Water Allocation Plan
Tindall Limestone Aquifer, Katherine
2016 - 2019

Department of Land Resource Management
Water Resource Division

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Minister's Foreword

The Tindall Limestone Aquifer in Katherine represents one of the Territory's highest yielding, good quality groundwater resources. This water allocation plan sets out an optimistic vision to ensure that the aquifer is managed sustainably with a balance between the environment and all other users.

The plan describes the hydrology and interaction of the Tindall Limestone Aquifer with the Katherine River and sets clear direction for water resource development and management through a flexible approach that accounts for climate variability from year to year.

Following its mid-term review, I am pleased to declare the Water Allocation Plan for the Tindall Limestone Aquifer, Katherine 2016 - 2019. This reviewed plan terminates on 19 August 2019, at which time it will be replaced by a new plan.

I extend my thanks to the Katherine Water Advisory Committee for their hard work in reviewing the initial plan and, in particular, the recommendations made (Appendix 3) for consideration in the development of the new plan.

I am also pleased to announce that the Katherine Water Advisory Committee will be established within 3 months for the purpose of guiding and advising on the implementation of this plan over the next 3 years and preparing for and contributing to the development of the new plan in 2019. I encourage the whole Katherine Community to assist with the committee in this important work.

Gary Higgins
Minister for Land Resource Management
6th April 2016

Part 1 Introduction

For hundreds of years, people from the clans of Jawoyn, Wardaman and Dagoman have lived on the lands surrounding Katherine. These people today still have an important connection to the many springs, sinkholes, streams and rivers, used for fishing, swimming, camping and dreaming.

This Water Allocation Plan acknowledges the traditional owners that live within the Plan area, and recognises a deep cultural connection to the many water features, which are interconnected with the Tindall Limestone Aquifer.

All community groups are encouraged to contribute to assist NRETAS to develop and improve future management of the Tindall Limestone Aquifer, through the Tindall Limestone Aquifer (Katherine) Water Implementation Strategy.

1. Name of Plan

This Plan is the, Water Allocation Plan for the Tindall Limestone Aquifer, Katherine 2009 - 2019 (hereafter ***this Plan***).

2. Legal relevance of this Plan

(i) This is a Plan under section 22B of the NT *Water Act* (hereafter ***the Act***).

(ii) This Plan refers to the current regulations of *the Act*.

(iii) This Plan relates to the Daly Roper Water Control District declared under section 22 of *the Act*.

3. Date of commencement

This Plan takes effect when declared by the Minister under *the Act*. The Plan will be reviewed within 5 years and cease to have effect 10 years from its commencement or upon declaration of a new plan covering the Tindall Limestone Aquifer within the Katherine River catchment, whichever occurs first.

4. Scope of this Plan

a. Area to which this Plan applies

The area to which this Plan applies is that part of the Tindall Limestone Aquifer bounded by the Katherine River Catchment (hereafter ***this water source***) as shown in the map in Schedule 3.

b. Waters to which this Plan applies

(i) This Plan applies to management of water contained within the unconfined and confined Tindall Limestone Aquifer within the Katherine River Catchment.

(ii) This Plan does not directly apply to the management of surface water extractions from the Katherine River but a range of groundwater management provisions are made which aim to achieve environmental and cultural outcomes which depend on groundwater discharge to the river.

Note: to achieve equity and to uphold the environmental, Indigenous cultural and other instream public benefit outcomes provided for in this Plan, licensed surface water extraction from the Katherine River (accessing base flow) may be subject to restrictions under s96 of the Act. Restrictions to surface water extraction will be consistent with the announced allocation for high security groundwater licences (see Part 7). A Water Allocation Plan encompassing the Katherine River, formalising the above arrangements will be made within the life of this Plan.

c. Purpose

The purpose of this Plan is to initiate strategies for sustainably allocating and managing water from this water source. These strategies, as detailed in Clause 18 were created by assessing:

(i) water availability in the context of climatic variability and community, environmental and Indigenous cultural needs;

(ii) community response to the economic opportunities associated with the use of this water source, including consumptive uses such as agriculture, industry and public water supply and non consumptive uses such as tourism and recreation;

(iii) opportunities and needs arising from growth in existing and emerging activities, including economic development opportunities for Indigenous landowners.

5. Interpretation

(i) Where new terms and concepts are introduced, notes have been included to provide clarification. These do not form part of this Plan.

(ii) Terms used in this Plan which are not used within *the Act*, are defined in Schedule 1.

(iii) Schedules do form part of this Plan.

(iv) Appendices do not form part of this Plan.

6. Effect on statutory instruments administered under the Act

From commencement, management of the Tindall Limestone Aquifer within the Katherine River Catchment in the Daly Roper Water Control District is to be in accordance with this Plan.

7. Relationship to other Plans

(i) This Plan contributes towards achieving relevant targets in the Northern Territory Integrated Natural Resource Management Plan (March 2005) as outlined in Schedule 6.

(ii) If, following commencement of this Plan, other Water Allocation Plans are made for water resources connected to this water source, they will be complementary to the objectives and strategies stated in this Plan.

8. Consultation

(i) The Katherine Water Advisory Committee was announced on 21 February 2007 under section 23 of *the Act* to incorporate community values and beliefs into the development of this Plan.

(ii) Prior to finalisation, drafts of this Plan were released for formal public comment periods on 26 June 2008 and on 18 December 2008.

(iii) A public information session was held in Katherine following the release of the first draft Plan on 16 July 2008.

Note: Clause 8 refers only to formally advertised consultation that was carried out during the two year planning process. Details of the complete consultation process are available in the Consultation Report for the Tindall Limestone Aquifer (Katherine) Water Allocation Plan (2009).

Part 2 Planning Context

9. Basis for water allocation planning

a. NT Water Act

This is a Plan under section 22B of *the Act*.

b. National Water Initiative

This Plan is made in accordance with the Northern Territory's commitments under the Intergovernmental Agreement on a National Water Initiative as signed on 25 June 2004.

10. Description of this water source

a. Hydrogeology and Recharge

(i) This water source originates from the Tindall Limestone formation which is a fractured and cavernous aquifer system.

(ii) Within the Plan area, groundwater within the Tindall Aquifer flows towards the Katherine River, where it discharges via springs.

(iii) As shown in Schedule 3, the Tindall Aquifer is confined where it is overlain by younger geologic formations and unconfined where it outcrops around Katherine.

(iv) Within the Plan area, recharge only occurs in the unconfined area.

(v) Based on historic climatic data, stream gauging data, calculated stream flows and hydrologic modelling as described in Part 2 clause 15, the average annual recharge to the Tindall Aquifer within the Plan area is estimated to be 74,000 megalitres (ML).

Note: Modelling using interpolated long term rainfall data has revealed that this estimated recharge may change. The Tindall Limestone (Katherine) Water Resources Report (2009) provides further detail on the hydrogeology, recharge characteristics and modelling of this water source.

b. Current Licences and Extraction

Immediately prior to the commencement of this Plan, water was allocated from this water source under licences as outlined in table 1. The estimated actual water use for the water accounting year 1 May 2006 to 31 April 2007 is also given in Table 1.

Table 1: Licensed volumes immediately prior to the commencement of this Plan and estimated use for the 2006/07 water accounting year

Purpose	Licensed volume (ML)	Estimated current use (ML)
Public Water Supply	7590	1085
Agriculture (inc. Horticulture)	18750	12456
Aquaculture	108	0
Industry	96	1195
Rural Stock and Domestic	0	1128

Note: Groundwater extraction for stock and domestic purposes is not required to be licensed under the Act. Estimated use for industrial purposes exceeds the licensed volume because groundwater extraction not exceeding 15L/s was not required to be licensed prior to the declaration of the Katherine Water Control District that preceded the Daly Roper Water Control District.

c. Relevant Research Reports

Details of research reports that were considered during the development of this Plan are provided in Appendix 3.

11. Regional population and employment profile

Following the 2006 census of population and housing the Australian Bureau of Statistics estimates that;

(i) 9,031 people reside in the town of Katherine
(ii) 20.2% of residents in Katherine township and 50.2% of residents in the Katherine region were identified as Indigenous
(iii) The largest employment sectors in the Katherine region include defence (28.2%), retail trade (9.2%), health and community services (9.2%), agriculture, forestry and fishing (7.6%) and education (6.9%)

Note: Reported statistics are for the Katherine region which includes Katherine township, Elsey, Victoria River and Gulf statistical areas.

12. Benefits associated with this water source

a. Environmental and Cultural

Water from this water source contributes to the perennial nature of surface water flows in the Katherine and Daly Rivers which is critical for maintaining:

(i) environmental integrity, recreational opportunities and aesthetic appeal;
(ii) the condition of places that provide physical and spiritual fulfilment to Indigenous people.

b. Public Water Supply

Water from this water source, in conjunction with surface water sourced from the Katherine River at Donkey Camp Weir, supplies the reticulated public water supply system for the town of Katherine and the Tindal RAAF base.

c. Rural Stock and Domestic and other Small Volume Groundwater Uses

(i) Water from this water source is used for domestic purposes and watering of stock on rural properties that are not connected to the reticulated public water supply system.

(ii) Water from this water source is also available for other purposes without the requirement for a licence, where total annual use does not exceed 5ML.

Note: An exemption to the Act has been declared for the Daly Roper Water Control District to allow water to be extracted from this water source without a groundwater extraction licence for any purpose providing annual use does not exceed 5ML. This is to provide for rural stock and domestic requirements and light industrial uses such as wash down facilities.

d. Agriculture, Horticulture and Industry

At the commencement of this Plan;

(i) The greatest consumptive demand for water from this water source was for irrigated agriculture and horticulture.

(ii) Fruit crops irrigated, or intended to be irrigated, from this water source included mangoes, grapefruit, paw paw, bananas, watermelons and pumpkins.

(iii) Other crops irrigated, or intended to be irrigated, from this water source include hay, sorghum, forage sorghum, cavalcade, rhodes grass and peanuts.

(iv) Irrigated forestry is limited to small areas of African Mahogany plantation.

(v) Industrial use from this water source is mainly for the purpose of irrigating large areas of lawn for community benefit such as golf courses, sporting fields and green space inc. public parks & gardens.

e. Economic Growth

This water source is critical to the success of tourism and agricultural industries and contributes to economic growth in the Katherine region.

Within the Katherine region:

(i) About 270,000 tourists visited each year from 2000 to 2005[1].

(ii) Visitors spend an average of $330 per person, equivalent to $101 million per year[2].

(iii) Tourism expenditure is estimated to grow by around 4.6% annually[3].

(iv) Fruit and vegetable production represents about 20% of Northern Territory's production by value whereas field crops account for 41% by value[4].

(v) Horticulture production has an estimated worth $33.8 million in 2005/06[5].

(vi) Hay, silage and crop production had and estimated worth $6.4 million in 2005/06[6].

(vii) Pastoral production had an estimated worth of $91 million, producing 37% of the Territory's stock in 2005/06[7].

(viii) Water made available through the review process as specified in Part 8, will provide a Strategic Indigenous Reserve (SIR) to enable access to the

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[1] ABS regional statistics 2006: NT 1362.7
[2] Territory Tourism Selected Statistics, TourismNT
[3] Northern Territory Tourism Forecasts 2006/07 to 2008/09
[4] Crops, Forestry & Horticulture Information Service, Department of Regional Development, Primary Industry, Fisheries and Resources
[5] *ibid*
[6] *ibid*
[7] *ibid*

consumptive pool by Indigenous people for the purpose of Indigenous economic development in this planning area[8].

Note: Reported statistics are for the Katherine region which includes Katherine township, Elsey, Victoria River and Gulf statistical areas

13. Groundwater Dependant Ecosystems

This Plan makes provision to protect ecosystems that depend on this water source.

Specifically, this Plan allocates water in a manner that ensures:

(i) that the Katherine and Daly Rivers do not cease to flow as a result of extractions from this water source;

(ii) that flows at the Katherine Railway Bridge are not reduced below the lowest recorded flow as a result of extractions from this water source; and

(iii) that the Katherine Hot Springs do not cease to flow as a result of extractions from this water source.

Note: This Plan cannot prevent the cessation of river flows or spring discharge caused by natural variability in climate. In the absence of research that quantifies the required environmental flows to provide for specific ecosystem processes, the Plan ensures flows in the Katherine River are not reduced beyond the lowest recorded flow at the Katherine Railway Bridge as a result of extraction from this water source. Other groundwater dependant ecosystems, such as riparian and terrestrial vegetation, are assumed to be maintained through the protection of discharge to the Katherine River, however specific provisions for these ecosystems may be introduced upon review of the plan should their specific water requirements become known through monitoring and research.

