6; corresponding to nil, low, medium, high, respectively) was implemented to categorise the percentage cover of a particular threat within each risk region.

A variety of risk metrics were calculated for both regions and assessment endpoints including:

- Sum of threats in risk region = Σ threats
- Sum of potential threat exposure in risk region = Σ (threat X habitat) only where there is potential exposure
- Total risk to ecological assessment endpoint = Σ (threat X habitat) only where there is potential exposure AND where the threat has the potential to impact the ecological assessment endpoint.
- Total risk to ecological assessment endpoint in risk region = Σ (total risk to ecological assessment endpoint).

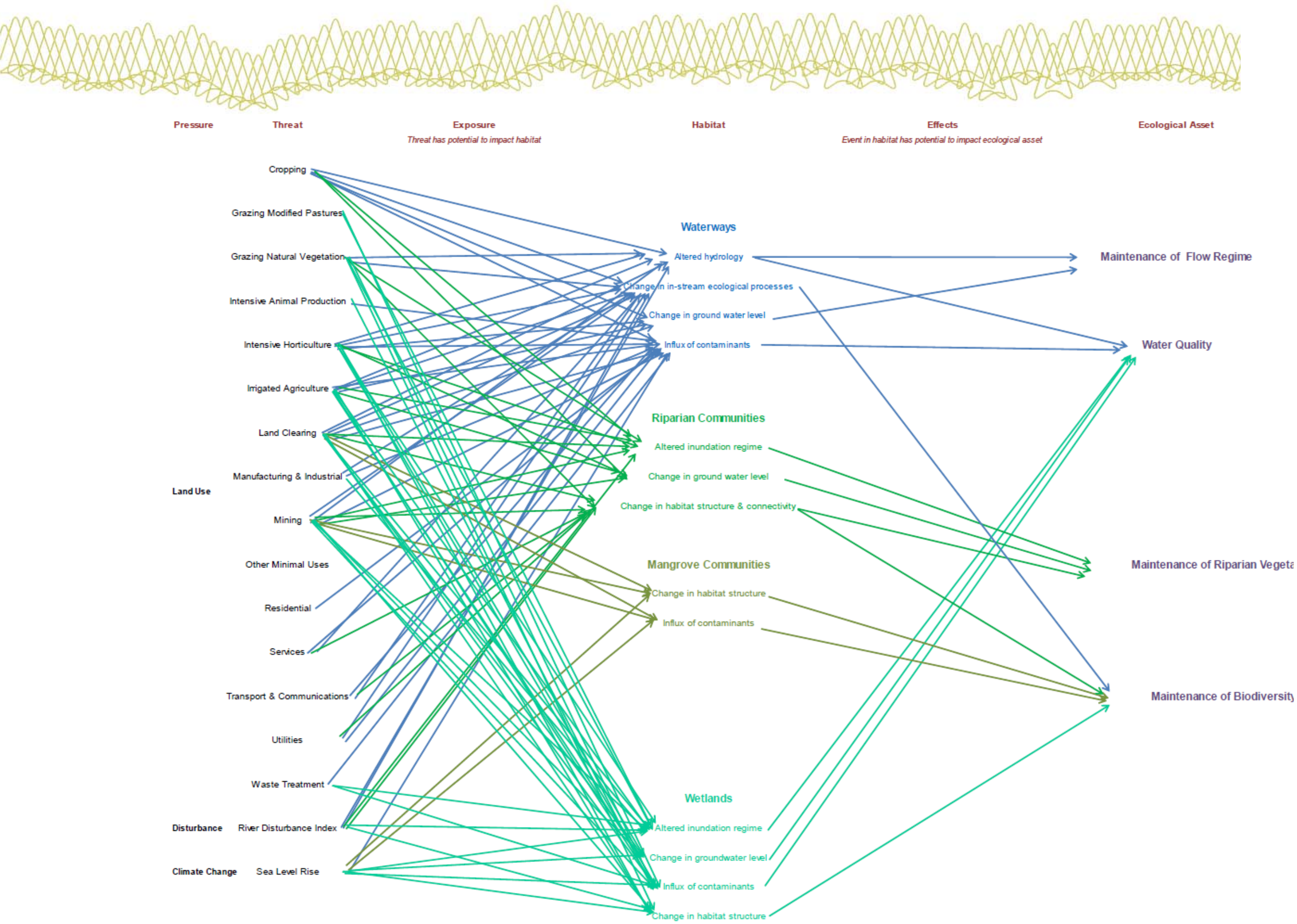
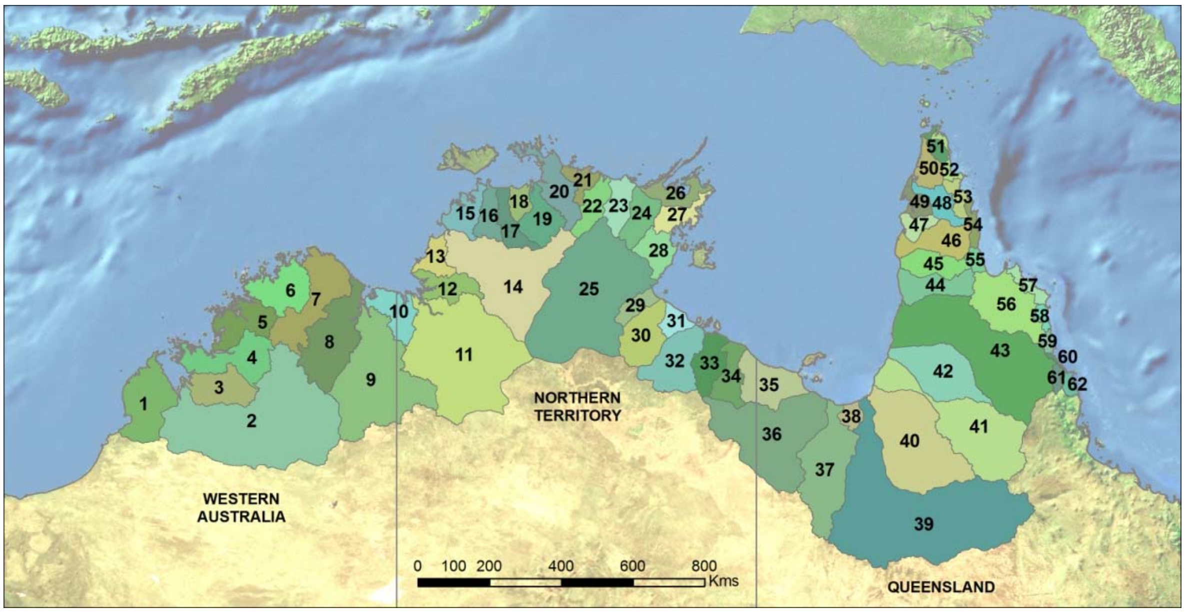