14. Assumptions

a. Climatic Variability

(i) This Plan recognises climatic variability and therefore that the annual and instantaneous discharge from this water source to the Katherine River will vary.

(ii) To give effect to subclause (i), this Plan contains provisions to manage discharge from this water source to the Katherine River on an annual basis.

(iii) All analyses in this Plan have been based on historic climatic data obtained between 1961 and 2007. It is therefore assumed that future climate will exhibit similar characteristics.

b. Climate Change

(i) The licence limits and reliabilities stated in Part 6 of this Plan have been determined based on historic climatic data only and do not consider the possible effect of climate change on the long term availability of water from this water source.

(ii) At such times when this Plan is reviewed as specified in Part 8, the period of record will be extended to include the latest climatic data and to take account of any available information on projected future changes to climate.

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[8] Rules surrounding the provision of water to Indigenous people from this reserve will be developed in partnership with Indigenous people, and documented in the implementation strategy.

c. Protection of Environmental and Indigenous Cultural Values

(i) This Plan assumes that the provision of discharge from this water source to maintain flows in the Katherine and Daly Rivers will maintain aquatic ecosystems and groundwater dependant riparian and terrestrial vegetation;

(ii) Despite subclause (i), it is recognised that specific environmental water requirements may be required in addition to the maintenance of river base flows and any research that becomes available in this regard will be considered as part of the review process specified in Part 8;

(iii) This Plan assumes that provision of discharge for environmental protection will also maintain the condition of places that are valued by Indigenous people for cultural purposes;

(iv) Despite subclause (iii), it is recognised that cultural flow requirements may not align entirely with environmental requirements and any research that becomes available in this regard will be considered as part of the review process specified in Part 8.

15. Modelling

(i) A numerical model (hereafter **modelling**) was used to determine the average annual discharge from the Tindall Aquifer to the Katherine River using the historic rainfall record.

(ii) Modelling will be used to predict the annual discharge to the Katherine River for the proceeding water accounting year to determine announced allocations as described in Part 7.

Note: in this Plan, modelling is used as the basis for determining annual and instantaneous discharge for environmental, Indigenous cultural and other instream public benefit outcomes as specified in Part 4, and the extraction limit as specified in Part 7. The model used for these annual calculations may be refined to better reflect actual conditions as required resulting from knowledge improvements.

16. Beneficial uses

(i) In accordance with section 22B of *the Act*, this Plan allocates water within estimated extraction limits to the following beneficial uses:

a. Environment and Cultural
b. Public Water Supply
c. Agriculture, Aquaculture and Industry
d. Rural Stock and Domestic

(ii) Water allocated to the beneficial uses of environment and cultural, is referred to in this Plan as water for environmental, Indigenous cultural and other instream public benefit outcomes and is specified in Part 4 in terms of groundwater discharge to be maintained from this water source to the Katherine River.

(iii) Water allocated for the beneficial uses of public water supply, agriculture, aquaculture and industry is specified as a volume for licence security categories, further distributed to entities holding licences of that security category as specified under Part 6, clause 24.

Part 3 Outcomes, Objectives, Strategies and Performance Indicators

17. Vision

Ensure that this water source is managed sustainably with a balance between the environment and all other users.

18. Outcomes, Objectives, Strategies and Performance Indicators

Note: Further details of strategies and performance indicators will be developed in an Implementation Strategy, to this Plan.

Outcomes	Objectives	Strategies	Performance Indicators
1. Ecosystems dependent on the Tindall Aquifer, which are important for biodiversity, tourism, aesthetics, recreation and Indigenous cultural values, including springs and the Katherine and Daly Rivers, are preserved in good condition.	To preserve the following proportions of annual discharge from the Tindall Aquifer to maintain base flow in the Katherine River: • During very dry years at least 87%; • During dry years at least 80%; • During normal or wet years at least 70% **(Part 4)** Protection of water quality within this water source and the Katherine River against degradation through extraction or bore construction	Annual extraction limits to be applied in accordance with Table 3, where the estimated un-impacted 1 Nov Katherine River flow is to be calculated at the beginning of each dry season using a model. **(Part 7)** Annual extraction limits in Table 3 may be adjusted following the review. **(Part 7)** To manage increases in extraction through water trading towards the Katherine River through water management zones. **(Part 7, CL34)** No new licences associated with bores able to take more than 20L/s within 100m of the Katherine River to be granted. **(Part 6, CL25)** Bores must not be drilled within 100m from potential sources of contamination. **(Part 6, CL25)** Bore construction permits will not be issued to properties that have access to reticulated water. **(Part 10, CL39)** Continue partnerships with research organisations to improve knowledge of ecosystem water requirements Undertake consultation and research to improve understanding of Indigenous water issues and options to address them	River health assessment parameters and ranges consistent with national guidelines will be developed in an implementation strategy to this Plan. Annual discharge from this water source to the Katherine River relative to other years and annual extraction from this water source Water quality in the Katherine River and Tindall Aquifer (Parameters and ranges consistent with national guidelines will be developed in an implementation strategy to this Plan.) Identification of methodology to quantify water requirements for Indigenous cultural purposes. Identification of specific environmental water requirements that maintain ecological processes in the Katherine and Daly Rivers.

Outcomes	Objectives	Strategies	Performance Indicators
2. Communities, including Katherine, Tindall RAAF base, other rural communities and rural properties, have access to water sufficient in quantity and quality for essential needs and for commercial development.	In all years except very dry years: • Rural stock and domestic use to have access to sufficient water, plus additional amount should there be growth in lawful exercise of water rights under s14 or the s47 exemption. **(Part 5)** • Katherine town, Tindall RAAF base and rural stock and domestic users to have access to sufficient water. **(Part 6)** Protection of water quality within this water source and the Katherine River against degradation through extraction or bore construction	Water made available under this Plan to rural properties in accordance with s14 and s47 of *the Act* **(Part 5)** Total security licence issued for public water supply will have first priority in allocation of water up to the annual extraction limit each year. **(Part 6)** Bores must not be drilled within 100m from potential sources contamination **(Part 6, CL25)** Bore construction permits will not be issued to properties that have access to reticulated water. **(Part 10, CL39)** No new licences will be given where bores of <20L/s are within 100m of an existing bore. **(Part 6, CL25)** Monitor number of bores for rural stock & domestic and other small volume groundwater uses as part of the Implementation strategy to this Plan.	Number and level of water restrictions applied within Katherine and Tindall RAAF Base Reports of contamination or interference of bores. Restrictions to total security licences, stock & domestic and other small volume groundwater uses. Water quality in the Katherine River and Tindall Aquifer (Parameters and ranges consistent with national guidelines will be developed in an implementation strategy to this Plan.) Estimated volume of water being extracted for rural stock and domestic and other small volume groundwater uses.
3. Indigenous people have access to water from the Tindall Aquifer for commercial development.	At the 5 year review, or sooner if practicable, aim to have sufficient water available from the consumptive pool to satisfy identified requirements on Indigenous owned land. **(Part 8)**	Reclaim water from licences that have not developed as proposed at the 5 & 10 year review of this Plan, and reallocate to purposes including Indigenous economic development. **(Part 8)** Allow up to 680ML to be made available for Indigenous Commercial Development upon successful Native Title claim **(Part 8)**.	Development of water reliant enterprises by Indigenous people Volume of water rights held for or issued to Indigenous people

Outcomes	Objectives	Strategies	Performance Indicators
4. Subject to outcomes 1 & 2 defined in this Section, economic benefits from agricultural and other uses of water from the Tindall Aquifer are maximised.	To achieve the following long term licence reliability levels: • High security licences able to access their full licensed entitlement in 70% of years; • Low security licences able to access their full licensed entitlement in 30% of years. **(Part 8)** Aim to improve licence reliability levels through the review process **(Part 8)** New or expanded commercial developments can obtain access to water without impacting existing water users. **(Part 6)**	Annual extraction limits to be applied in accordance with Table 3, where the estimated un-impacted 1 Nov Katherine River flow is to be calculated at the beginning of each dry season using a model. **(Part 7)** Reclaim water from licences that have not developed as proposed at the 5 & 10 year review of this Plan, and retire as needed to contribute to achieving reliability objectives. **(Part 8)** No new licences will be given where bores of <20L/s are within 100m of an existing bore. **(Part 6, CL25)** Temporary and permanent trading of issued annual allocations to be made available subject to application processes. **(Part 7, CL34)**	Value of production from irrigation and other water reliant enterprises. Announced allocations for each category of water licence. Water trading activity.
5. Water dependent sites with identified Indigenous cultural importance, including the Katherine Hot Springs, are preserved.	Annual Tindall Aquifer discharge to the Katherine Hot Springs, Katherine River and other sites identified of Indigenous cultural importance to have essential water requirements met. **(Part 4)**	Annual extraction limits to be applied in accordance with Table 3, where the estimated un-impacted 1 Nov Katherine River flow is to be calculated at the beginning of each dry season using a model. **(Part 7)** Through engagement and research identify sites of Indigenous cultural importance which are dependent on water from the Tindall Aquifer, and assess essential water requirements. To be detailed in an Implementation strategy to this Plan. At mid term review, adjust water management rules as needed to meet the assessed essential water requirements at identified sites. Through engagement increase understanding of the importance of the Tindall Aquifer to Indigenous people. To be detailed in an Implementation strategy to this Plan.	Number of sites identified as having Indigenous cultural importance identified by this process. Percentage of identified sites with water requirements for Indigenous cultural purposes assessed. Percentage of identified sites with assessed essential water requirements met. Level of engagement and knowledge of sites of Indigenous cultural importance.

Part 4 Water for Environmental, Indigenous Cultural and other Instream Public Benefit Outcomes

Note: the Katherine and Daly Rivers rely on groundwater discharge to maintain their perennial nature, the protection of these river base flows is critical to maintain ecosystem function as well as to protect instream public benefit outcomes, including the social and cultural values intrinsically linked to these rivers such as; fishing, boating, aesthetics and spiritual fulfilment. The following provisions ensure adequate flows from this water source contribute to the maintenance of recommended environmental flows for the Daly River as described in Erskine et al, 2003.

19. Protection of discharge to surface waters during very dry years

(i) During very dry years, 87% of annual groundwater discharge from this water source to the Katherine River will be reserved for environmental and other instream public benefit outcomes.

(ii) Very dry years are defined as those years for which modelling predicts that the flow in the Katherine River at Katherine Railway Bridge on November 1, will be less than or equal to 0.6 cumecs.

(iii) In very dry years, no extraction is permitted, other than for rural stock and domestic, other small volume users and total security licences as specified under Part 5 and Part 7 of this Plan.

Note: in recognition of the importance of groundwater discharge to environmental, Indigenous cultural and other instream values, during very dry years a greater proportion of discharge from this water source is reserved for environmental and other instream public benefit outcomes, whilst providing water for essential services. Modelling indicates that at a November 1 instantaneous flow of 0.6 cumecs, 87% of annual discharge from this water source represents 29,043ML.

20. Protection of discharge to surface waters during dry years

(i) During dry years, 80% of annual groundwater discharge from this water source to the Katherine River will be reserved for environmental and other instream public benefit outcomes.

(ii) Dry years are defined as those years for which modelling predicts that the flow in the Katherine River at Katherine Railway Bridge on November 1 will be greater than 0.6 cumecs and less than or equal to 1 cumec.

(iii) In dry years, extraction is permitted by rural stock and domestic, other small volume users and licence holders as specified under Part 5 and Part 7 of this Plan.

Note: modelling indicates that at a November 1 instantaneous flow of 0.7 cumecs, 80% of annual discharge from this water source represents 31,088ML, and that at a November 1 instantaneous flow of 1 cumec, 80% of annual discharge from this water source represents 44,511ML.

21. Protection of discharge to surface waters during normal & wet years

(i) During normal and wet years, 70% of annual groundwater discharge from this water source to the Katherine River will be reserved for environmental and other instream public benefit outcomes.

(ii) Normal and wet years are defined as those years which modelling predicts that the flow in the Katherine River at Katherine Railway Bridge on November 1 will be greater than 1 cumec.

(iii) In normal and wet years, extraction is permitted by rural stock and domestic, other small volume users and licence holders as specified under Part 5 and Part 7 of Plan.