Figure 2. Conceptual model describing ecological risks for northern Australia.



1, Cape Leveque Coast, 2, Fitzroy River, 3, Lennard River, 4, Isdell River, 5, Prince Regent River, 6, King Edward River, 7, Drysdale River, 8, Pentecost River, 9, Ord River, 10, Keep River, 11, Victoria River, 12, Fitzmaurice River, 13, Moyle River, 14, Daly River, 15, Finniss River, 16, Adelaide River, 17, Mary River, 18, Wildman River, 19, South Alligator River, 20, East Alligator River, 21, Goomadeer River, 22, Liverpool River, 23, Blyth River, 24, Goyder River, 25, Roper River, 26, Buckingham River, 27, Koolatong River, 28, Walker River, 29, Towns River, 30, Limmen Bight River, 31, Rosie River, 32, McArthur River, 33, Robinson River, 34, Calvert River, 35, Settlement Creek, 36, Nicholson River, 37, Leichhardt River, 38, Morning Inlet, 39, Flinders River, 40, Norman River, 41, Gilbert River, 42, Staaten River, 43, Mitchell River, 44, Coleman River, 45, Holroyd River, 46, Archer River, 47, Watson River, 48, Wenlock River, , 49, Embley River 50, Ducie River, 51, Jardine River, 52, Jacky Jacky Creek, 53, Olive-Pascoe Rivers, 54, Lockhart River, 55, Stewart River, 56, Normanby River, 57, Jeannie River, 58, Endeavour River, 59, Daintree River, 60, Mossman River, 61, Barron River, 62, Mulgrave-Russell Rivers

Figure 3. The sixty two (62) risk regions identified for northern Australia.

4. Interpreting the geospatial database

A geodatabase containing spatially explicit maps of Relative Risks and Vulnerabilities (based on semi-quantitative RRMs) for all of northern Australia's coastal river catchments is available (Ward et al., 2015).

An example output of the RRMs from the geodatabase is provided below (**Error! Reference source not found.**4, Figure 5). The output shown in **Error! Reference source not found.** was obtained by selecting the Jardine River. The output shows total relative risk scores for all river basins coded by colour. It also provides the specific risk profile for the Jardine River.

This data base also provides a summary of risks to each assessment endpoint: maintenance of flow regime; water quality; maintenance of riparian vegetation; and maintenance of biodiversity (Figure 5).

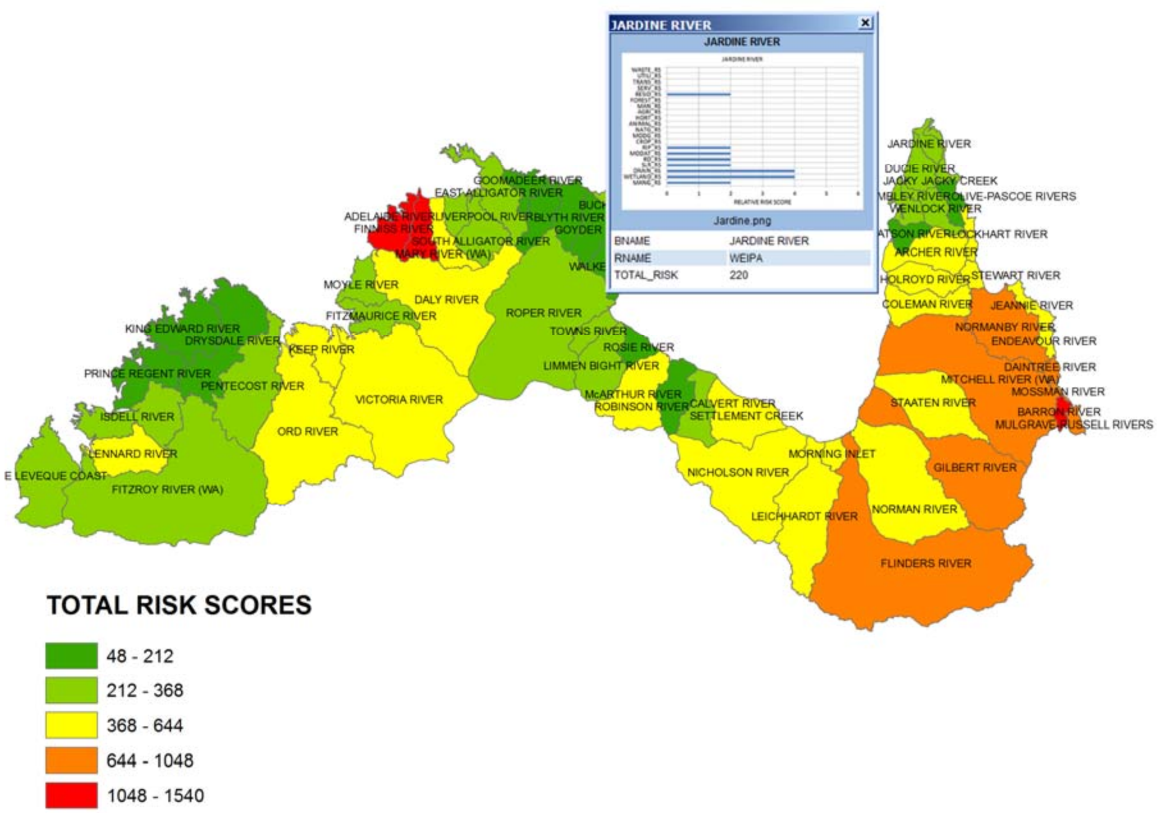


Figure 4. Example output from the geodatabase containing spatially explicit maps of relative risks and vulnerabilities (based on semi-quantitative RRMs).