Note: modelling indicates that at a November 1 instantaneous flow of 1.1 cumecs, 70% of annual discharge from this water source represents 42,842ML, and that at a November 1 instantaneous flow of 2 cumecs, 70% of annual discharge from this water source represents 77,895ML.

Part 5 Water for Rural Stock and Domestic and Other Small Volume Groundwater Uses

22. Water for Rural Stock and Domestic and Other Small Volume Groundwater Uses

(i) At the commencement of this Plan the estimated use of water from this water source for rural stock/ domestic and other small volume groundwater uses was 1,128ML/yr. Based on bore construction permits issued since commencement of the Plan, the allocation for rural stock and domestic and other small volume groundwater uses for the remaining five years of the Plan is as follows.

a. 1,122ML/yr (previously 950ML/yr) for unlicensed rural domestic and other small volume groundwater uses,

b. 75ML/yr (unchanged) for unlicensed rural stock watering, and

c. 103ML/yr (unchanged) for the rural stock and domestic use component of existing licences.

(ii) 1,300ML/yr is allocated for rural stock and domestic purposes in addition to the licence limits stated in Part 6.

(iii) Access to water for stock and domestic purposes is given the same priority as total security licences and is subject to Clause 33.

Note: rural stock and domestic use is exempt from licensing under the Act. Small volume groundwater users (<5ML/yr/property) and stock water use within the Daly Roper Water Control District are not required to be licensed under an exemption to the Act.

For properties where groundwater is used for rural domestic and other small volume groundwater uses is estimated at 5ML/yr/property. Water for rural stock is estimated using a maximum carrying capacity of suitable land overlying this water source at 50L/head/day, where bores extracting from this water source exist. For licensed properties, water for rural stock and domestic purposes is estimated using actual stocking rates (50L/head/day), the number of residents in communal living arrangements (200L/person/day) and the number of houses (4.5ML/house/year). An increase in water required for rural stock/ domestic and other small volume groundwater uses may occur as a result of increased landholdings overlying this water source, or as a result of the increase in the exercise of these rights by existing landholders.

Part 6 Licences to Take Groundwater

23. Licence Security Categories and Reliability

(i) There are four security categories for licences each representing a different level of reliability, being:

a. Total security;

Note: Total security licence holders can expect to be able to access their maximum annual volume in all but extreme circumstances.

b. High security;

Note: If all total and high security licences were fully utilised, high security licence holders could expect to be able to access their maximum annual volume in about 70% of years.

c. Medium security, and

Note: if all total, high and medium security licences were fully utilised, medium security licence holders could expect to be able to access their maximum annual volume in about 30% of years. If there is under-development, the reliability of this security category will be higher.

d. Low security;

Note: If all licences were fully utilised, low security licence holders could expect to be able to access their maximum annual volume in about 15% of years. If there is under-development, the reliability of this security category will be higher.

(ii) Reliability represents the percentage of years, based on the stated period of record, that the stated extraction limits would have been equalled or exceeded, and is depicted in Table 1. The historic extraction limits are calculated using the lowest annual daily flow recorded for the Katherine Railway Bridge and an average annual recharge of 74,000ML.

Table.1 The following table provides context of licence security and reliability.

Security Category	Total	High			Medium			Low		
Demand	100%	60%	80%	100%	60%	80%	100%	60%	80%	100%
Equivalent required extraction limit (ML)	3004	12091	15120	18149	25221	27579	29937	33353	34492	35631
Period of record	**Reliability**									
1961-2007	100%	87%	84%	72%	40%	37%	28%	21%	17%	14%
1961-1975	100%	45%	38%	30%	0%	0%	0%	0%	0%	0%
1975-2007	100%	100%	100%	86%	52%	48%	36%	27%	23%	17%
1996-2007	100%	100%	100%	86%	77%	75%	73%	72%	71%	60%

Note: Reliability figures are approximated from flow exceedance curves using the lowest annual recorded flows at the Katherine Railway Bridge for the periods of record stated in table 1. It is assumed that the lowest annual recorded flow at the Katherine Railway Bridge is sourced entirely from Tindall Aquifer discharge.

All reliability figures take into account an additional 1,128ML demand for rural stock and domestic purposes. Rural stock and domestic use is treated as per total security licences whereby access will not be restricted unless the announced allocation to high security licences is calculated to be zero.

24. Limits to licences

(i) The licence limit is the maximum volume of water that may be extracted under licences in any single water accounting year and is subject to an annual extraction limit as specified in Part 7.

(ii) At commencement of this Plan, the licence limit was 34,503ML/yr. Accounting for successful appeals against six licences granted with declaration of the Plan, the handing back of a small number of licences and the capacity for additional licensing available with the extension of Table 3 (from 2.1 cumecs to 2.2 cumecs), the licence limit for the remaining term of the Plan is 37,091ML/yr.

(iii) Table 2 specifies limits to licences for beneficial uses, and each security category in this water source.

Beneficial Use	Security Category and Licence Limit (ML/yr)				Total ML/yr
	Total	High	Medium	Low	
Public Water Supply	1,876	483	0	1,717	**4,076**
Agriculture, Aquaculture and Industry	0	22,722	4,344	5,949	**33,015**
Total ML/yr	**1,876**	**23,205**	**4,344**	**7,666**	**37,091**

Note: Table 2 does not include rural stock and domestic and other small volume groundwater use, which is exempt from licensing under the Act (see clause 22).

25. Rules for granting licences

(i) This clause is made in accordance with sections 60 and 71 of *the Act.*

(ii) The taking of groundwater without a licence from this water source is prohibited unless provided for in Part 5 of this Plan.

(iii) From the commencement of this Plan, no additional licences will be granted for any beneficial use, in any security category prior to the five year review..

(iv) Notwithstanding subclause (iii) new licence/s may be granted upon approval of a trade in accordance with Clause 34 or as a result of a property sale or subdivision as detailed in Clause 27 and 28 respectively.

(v) The maximum annual announced allocation, as described in Part 7, must not be exceeded without prior approval from the NT Controller of Water Resources (hereafter Controller).

Note: the Controller refers to an officer appointed under section 18 of the Act.

(vi) 30% of the annual announced allocation must not be exceeded in any one month unless approved by the Controller.

(vii) The granting of licences will not be permitted where bores constructed within 1km of the Katherine River, equipped to supply in excess of 20L/s are proposed for use.

(viii) The granting of licences will not be permitted where bore/s proposed to pump in excess of 20L/s have been constructed within 100m of an existing operational bore.

(ix) The Controller may on application by a licensee, reduce the distance/s specified in subclauses (vi) or (vii) if studies undertaken by the licensee, and assessed as adequate and approved by the Controller, demonstrate minimum potential for impact on other users or spring discharge and location, as well as the other environmental and instream public benefit outcomes provided for in this Plan.

(x) All applications for licence/s from this water source will be published in a newspaper circulating throughout the Territory and also may be published in a newspaper circulating in the general Katherine community, in accordance with section 71B of *the Act.*

(xi) All decisions on applications for licence/s to take groundwater will be published in the same newspapers as stipulated in the subclause above, and a copy of the full decision will be publicly available including the reasons for the decisions and how these were taken into account, in accordance with sections 71C and 71D of *the Act.*

(xii) The details of licence/s will be contained on a register posted on the Northern Territory Government website in accordance with section 95 of *the Act.*

Note: a hard copy of the register may be viewed at either the Katherine or Darwin offices (see locations at Appendix 1).

(xiii) The mandatory conditions as specified in the *Water Regulations* will be imposed on licence/s granted, in addition to any specific conditions imposed by the Controller on a case by case basis.

(xiv) Licence/s, excluding those licences arising from approved annual trades, will remain in force for the period for which this Plan is in force, not exceeding 10 years.

(xv) Rules surrounding the provision of water to Indigenous people from this reserve will be developed in partnership with Indigenous people, and documented in the implementation strategy.

Note: a licence to take groundwater includes maximum volumes as well as conditions relating to the use of the licence and obligations of the licensee. Allocations to licences will be made on an annual basis in accordance with the extraction limit in Part 7, implemented through clause 32 of this Plan.

26. Licence applications

Note: this water source is fully allocated at the commencement of this Plan. New licences may only be issued in accordance with trades, sales or subdivision or following the five year review of this Plan.

(i) No new applications for licence/s to extract water from this water source, will be accepted, prior to the five year review.

(ii) All licence applicants are required to complete and submit the approved form under *the Act*.

(iii) The Controller may require a licence applicant to undertake hydrogeological investigations if unacceptable interference between proposed production bores and existing production or stock and domestic bores is suspected.

(iv) The Controller may require a licence applicant to undertake hydrogeological and/or cultural and ecological investigations if it is suspected that proposed development shall compromise the environmental and other instream public benefit outcomes provided for in this Plan.

(v) New licence applicants, excluding trades, must provide supporting information for the proposed development including any information required or requested by the Controller specifically that:

a. without limitation, supporting information must demonstrate access to the resource and a capacity to undertake the proposed development within resource constraints;

b. where applicable, stated water requirements accompanying an application must not exceed the maximum figures for specified crops, at Schedule 7;

c. without limitation, for public water supplies, supporting information must:

i. substantiate demand for the water supply though, population projections and estimates of water use per capita; and

ii. establish a water quality target in accordance with the Australian Drinking Water Guidelines, 2004.

27. Transfer of water licenses through property sales

(i) In situations where an NT Portion is sold, the volume specified on the existing licence at the time of sale is transferred, subject to any water trades that may have taken place in accordance with Part 7 clause 34 of this Plan.

(ii) Subject to the above clause (i), a new licence will be issued to reflect the change of ownership only once the sale of a property is confirmed with the NRETAS Water Resource Branch.

(iii) All agricultural licences including those transferred through property sales or subdivision are subject to the 5 and 10 year review, as specified in Part 8 of this Plan.

(iv) In situations where an NT Portion is sold and new owner's property development water demands are greater than the volume specified on the existing licence, additional water may be traded to meet any additional demand, as specified in Part 7 of this Plan.

28. Subdivision

(i) In situations where an NT Portion with a valid water licence attached is subdivided, and/ or re-zoned:

a. The attached water licence expires, however, one or more of the owners of land to which the expired licence related, may apply for one or more licences to replace the expired licence.

b. The volume of water issued under new licences will not exceed the requirement for the level of development existing prior to the subdivision taking place.

c. Any forfeited water will be allocated as described in Part 8 of this Plan.

29. Assignment of Risk

(i) Water licence holders are to bear the risks of any reduced or less reliable water allocation, under their licence arising from reductions to water availability as a result of:

a. seasonal or long term changes in climate; and

b. periodic natural events such as drought or contamination.

(ii) The risk of any reduced or less reliable water allocation under a water licence, arising as a result of bona fide improvements in the knowledge of the water systems capacity to sustain particular extraction levels are also to be borne by the users for the duration of this Plan.

Note: this Plan ensures that the reliability of licences is not eroded as a result of management decisions i.e. through rules which prohibit issue of additional licences which would degrade reliability, and to establish local management and trading rules.

Part 7 Rules for management of licences to take groundwater

30. Extraction Limits

(i) The maximum annual extraction limit at commencement of this Plan was 35,631ML/yr. Accounting for the revised allocation for rural stock & domestic and other small volume groundwater uses (see clause 22), and the revised licence limit (see clause 24), the maximum annual extraction limit for the remaining five years of the Plan is 38,391ML/yr.

(ii) The long term average annual extraction limit under this plan based on the period of record from 1961 to 2004 is 22,200ML.

(iii) Notwithstanding subclauses (i) and (ii), the extraction limit for this water source is dynamic and will vary from year to year in response to variable discharge from this water source to the Katherine River.

Note: this water source and the Katherine River are highly connected systems, and Katherine River base flow is dominated by water discharged from this water source. Environmental and other instream public benefit outcomes are highly dependent on these base flows, and extraction will be managed in such a way as to protect its critical elements. Extraction Limits referred to in this Plan are an estimation of Sustainable Yield, a requirement of Water Allocation Plans declared under the Act.

(iv) Table 3 specifies the maximum extractions permitted for unlicensed rural stock & domestic & other small volume groundwater use and for licensed public water supply, agriculture & industry use in a water accounting year for modelled natural flows predicted to occur on November 1 of that year in the Katherine River at Katherine Railway Bridge.

Table 3

Modelled natural flow at Katherine Railway Bridge (cumecs)	Overall Extraction Limit (ML/yr)	Extraction Limits for Beneficial Uses (ML/yr)						
		Stock & Domestic	Public Water Supply			Agriculture & Industry		
			Security Level			Security Level		
			Total	High	Low	High	Medium	Low
≤ 0.6	4,340	1,300	1,876	0	0	1,164	0	0
>0.6, and ≤ 0.7	7,772	1,300	1,876	0	0	4,596	0	0
>0.7, and ≤ 0.8	8,902	1,300	1,876	0	0	5,726	0	0
>0.8, and ≤ 0.9	10,015	1,300	1,876	0	0	6,839	0	0
>0.9, and ≤ 1.0	11,128	1,300	1,876	0	0	7,952	0	0
>1.0, and ≤ 1.1	18,361	1,300	1,876	0	0	15,185	0	0
>1.1, and ≤ 1.2	20,030	1,300	1,876	0	0	16,854	0	0
>1.2, and ≤ 1.3	21,699	1,300	1,876	0	0	18,523	0	0
>1.3, and ≤ 1.4	23,369	1,300	1,876	0	0	20,193	0	0
>1.4, and ≤ 1.5	25,038	1,300	1,876	0	0	21,862	0	0
>1.5, and ≤ 1.6	26,707	1,300	1,876	483	0	22,722	326	0
>1.6, and ≤ 1.7	28,376	1,300	1,876	483	0	22,722	1,995	0
>1.7, and ≤ 1.8	30,005	1,300	1,876	483	0	22,722	3,624	0
>1.8, and ≤ 1.9	31,714	1,300	1,876	483	0	22,722	4,333	0
>1.9, and ≤ 2.0	33,383	1,300	1,876	483	0	22,722	4,344	2,658
>2.0, and ≤ 2.1	35,052	1,300	1,876	483	263	22,722	4,344	4,064
>2.1, and ≤ 2.2	36,722	1,300	1,876	483	1,717	22,722	4,344	4,280
>2.2	38,391	1,300	1,876	483	1,717	22,722	4,344	5,949

Note: If the modelled flow at Katherine Railway Bridge on 1 Nov is less than 2 cumecs, it is assumed there is no measurable inflow from the Katherine River upstream of Ironwood gauging station.

Extraction limits for groundwater extraction licences in this source will be determined first in accordance with Table 3; with extraction limits for surface water extraction licences in the Katherine River within the Plan Area determined subsequently to preserve Other Public Benefit Outcomes within the remaining available river flows.

31. Announced allocation accounting

(i) The accounting for announced allocations begins May 1 and continues for 12 months (hereafter **water accounting year**).

(ii) The annual licensed volume for the relevant year, as specified on individual licence entitlements (hereafter **annual licensed volume**) is the maximum volume of water that may be accessed (extracted or traded) in each water accounting year.

(iii) Once a licensee has reached full development, the annual licensed volume will be the maximum water entitlement stated on the licence.

Note: The annual licensed volume is based on the proposed level of development for each year as specified in the licensee's property development plan. A property development plan was submitted as supporting information to each licensee's application for grant of licence to take or use groundwater from this source.

(iv) Debit to announced allocation accounts will be made following the receipt of pumpage returns on a monthly basis.

(v) The carrying over of yearly announced allocations from one water accounting year to the next is not permitted.

(vi) An announced allocation account shall remain above zero at all times.

32. Announced allocations

This clause is made pursuant to section 70 of *the Act* with respect to the power to give direction.

(i) The announced allocation is the percentage of the annual licensed volume that may be accessed (extracted or traded) each year.

Note: Announced allocations are necessary to adjust the volume of water extraction from this water source to accommodate natural variations in water availability i.e. annual extraction limit.

(ii) Announced allocations shall be determined prior to the beginning of each water accounting year to ensure total extractions from this water source remain within the extraction limits specified in Part 7 of this Plan.

(iii) Announced allocations will consider the proposed annual water extraction regime for the following water accounting year calculated using:

a. The combined annual licensed volume of all licenses assigned to the beneficial use of public water supply, agriculture, aquaculture and industry for the relevant water accounting year.

b. water assigned for rural stock and domestic and other small volume groundwater uses, as specified in Part 5 of this Plan; and

(iv) Announced allocations will be made based on the following criteria:

a. In this section, **total security demand** means:
   i. the volume of water assigned for rural stock and domestic and other small volume groundwater uses specified in clause 22; and
   ii. the total security licence volume for public water supply as specified in clause 24.

Note: The licence limit is the combined total of maximum water entitlements, as specified on individual licences.

b. If the extraction limit is greater than or equal to the sum low, medium and high annual licensed volumes and the total security demand, the announced allocation for each individual licence will be 100% of the annual licensed volume.

c. If the extraction limit is less than the sum of low, medium and high annual licensed volumes and total security demand, but greater than or equal to the sum of the annual licensed volume for low, medium high security licences and total security demand, excluding the volume allocated for public water supply in low security then:

   i. the announced allocation will be 100% of the annual licensed volume for all total, high, medium and low security licences excluding the low security licence for public water supply; and
   ii. the announced allocation for low security public water supply will be a percentage of the maximum water entitlement volume, not exceeding 100%.

d. If the extraction limit is less than the sum of the annual licensed volume for low, medium and high security licences and total security demand but greater than or equal to the sum of the annual licensed volume for medium and high security licences and total security demand then:

   i. the announced allocation will be 100% of the annual licensed volume for medium, high and total security licences; and
   ii. the announced allocation for low security licences, excluding the volume for public water supply, will be a percentage of the annual licensed volume, not exceeding 100%; and
   iii. the announced allocation for low security public water supply will be reduced to zero.

e. If the extraction limit is less than the sum of the annual licensed volume for medium and high security licences and total security demand but greater than or equal to the sum of the annual licensed volume for high security licences and total security demand then:

   i. the announced allocation will be 100% of the annual licensed volume for high and total security licences; and
   ii. the announced allocation for medium security licences will be a percentage of the annual licensed volume, not exceeding 100%; and
   iii. the announced allocation for all low security licences will be reduced to zero.

f. If the extraction limit is less than the sum of the annual licensed volume for high security licences and total security demand but greater than or equal to the sum of the annual licensed volume for high security licences and total security demand, excluding the volume allocated for public water supply in high security then:

   i. the announced allocation will be 100% of the annual licensed volume for total and high security licences, excluding the high security licence for public water supply; and
   ii. the announced allocation for high security public water supply will be a percentage of the maximum water entitlement volume, not exceeding 100%.
   iii. the announced allocation for all medium and low security licences will be reduced to zero.

g. If the extraction limit is less than the sum of the annual licensed volume for high security licences and total security demand, excluding the volume allocated for public water supply in high security then:

   i. the announced allocation for total security licences will be 100%; and
   ii. the announced allocation for high security licences, excluding public water supply, will be a percentage of the maximum annual licence volume, not exceeding 100%.
   iii. the announced allocation for high security public water supply and all medium and low security licences will be reduced to zero.

Note: *If announced allocations under subclause (iv) are required, an early indication of proposed allocations shall be estimated as soon as possible preceding the final announced allocations by 1 May*

(v) Licensees shall be notified of the announced allocations in writing prior to the commencement of the water accounting year, a notice shall be placed in a newspaper circulating in the general Katherine community, and a report which includes reasoning for the decision, shall be available on the Northern Territory Government website.

33. Emergency Powers to Limit Rights to Take Water

This clause is made pursuant to section 96 of *the Act* with respect to emergency powers to limit the right to take water

(i) In times of severe water scarcity, the Controller may place water restrictions on total security licence holders as well as rural stock/ domestic and other small volume groundwater users to achieve the outcomes provided for in Part 4 of this Plan.

Note: severe water scarcity refers to a flow at Katherine Railway Bridge of less than 0.6 cumecs.

(ii) In times of severe water scarcity, restrictions may be applied to users supplied within the Katherine Urban Water Reticulation Area.

34. Water trading

(i) Water management zones

a. The following water management zones have been defined for this water source:

i. Zone 1 – extraction from this source in zone 1 will impact on flows in the Katherine River within 1 year; and

ii. Zone 2 – extraction from this source in zone 2 will impact on flows in the Katherine River more than 1 year later.

b. The locations of these zones are shown in Schedule 5.

(ii) Temporary trade

a. Temporary trade is the transfer of water entitlement and associated security level from one licence to another licence within, and for the maximum duration of, one water allocation year only.

b. A temporary trade can be up to 100% of the water entitlement and associated security level made available in the water accounting year for the licence from which trade occurs.

(iii) Permanent trades

a. Permanent trade is the transfer of water entitlement and associated security level from one licence to another licence for the full remaining term of the licence from which the transfer is made.

b. A permanent trade can be up to 100% of the maximum water entitlement and associated security level specified in the licence from which the transfer is made.

Note: The licence to which a temporary or permanent trade is made can be either an existing licence that had been granted before the trade was approved or it can be a new licence granted in accordance with clause 34 (vi) of this Plan.

(iv) Zone 1 Trading

a. Extraction from this source in zone 1 will reduce flow in the Katherine River within one year and, therefore, only 15% of the total extraction from this source (see clause 30; Table 3) is permitted from zone 1 in order to protect environmental flows in the river.

b. Temporary and permanent trades within zone 1 and from zone 1 into zone 2 can only occur on the provisos that:

i. there will be no unacceptable interference with water supply from any third party bore;

ii. the requirements of clause 25 of this Plan are met; and

iii. approval is sought and given in accordance with clause 34 (vi) of this Plan.

c. Temporary and permanent trade from water management zone 2 into water management zone 1 can only occur on the provisos that:

i. the resultant total of licensed extractions and unlicensed extractions for rural stock & domestic and other small groundwater uses in water management zone 1 is not greater than 15% of the annual extraction limit (see Clause 30, Table 3) for the water accounting year applying at the time of trade;

ii. there will be no unacceptable interference with water supply from any third party bore;

iii. the requirements of clause 25 of this Plan are met; and

iv. approval is sought and given in accordance with clause 34 (vi) of this Plan.

Note: Clause 34 (iv) c i means that a permanent trade into zone 1 can only occur if there has previously been nett permanent trade (or surrender of water entitlements) out of zone 1 of equivalent or greater volume to that sought with the permanent trade.

(v) Zone 2 Trading

a. Extraction from this source in zone 2 will not reduce flow in the Katherine River within one year and, therefore, up to 100% of the total extraction from this source (see clause 30; Table 3) can occur from zone 2 without risk to environmental flows in the Katherine River.

b. Temporary and permanent trades within zone 2 and from zone 1 into zone 2 can only occur on the provisos that:

i. there will be no unacceptable interference with water supply from any third party bore;

ii. the requirements of clause 25 of this Plan are met; and

iii. approval is sought and given in accordance with clause 34 (vi) of this Plan.

c. Temporary and permanent trade from water management zone 2 into water management zone 1 can only occur on the provisos that:

i. the resultant total of licensed extractions and unlicensed extractions for rural stock & domestic and other small groundwater uses in water management zone 1 is not greater than 15% of the annual extraction limit (see Clause 30, Table 3) for the water accounting year at the time of trade;

ii. there will be no unacceptable interference with water supply from any third party bore; and

iii. the requirements of clause 25 of this Plan are met; and

iv. approval is sought and given in accordance with clause 34 (vi) of this Plan.

(vi) Approvals

a. An application for a groundwater extraction licence should be submitted by each trading party after they have agreed on the trade details.

Note: Trading in water entitlements can be undertaken on an agreed commercial basis between the trading parties or it can be undertaken on a non-financial basis as agreed between the trading parties. All trade negotiations are a matter for the trading parties alone and the commercial basis of any trade will be treated as confidential if requested by either trading party.

b. The application for the licence from which the water entitlement and associated security level is to be traded will request either a temporary or permanent reduction in licensed water entitlement and associated security level.

c. The application from the entity to which the water entitlement and associated security level is to be traded will request either a temporary or permanent increase in currently licensed water entitlement and associated security level or request the grant of a new licence.

d. The application to which the water entitlement and associated security level is to be permanently traded will include a property/business development plan that supports the requirement for the increased or new water entitlement and associated security level being sought.

e. Both applications will be processed jointly, including the requirement under the *Water Act* to advertise the applications for transfer of water entitlement and associated security level.

f. Subject to compliance with clauses 34 (iv) b, (iv) c, (v) b and (v) c of this Plan, new licences will be issued to the trading parties that reflect the agreed and/or approved transfer of water entitlements and associated security levels.