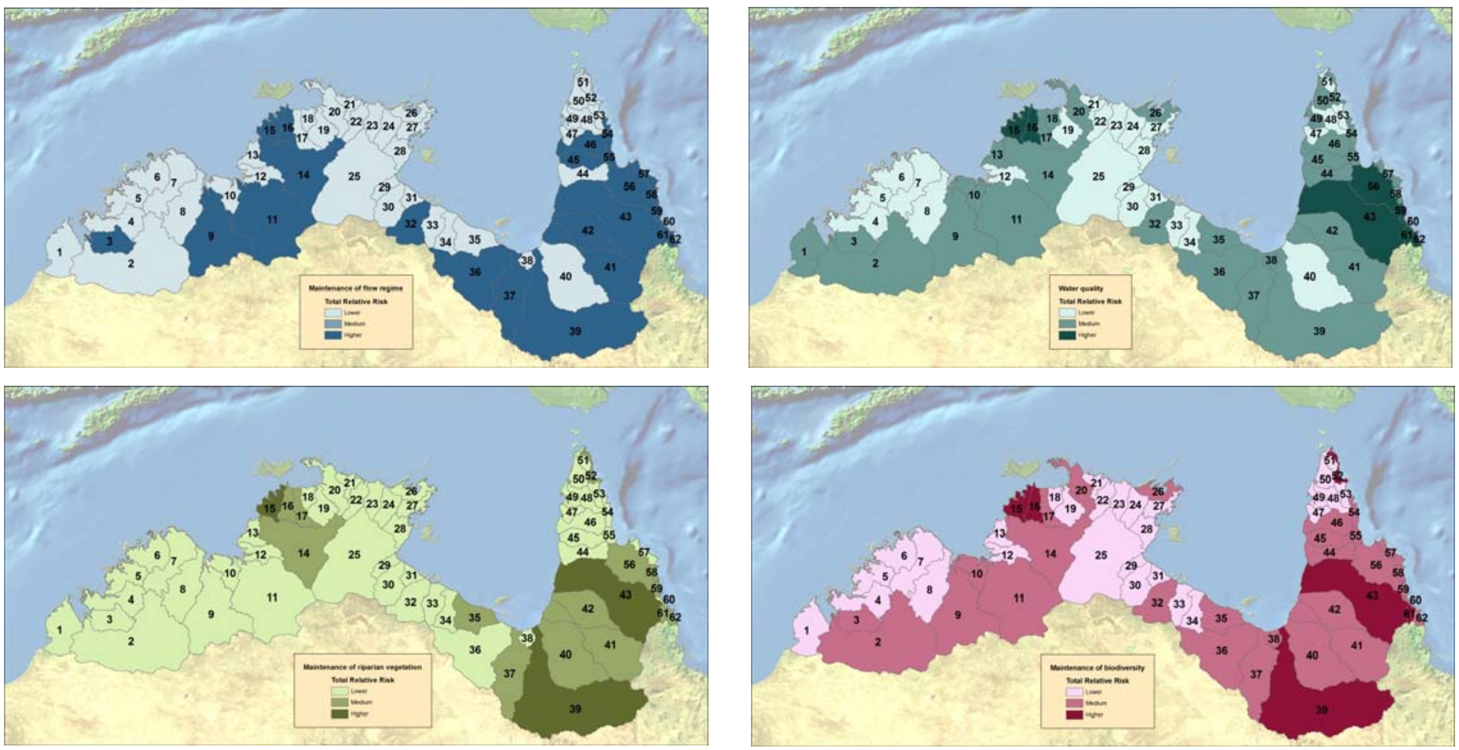


Figure 5. Relative risk to ecological assessment endpoints across the 62 risk regions of northern Australia. A- maintenance of flow regime; B- water quality; C- maintenance of riparian vegetation; and D- maintenance of biodiversity.

References

Bartolo, R., Bayliss, P., van Dam, R. (2008). *Ecological risk assessment for Australia's northern tropical rivers. Sub-project 2 of Australia's Tropical Rivers – an integrated data assessment and analysis (DET18)*. A report to Land & Water Australia. Environmental Research Institute of the Supervising Scientist, National Centre for Tropical Wetland Research, Darwin NT. Available at: http://www.environment.gov.au/resource/ecological-risk-assessments-australias-northern-tropical-rivers

Close, P.G., Wallace, J., Bayliss, P., Bartolo, R., Burrows, D., Pusey, B.J., Robinson, C.J., McJannet, D., Karim, F., Byrne, G., Marvanek, S., Turnadge, C., Harrington, G., Petheram, C., Duta, L., Dobbs, R., Pettit, N., Jankowski, A., Wallington, T., Kroon, F., Schmidt, D., Buttler, B., Stock, M., Veld, A., Speldewinde, P., Cook, B.A., Cook, ., Douglas, M., Setterfield, S., Kennard, M., Davies, P., Hughes, J., Cossart, R., Conolly, N., and Townsend, S. (2012). *Assessment of the likely impacts of development and climate change on aquatic ecological assets in Northern Australia*. A report for the Australian Government Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) and the National Water Commission (NWC). Tropical Rivers and Coastal Knowledge (TRaCK) Commonwealth Environmental Research Facility, Charles Darwin University. ISBN: 978-1-921576-66-9. 561pp. Available at: http://www.environment.gov.au/resource/assessment-likely-impacts-development-and-climate-change-aquatic-ecological-assets-northern

Ward, D., Tews, K, & Bartolo, R. & Kennard, M. (2015). *Northern Australian Aquatic Assets Geodatabase V2.0. User Guide*. Climate Change Adaptation across Australia's Monsoonal North – Northern Monsoon Cluster (Stream 2 of the Regional Natural Resource Management Planning for Climate Change Fund). Australian Rivers Institute, Griffith University.

Contact Details

Mark Kennard, Australian Rivers Institute, Griffith University
07 3735 7401, m.kennard@griffith.edu.au, www.rivers.edu.au

Brendan Edgar
0419 781 676, brendan.edgar@gmail.com