Part 8 Review of this Plan

35. General

In accordance with section 22B of *the Act*, the Minister must ensure:

(i) that a review of this Plan (hereafter **the review**) is conducted at intervals not longer than 5 years;

(ii) that the review considers the extent to which the Plan has achieved its outcomes and objectives;

(iii) that the provisions of section 18 of this Plan are fully carried out;

(iv) that the review is informed by the outcomes of the monitoring program, and research findings as well as consultation with a relevant Water Advisory Committee and the broader Katherine Community; and

(v) that all public submissions as well as any Territory or regional policies or agreements coming into force after the initial declaration and with relevance to this Plan are considered at the review.

(vi) If the existence of Native Title (under application NTD6002/00) is recognised within the lifetime of this Plan, the relevant Parts of the Plan must be amended to include 680ML for Indigenous commercial development (through grant of licences upon application), including:

a. Licence Security Categories and Reliability defined in Part 6 of the Plan;

b. Limits to Licences defined in Part 6 of the Plan.

c. The maximum extraction Limit defined in Part 7 of this Plan

Note: There will be no reduction to environmental allocations described in Part 4 of this Plan if water is required to be allocated as described in Clause 35 (vi). If water for Indigenous commercial development is allocated prior to the 5 year review, this will result in a small reduction in reliability for licence holders. However, it is intended that any water allocated for Indigenous commercial development be offset during the 5 year review process described in clauses 36 and 37.

36. Review of extraction limit

(i) If following the review of this Plan, if it is necessary to increase the provisions for environmental, Indigenous cultural and other instream public benefit outcomes, the extraction limits specified in clause 30 may be modified to increase these provisions. As far as possible, the amendments to licences as provided for under clause 37 will offset the reduction of extraction limits.

(ii) Subject to subclause 'i', any water made available for consumptive purposes following the review of the Plan, either through amendments to licences under clause 37 of this Plan, or through an increase in the extraction limit, may be re-assigned at the review of this Plan in accordance with the order of below priorities:

a. to account for an increase in demand from rural stock/ domestic and other small volume groundwater uses;

b. to hold up to 680ML in trust for Indigenous commercial development at the security level from which it is recovered; and

c. to achieve the following reliability targets for licence security categories at full licence development:

   i. Medium security = 50%

   ii. Low security = 30%

d. to issue new licences, by means of the market or other processes established by the Controller.

(iii) If at the 5 year review, outcomes of the monitoring program and research findings indicate more water is available than prescribed under this Plan, and the risk associated with licence reliability has been significantly reduced, water entitlements may not be actively reclaimed as part of the review process.

(iv) If at the 5 year review, outcomes of the monitoring program and research findings indicate, less water is available, than prescribed under this Plan, the average discharge for this Plan will be reduced, resulting in reductions of annual extraction limits, impacting all allocations from this water source.

37. Rules for amending and renewing licences

(i) The provisions of clause 37 at commencement of this Plan were assessed during the 5 year review and found to be too inflexible and onerous in the context of the current stage of water resource development utilising this water source and also in the context of emerging biosecurity threats.

(ii) Consequently, as soon as practicable following the completion of the 5 year review of this Plan:

a. all groundwater extraction licences granted in this water source will be amended to provide uniform, specific conditions in regard to underutilisation or non-use of water entitlements (see Schedule 8); and

b. holders of licences for which there has been no reported extraction, or who have not commenced on-ground development, since commencement of the Plan will be required to justify the retention of those licences in writing to the Controller of Water Resources.

(iii) Providing the requirements of the *Water Act*, Water Regulations and the licence conditions have been met, a licence expiring at the end of this Plan shall be renewed upon application by the licence holder.

Part 9 Licence conditions

38. General

(i) All licences must meet the requirements of *the Act* and its Regulations and associated Approved Forms.

(ii) Mandatory licence conditions will be imposed by the Controller to achieve the provisions in this Plan.

(iii) Mandatory conditions are outlined in the Water Regulations and associated Approved Forms

Part 10 Bore Construction Permit Conditions

39. General

(i) Bore construction permits (hereafter **Permits**) are required for the construction of all bores in this water source, irrespective of their intended use or capacity.

(ii) Permits shall not be issued to properties that have access to reticulated water, when the intended purpose/s of the proposed bore is unlicensed rural stock/ domestic or other small volume groundwater uses.

Note: A map of Power Water Corporation reticulated supply scheme around Katherine (Schedule 4).

(iii) Mandatory conditions will be imposed by the Controller on all bore construction permits issued in this Plan area to achieve the provisions in this Plan.

(iv) Mandatory conditions are outlined in the Water Regulations and associated Approved Forms.

Note: That all construction activities must be in accordance with the minimum construction requirements for water bores in Australia and other requirements as referred to by the Controller.

Part 11 Monitoring and Evaluation

40. General

(i) The monitoring of the performance indicators specified in Part 3 shall be directed by the Controller as specified in Appendix 2.

41. Implementation of this Plan

(i) The strategies as outlined in Part 3 will be implemented upon commencement of this Plan.

(ii) Announced allocations to licences will be made immediately upon commencement of this Plan for the water accounting year from 1 May 2009 to 30 April 2010 in accordance with Clause 32 (ii – iv)

(iii) The Controller will establish an Implementation Strategy to this Plan that outlines how objectives and strategies made in this Plan will be achieved.

Note: An announced allocation to licences must be made upon declaration of this Plan for the 2009/2010 water accounting year as the Plan was declared following 1 May 2009.

It is intended that the Implementation strategy will be developed as a separate process to be completed following the formal declaration of this Plan.

Schedule 1 Glossary of Terms

Note: terms defined in Part 1 of the Act, have not been repeated in this Schedule. The same definitions detailed in the Act apply to this Plan.

Announced allocation: is the percentage of the annual licensed volume that may be accessed (extracted or traded) each year

Aquifer: refers to a geological formation, group of formations, or part of a formation that stores and/ or allows movement of groundwater.

Base flow: refers to the part of total flow in a river or stream derived from groundwater discharge.

Climatic variability: refers to changes in discharge from the Tindall Limestone Aquifer to the Katherine River within the Plan area resulting from a change in rainfall recharge to the aquifer.

Cumec: cubic meters per second - a unit of measurement used to describe flow in surface water systems; one cumec is equal to one thousand litres per second.

Extraction limit: refers to the volumetric limit of water made available for extraction from the system on an annual basis.

Groundwater: refers to water stored underground in rock fractures, cavities and pores.

Katherine Railway Bridge: refers to the old railway bridge currently used for pedestrian traffic only, approximately 50 metres down-stream from the Stuart Highway (high level) bridge.

Licence security category: refers to a licence group for which the rules relating to annual allocation announcements are similar.

Reliability for a licence category is the percentage of years during a simulated period when all licences of a licence security category would receive a hundred percent of licensed entitlement as an announced allocation, as determined using a numerical model of the Tindall Aquifer using climatic data from 1960 to 2007, and assuming all licences are fully developed.

Numerical model: refers to a mathematical representation of a physical system intended to mimic the behaviour of a real system, allowing description about empirical data and prediction about untested states of the system.

Severe water scarcity: refers to a flow in the Katherine River at Katherine Railway Bridge of less than 0.6 cumecs.

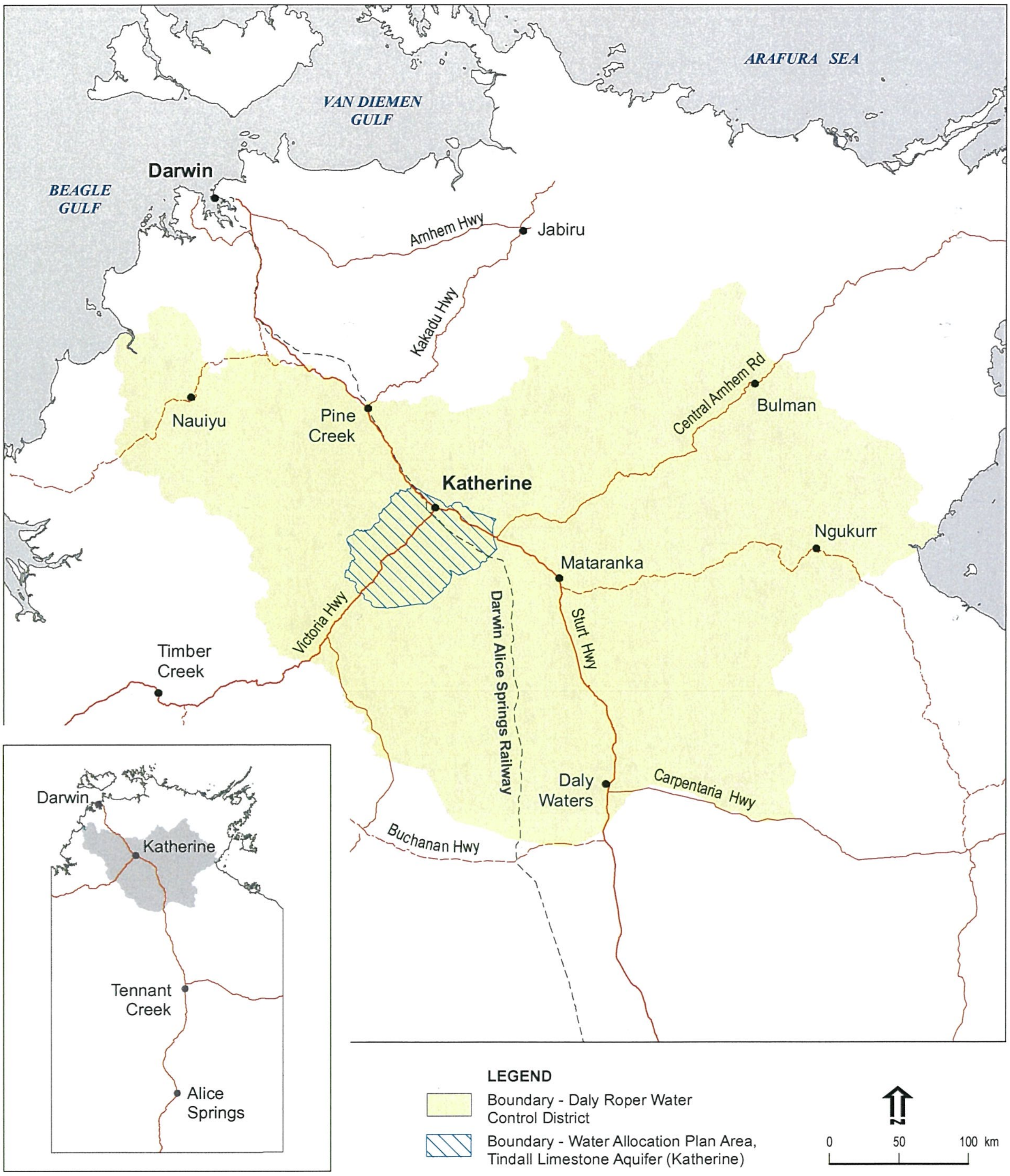
Standardised water figures: refer to the predicted water requirements of the various crops grown in the Katherine Region assuming a D10 rainfall event (655mm/yr).

Unimpacted flow in the Katherine River at Katherine Railway Bridge is the flow which it is estimated would occur were there no extraction of water, as determined using a numerical model.

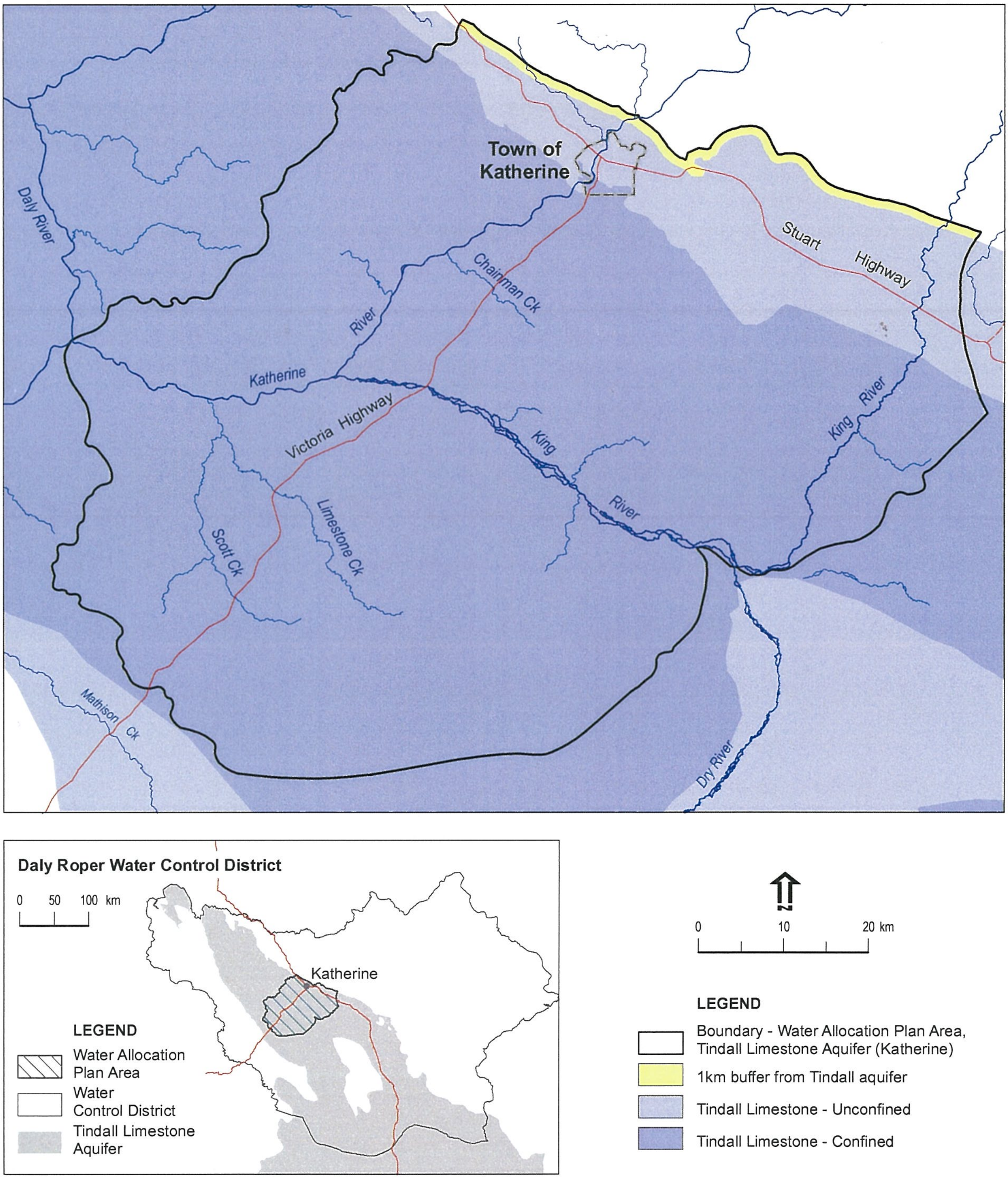
Water management zone: refers to part of an aquifer system that is treated as a single unit for water trading and other regulatory purposes.

Water Trading: Trade is the key mechanism through which water resources are able to be reallocated among competing users and uses. Through trade, markets create incentives for participants to use water more efficiently, responding to price signals which are transparent and responsive to fluctuations in demand.

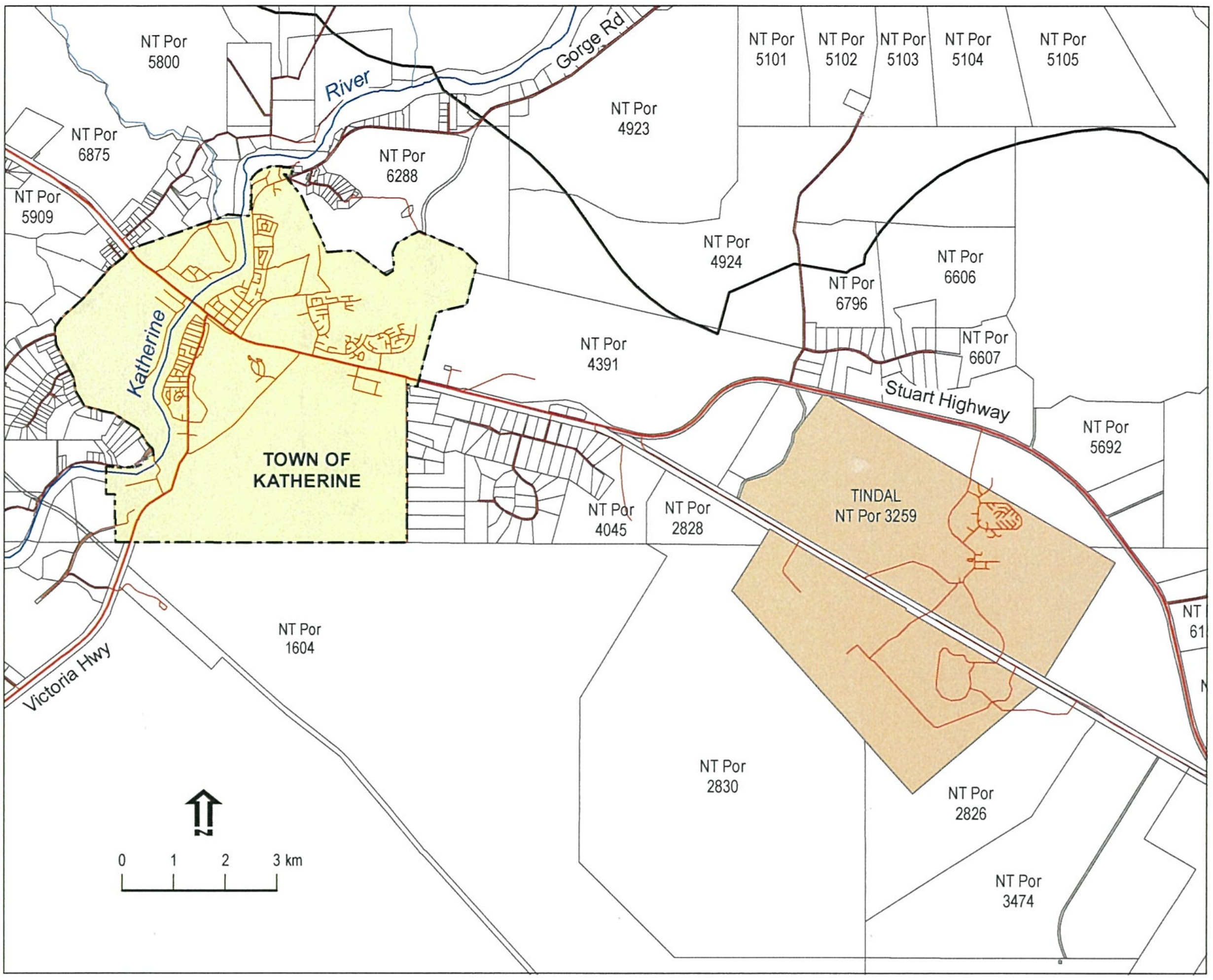
Schedule 2 Daly Roper Water Control District

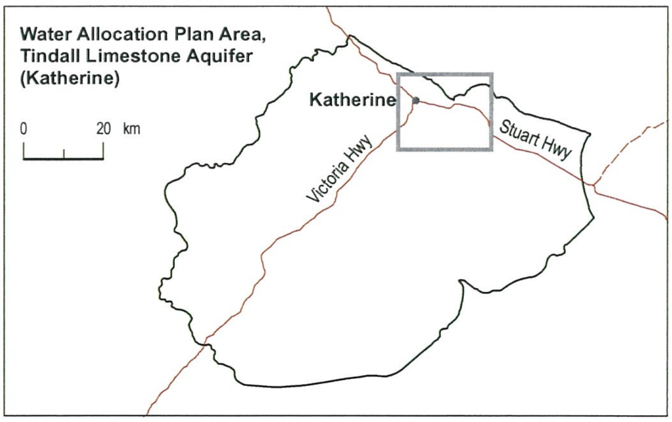


Schedule 3 The Plan area – Defined by the extent of Tindall Limestone within the Katherine River Catchment



Schedule 4 Katherine Urban Water Reticulation Area



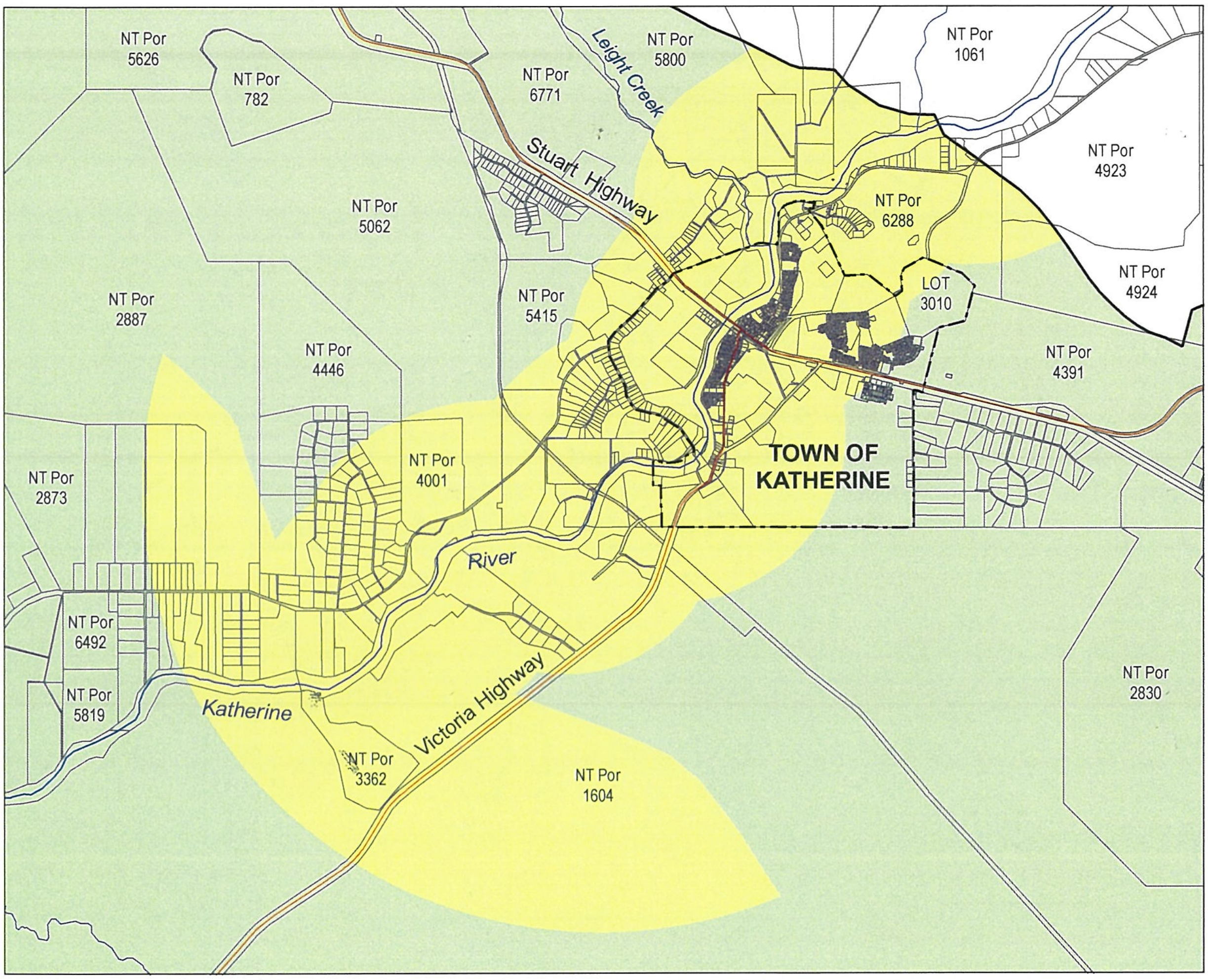


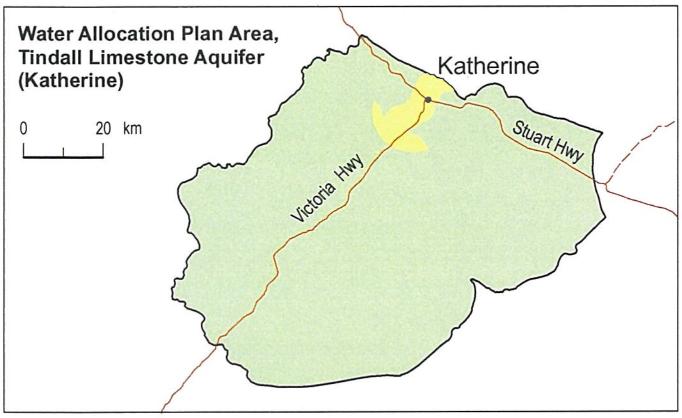
LEGEND

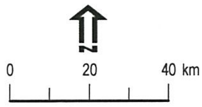
- Boundary - Water Allocation Plan Area, Tindall Limestone Aquifer (Katherine)
- Katherine Town Boundary
- Tindal RAAF Base - Commonwealth Land
- Cadastral property boundaries

NOTE:
Extent of reticulated water supply is generally within the Katherine Town Boundary and Tindal RAAF Base. Reticulated water may also be supplied to other locations beyond these areas.

Schedule 5 Water Management Zones







LEGEND

	Boundary - Water Allocation Plan Area, Tindall Limestone Aquifer (Katherine)
	Zone 1 (< 1 year) Short term lag between extraction and impact on the Katherine River
	Zone 2 (> 1 year) Medium to long term lag between extraction and impact on the Katherine River
	Cadastral property boundaries

Schedule 6 Contribution to Relevant Targets in the March 2005 Integrated Natural Resource Management Plan

Assessed levels of contribution:
FULL contributes to the target in full
HIGH a significant but not full contribution to the target
PARTIAL goes part way to contributing to the target
LOW only a slight contribution to the target

Management Action Targets	Level of Contribution	Comments
MAT 5-6 In collaboration with local stakeholders monitor with community involvement and participation, and report in water dependent ecosystems in at least 5 catchments subject to increasing development pressure and model biophysical responses to groundwater extraction.	High	This water allocation planning process and its implementation has and will continue to involve the participation of the community and peak stakeholder bodies in order to achieve sustainable water resource use in a catchment under considerable development pressure.
MAT 5-8 review current inland aquatic information, determine gaps in critical information for planning and sustainable resource use, and prioritise research and monitoring work to fill these gaps, taking into account the technical forum identified in MA5-41	High	NRETAS Technical Expert group and KWAC are responsible for reviewing existing information, as well as the identification of knowledge gaps and monitoring programs. This will be an ongoing task with progress updates annually and their findings incorporated into WAP review.
MAT 5-9 Undertake an annual program of regional rainfall, stream flow, groundwater levels and water quality monitoring in all Water Control Districts to inform water allocation planning and management.	High	Monitoring the impacts on this water source is a key component of the implementation of this Plan, it is also required to test conceptualisation and modelling of this water source and to inform reviews.
MAT5-10 Determine the sustainability of all towns and community public water supplies.	High	This Plan ensures diversity of supply to the Katherine municipality and provides adequate access for the duration of this Plan.
MA5-13 Develop or finalise Water Allocation Plans for Alice Springs, Darwin, Gove, Katherine, Tennant Creek and Ti Tree regions, and prioritise other regions for similar planning processes.	High	This Plan is a Water Allocation Plan for the water source under most pressure within the Katherine Region.
MA5-14 Implement Water Allocation Plans for all Water Control Districts.	High	As above
MA5-41 Establish a cross-sectoral, community inclusive forum with technical expertise to recommend planning decisions, policy development and management for inland water adheres to ESD principles.	High	The main route of consultation used in the formation of this Water Allocation Plan was through a statutory stakeholder based water advisory committee appointed under the NT *Water Act*.
MA5-44 Develop data sharing arrangements between Government agencies, resource users, landholders, and local communities to ensure water quality data, biological data, environmental flow requirements, and groundwater abstraction data are available for all regional and property based planning.	Medium	This information is freely available, public reports displaying and interpreting this data will be produced periodically by the Department as specified in Appendix 2 of this Plan. It is envisaged that the Bureau of Meteorology will compile and make publicly available all water resource information including extractions on a resource by resource basis, within the life of this Plan.

Schedule 7 Standardised Crop Water Use Figures

(i) Perennial Crops

Crop Type	Stage of Growth	ML/Ha/Yr
Avocados	Mature	9.6
Bananas	Mature	19.6
Citrus	1 yr	0.3
	2 yr	1.6
	3 yr	3.6
	4 yr	5.7
	Mature (5+ yrs)	9
Leucaena	1 yr	2.1
	2 yr	4.1
	3 yr	6.7
Mahogany Trees	1 yr	1.3
	2 yr	2.6
	3 yr	2.8
	4 yr	0
Mangoes	1 yr	0.3
	2 yr	0.9
	3 yr	2
	4 yr	3.1
	5 yr	4.8
	6 yr	7.4
	Mature (7+ yrs)	8.6
Paw Paws	Mature	18.5

(ii) Annual Crops

Crop Type	Growing Time-Frame	ML/Ha/Yr
Rhodes Grass	March – Dec	12.3
Forage Sorghum/Millet	April – Nov	10.5
	May - Dec	10.7
Lawn	March - Nov	3.9 (0.5ha)
Lucerne	March - Nov	10.3
Maize	April – Aug	5.8
Melons	Mar - May	2.9
	April – June	2.9
	May – July	3
	June – Aug	3.4
	July – Sept	3.8
	Aug – Oct	4.5
	Sept - Nov	3.8
Nursery/Shade house	N/A	1.74 (0.1ha)
Onions	Apr – Aug	5.4
	May - Sept	5.9
Peanuts	Mar – Aug	7.2
	April – Sept	7.9
	May - Oct	8.8
	May - Nov	10.1
Potatoes	16 weeks	4.7
	18 weeks	5.8

Schedule 8 Template for Groundwater Extraction Licence

NORTHERN TERRITORY OF AUSTRALIA
LICENCE TO TAKE GROUNDWATER
Pursuant to section 60 of the *Water Act*
Licence No:

Licence Holder:			
Address:			
Expiry Date:			
Groundwater Resource:	Tindall Limestone Aquifer, Katherine		
Bores:	RNXXXX and additional bore/s to be completed in the future (see additional condition 12h)		
Water Control District:	Daly Roper		
Management Zone:	Zone 1/ 2		
Property on which water is used:			
Beneficial Use of Water Entitlement	**Maximum Water Entitlement ML/year**	**Security Level**	**Licence Trading Allowed?**
Total Maximum Water Entitlement:			

Terms and Conditions:

1. This licence is valid until the expiry date stated on the licence, subject to terms 2, 3 and 4.
2. The licence holder can surrender or apply for modification of this licence at any time.
3. This licence may be revoked, suspended or modified at any time by the Controller of Water Resources, as provided for in section 93 of the *Water Act*.
4. Non-use or underutilisation of the water entitlement(s) conferred under this licence may result in full or partial revocation of the licence by the Controller of Water Resources.
5. No guarantee is given or implied by this licence that water will be available from the listed groundwater resource at any given time.
6. If a Water Allocation Plan is declared for the stated groundwater resource, the licensed water entitlement(s) may only be traded in accordance with the requirements of that plan.
7. The licence holder must take or use no more than the stated maximum water entitlement from the listed groundwater resource, subject to the *Water Act*, the Water Regulations and this licence.
8. Chemical and/or fertiliser injection systems shall not be installed into the pump discharge lines without the prior approval of the Controller of Water Resources
9. Extraction from the listed groundwater resource must be recorded by a meter or meters supplied, installed and maintained by the licence holder to the satisfaction of the Controller of Water Resources.
10. The record of extraction must be supplied to the Controller of Water Resources as stated in the additional conditions of this licence.
11. The water entitlement shown for each listed beneficial use must be used for no other purpose than that beneficial use without approval of the Controller of Water Resources.

The following additional conditions apply:

12a) The licence holder must not, nor permit any person to, tamper with any meter installed in accordance with this licence.

12b) Except as allowed by additional condition 12c), within two (2) weeks following the end of each month, the licence holder must supply the Controller of Water Resources with a record of total extraction from the listed bores or advise when that record will be supplied.

12c) The licence holder must ensure that no more than 3 months extraction records as required under additional condition 12b) are outstanding at any time during the term of this licence.

12d) Subject to additional conditions 12e) & 12f) below, the licence holder must ensure that total extraction from the listed bores over the term of this licence shall not exceed the following Entitlements:

Period	Entitlement

12e) Between [Date 1 and Date 2], the licence holder must ensure that total extraction from the listed bores in each 12 month period ending on 30 April does not exceed the Extraction Limit, which is determined as follows:

- Extraction Limit (ML/yr) = Entitlement (ML) x Announced Allocation (%); and
- Announced Allocation is notified on 1 May each year thereafter in writing to the licence holder by the Controller of Water Resources as the factor by which the relevant Entitlement shown in additional condition 12d) must be adjusted in order to maintain an appropriate level of environmental protection and water supply security in regional water resources that are connected to the Tindall Limestone Aquifer, Katherine.

12f) The licence holder must ensure total extraction for the listed bores in any one month does not exceed 30% of the Extraction Limit unless approved by the Controller of Water Resources.

12g) In the event that the total extraction reported under this licence is less than 75% of the Extraction Limits determined for 3 consecutive 12 month periods by additional condition 12e), the licence holder must provide a written report upon request from the Controller of Water Resources that explains why the Extraction Limits were not reached and provides a projection of water requirements under this licence for the next three years or remaining term of the licence, whichever is the lesser.

12h) The licence holder must notify the Controller of Water Resources of any bore or bores, other than those listed on this licence, from which it is intended to extract water for the purpose of this licence and must not use that bore or bores until the licence is reissued with all extraction bores listed.

Controller of Water Resources.. Date: / /

Appendix 1 Location of Maps

The maps created for this Plan may be inspected at:

Darwin Head Office
Department of Natural Resources, Environment, The Arts and Sport
Goyder Centre, Chung Wah Terrace
PO Box 30, Palmerston NT 0830
Phone 08 8999 4892
Fax 08 8999 4403

Katherine Regional Office
Department of Natural Resources, Environment, The Arts and Sport
32 Giles Street, Katherine
PMB 123, Katherine NT 0852
Phone 08 8973 8115
Fax 08 8973 8122

Appendix 2 Monitoring Program

The monitoring program for this Plan will be finalised in an implementation strategy to this Plan. The monitoring programs presented in the following table may be reviewed and expanded during the development of the implementation strategy.

The Monitoring Program is based upon the Performance Indicators stipulated in this Plan

Performance Indicator	Related Outcome	As Measured By	Reporting Type and Frequency
River health	1	Assessment parameters and ranges consistent with national guidelines will be developed in an implementation strategy to this Plan	Annual written report
Annual discharge from this water source to the Katherine River relative to other years and annual extraction from this water source.	1	Stream flows at gauging stations located at Ironwood and Wilden Stations. Pumpage returns from all licensed bores on a monthly basis under licence condition. A network of monitoring bores comprising bores fitted with continuous loggers and others monitored manually.	Annual written report. Telemetered data will be available from gauging stations in real time.
Water quality in the Katherine River and Tindall Aquifer	1 & 2	Parameters and ranges consistent with national guidelines will be developed in an implementation strategy to this Plan.	Annual written report.
Identification of methodology to quantify water requirements for Indigenous cultural purposes.	1 & 5	Desk top analysis to review the application and assessment methodology developed through a social study.	Written report prior to the review.
Identification of specific environmental water requirements that maintain ecological processes in the Katherine and Daly Rivers.	1	In addition to 'River Health' (previously mentioned in this table); Fish, macroinvertebrates, aquatic plants and physical habitat in the Katherine River downstream of Knott's Crossing, and sites in the Daly River - to be determined.	Annual written report.
Number and level of water restrictions applied within Katherine and Tindall RAAF Base.	2	Desktop analysis to be completed in partnership with Power and Water Corp.	Written report prior to the review.
Reports of contamination or interference of bores.	2	Desktop analysis of compliance reports detailing cases of contamination or interference of bores.	Written report prior to the review.
Restrictions to total security licences, stock & domestic and other small volume groundwater uses.	2	Desktop analysis to review details of restrictions.	Written report prior to the review.
Estimated volume of water being extracted for rural stock and domestic and other small volume groundwater uses.	2	Desktop review of changes to land use zoning that may impact on the utilisation of water for rural stock & domestic purposes, and other small volume groundwater uses.	Written report prior to the review.

Development of water reliant enterprises by Indigenous people.	3	Desktop review of Indigenous owned/ managed water reliant enterprises, using groundwater from the Tindall Aquifer.	Written report following the 5 year review, but prior to the 10 year review.
Volume of water rights held for or issued to Indigenous people.	3	Desktop analysis of water held in trust and issued to Indigenous people.	Written report following the 5 year review, but prior to the 10 year review.
Value of production from irrigation and other water reliant enterprises.	4	Desktop review in association with ABS and other NT Govt Departments i.e. RDPIFR.	Written report prior to the review.
Announced allocations for each category of water licence.	4	Desktop review comparing announced allocations and demand based on estimated property development.	Written report prior to the 5yr review.
Water trading activity.	4	Desktop analysis of all trading activity.	Written report prior to the review.
Percentage of known sites identified of Indigenous cultural importance identified by this process	5	A social study, detailing the social and cultural importance of sites dependant on groundwater from the Tindall Aquifer, with references made to other existing Indigenous studies of the Katherine area.	Written report prior to the review.
Level of engagement and knowledge of sites of Indigenous cultural importance.	5	A social study, detailing the social and cultural importance of sites dependant on groundwater from the Tindall Aquifer, and input from Indigenous groups into the process.	Written report prior to the review.

Appendix 3 Review Report by Katherine Water Advisory Committee February 2016

WATER ALLOCATION PLAN

for the

TINDALL LIMESTONE AQUIFER, KATHERINE

2009 - 2019

REVIEW REPORT

KATHERINE WATER ADVISORY COMMITTEE

February 2016

CONTENTS

MESSAGE FROM THE CHAIR OF THE KATHERINE WATER ADVISORY COMMITTEE

Understanding and maintaining our water resources is vital for the growth and prosperity of the Northern Territory. As we encourage agricultural and industry development we must be cognisant of the competing priorities of business and recreational uses of this finite resource, attuned to Indigenous cultural purposes and ensure that the environment is sustainable and protected for future generations.

The Katherine Water Advisory Committee was established to review the 2009 - 2019 Water Allocation Plan for the Tindall Limestone Aquifer. Committee members volunteered their time and represented a cross section of interests for the Katherine area including horticulture, science, property development and public amenity.

During the course of the Review, committee members progressively worked through the Plan to understand where changes need to be made to meet administrative requirements, assumptions in water usage in the original drafting of the Plan, current issues facing water users in the region and future directions or considerations that could be incorporated into future versions of the Plan.

The Committee members provided an important link with the broader community and contributed practical insights into water usage and cropping needs.

A key finding of the Review was that there is not a straight forward relationship between water usage and rainfall; it's not all about the science, other factors also need to be taken into consideration.

Horticultural development, for example, in the Katherine region is in its first generation of development. As horticultural enterprises in the region develop, cropping information will become more sophisticated and water usage more predictable. Conversely crop issues, such as the melon virus, were unforeseen when the Plan was developed.

Increased rural living subdivisions will also have an impact on water extraction and all users of the aquifer and Katherine River need to manage its use collectively to ensure we are maximising sustainable use and a healthy environment.

The concept of water trading was extensively discussed and identified as a key priority moving forward for ensuring that water allocations are available for other users when not required and also safe guarded for future requirements.

I would like to thank the Committee members for their time in reviewing this Plan, for their robust discussion and sincere commitment to ensuring that this precious resource can assist in the development of the region for the community of today and future generations.

26/2/2016

Jeannette Button

Chair of the Katherine Water Advisory Committee

1. KATHERINE WATER ADVISORY COMMITTEE

Jeannette Button (Chair)

Peter Marks

Ash Beechey

David George (alternate Shane Papworth)

Sue Brosnan

Jon Shaw (alternate Sharon Shaw)

Andrew Dalglish

Secretariat support: Pru Ducey from the Department of Land Resource Management

2. BACKGROUND

The Water Allocation Plan for the Tindall Limestone Aquifer, Katherine was declared on 19 August 2009. The purpose of the Plan is to provide a framework for the sustainable management and allocation of water from the Tindall Aquifer within the Katherine Region. In accordance with section 22B of the *Water Act* the Minister for Land Resource Management must ensure that a review of the Plan is conducted at intervals not longer than 5 years.

In 2014, the Minister for Land Resource Management called for Expressions of Interest from persons interested in participating in the review of the Plan and a new Katherine Water Advisory Committee was established to undertake the review. The work of this Committee builds on the work undertaken by the original Katherine Water Advisory Committee that was instrumental in contributing to the development of the Plan.

3. THE REVIEW PROCESS

The Katherine Water Advisory Committee held regular meetings commencing in January 2015 and worked systematically through the Plan to identify any areas that needed revision. Briefings were provided to the Committee by the Department of Land Resource Management staff on the condition of the Katherine Tindall Aquifer, the usage of water by licence holders, research undertaken within the aquifer and changes in demand since 2009. An audit was conducted using GIS to determine the number of bores using water for rural stock and domestic and other small volume uses. This allowed for recalculation of the allocation for rural stock and domestic use in the Plan.

Letters were sent to all licence holders advising them of the review and encouraging them to raise any issues or concerns either directly with Committee members or through written submission. Minutes of each meeting were published on the Department of Land Resource Management website to allow community members easy access to the activities and discussions of the Committee.

The Chair of the Committee presented at the Katherine Water Forum on 15 May 2015 on the activities of the Committee and the preliminary findings of the review process.

4. REVIEW OUTCOMES

The Committee considers that overall the Plan has in its first five years provided a reasonable framework for the sustainable management of the Katherine Tindall Limestone Aquifer and that the operation of the Plan provides a transparent process for the community and licence holders to measure the effectiveness of management strategies.

The Committee has identified that the Plan would benefit from some amendments following this Review process and recommends that the Minister for Land Resource Management considers the following changes:

Clause 22. Water for Rural Stock and Domestic and Other Small Volume Groundwater Uses

The allocation provided for rural stock and domestic and other small volume groundwater uses should be revised from 1,128 ML/year to 1,300 ML/year to account for the growth in rural subdivision since 2009.

The recommended revised wording is as follows:

(i) At the commencement of this Plan the estimated use of water from this water source for rural stock/ domestic and other small volume groundwater uses was 1,128ML/yr. Based on bore construction permits issued since commencement of the Plan, the allocation for rural stock and domestic and other small volume groundwater uses for the remaining five years of the Plan is as follows.

a. 1,122ML/yr (previously 950ML/yr) for unlicensed rural domestic and other small volume groundwater uses,
b. 75ML/yr (unchanged) for unlicensed rural stock watering, and
c. 103ML/yr (unchanged) for the rural stock and domestic use component of existing licences.

(ii) 1,300ML/yr is allocated for rural stock and domestic purposes in addition to the licence limits stated in Part 6.

(iii) Access to water for stock and domestic purposes is given the same priority as total security licences and is subject to Clause 33.

Note: For properties where groundwater is used for rural domestic and other small volume groundwater uses is estimated at 5ML/yr/property.

Water for rural stock is estimated using a maximum carrying capacity of suitable land overlying this water source at 50L/head/day, where bores extracting from this water source exist. For licensed properties, water for rural stock and domestic purposes is estimated using actual stocking rates (50L/head/day), the number of residents in communal living arrangements (200L/person/day) and the number of houses (4.5ML/house/year).

An increase in water required for rural stock/ domestic and other small volume groundwater uses may occur as a result of increased landholdings overlying this water source, or as a result of the increase in the exercise of these rights by existing landholders.

Rural stock and domestic and other small volume (<5ML/property) groundwater use is not required to be licensed due to exemptions that are currently in force under the Act.

Clause 24. Limits to Licences

The limits to licences for high, medium and low security categories should be amended to accommodate the successful appeals against 6 licences granted with declaration of the Plan in 2009, the handing back of licences since commencement of the Plan and to reflect the extension from 2.1 cumecs to 2.2 cumecs for the upper limit of modelled natural flows in the Katherine River for which Extraction Limits are set (Clause 3, Table3). As a result, the maximum total licence limit should be increased from 34,503 to 37,091ML/year.

The recommended revised wording is as follows:

(i) The licence limit is the maximum volume of water that may be extracted under licences in any single water accounting year and is subject to an annual extraction limit as specified in Part 7.

(ii) At commencement of this Plan, the licence limit was 34,503ML/yr. Accounting for successful appeals against six licences granted with declaration of the Plan, the handing back of a small number of licences and the capacity for additional licensing available with the extension of Table 3 (from 2.1 cumecs to 2.2 cumecs), the licence limit for the remaining term of the Plan is 37,091ML/yr.

(iii) Table 2 specifies limits to licences for beneficial uses, and each security category in this water source.

Beneficial Use	Security Category and Licence Limit (ML/yr)				Total ML/yr
	Total	High	Medium	Low	
Public Water Supply	1,876	483	0	1,717	**4,076**
Agriculture, Aquaculture and Industry	0	22,722	4,344	5,949	**33,015**
Total ML/yr	**1,876**	**23,205**	**4,344**	**7,666**	**37,091**

Note: Table 2 does not include rural stock and domestic and other small volume groundwater use, which is exempt from licensing under the Act (see clause 22).

Clause 30. Extraction Limits

This clause should be amended to accommodate the recommended changes to Clause 22 and Clause 24, which increase the maximum annual extraction limit to 38,391 ML/year (year Clause 22 – 1,300ML/year plus Clause 24 - 37,091ML/). Table 3 should be expanded to provide more information about licence limits for the full range of beneficial uses and security categories for modelled river flows up to 2.2 cumecs.

The recommended revised wording is as follows:

(i) The maximum annual extraction limit at commencement of this Plan was 35,631ML/yr. Accounting for the revised allocation for rural stock & domestic and other small volume groundwater uses (see clause 22), and the revised licence limit (see clause 24), the maximum annual extraction limit for the remaining five years of the Plan is 38,391ML/yr.

(ii) The long term average annual extraction limit under this plan based on the period of record from 1961 to 2004 is 22,200ML/yr.

(iii) Notwithstanding subclauses (i) and (ii), the extraction limit for this water source is dynamic and will vary from year to year in response to variable discharge from this water source to the Katherine River.

Note: this water source and the Katherine River are highly connected systems, and Katherine River base flow is dominated by water discharged from this water source. Environmental and other instream public benefit outcomes are highly dependent on these base flows, and extraction will be managed in such a way as to protect its critical elements. Extraction Limits referred to in this Plan are an estimation of Sustainable Yield, a requirement of Water Allocation Plans declared under the Act.

(iv) Table 3 specifies the maximum extractions permitted for unlicensed rural stock & domestic & other small volume groundwater use and for licensed public water supply, agriculture & industry use in a water accounting year for modelled natural flows predicted to occur on November 1 of that year in the Katherine River at Katherine Railway Bridge.

Table 3

Modelled natural flow at Katherine Railway Bridge (cumecs)	Overall Extraction Limit (ML/yr)	Extraction Limits for Beneficial Uses (ML/yr)						
		Stock & Domestic	Public Water Supply Security Level			Agriculture & Industry Security Level		
			Total	High	Low	High	Medium	Low
≤ 0.6	4,340	1,300	1,876	0	0	1,164	0	0
>0.6, and ≤ 0.7	7,772	1,300	1,876	0	0	4,596	0	0
>0.7, and ≤ 0.8	8,902	1,300	1,876	0	0	5,726	0	0
>0.8, and ≤ 0.9	10,015	1,300	1,876	0	0	6,839	0	0
>0.9, and ≤ 1.0	11,128	1,300	1,876	0	0	7,952	0	0
>1.0, and ≤ 1.1	18,361	1,300	1,876	0	0	15,185	0	0
>1.1, and ≤ 1.2	20,030	1,300	1,876	0	0	16,854	0	0
>1.2, and ≤ 1.3	21,699	1,300	1,876	0	0	18,523	0	0
>1.3, and ≤ 1.4	23,369	1,300	1,876	0	0	20,193	0	0
>1.4, and ≤ 1.5	25,038	1,300	1,876	0	0	21,862	0	0
>1.5, and ≤ 1.6	26,707	1,300	1,876	483	0	22,722	326	0
>1.6, and ≤ 1.7	28,376	1,300	1,876	483	0	22,722	1,995	0
>1.7, and ≤ 1.8	30,005	1,300	1,876	483	0	22,722	3,624	0
>1.8, and ≤ 1.9	31,714	1,300	1,876	483	0	22,722	4,333	0
>1.9, and ≤ 2.0	33,383	1,300	1,876	483	0	22,722	4,344	2,658
>2.0, and ≤ 2.1	35,052	1,300	1,876	483	263	22,722	4,344	4,064
>2.1, and ≤ 2.2	36,722	1,300	1,876	483	1,717	22,722	4,344	4,280
>2.2	38,391	1,300	1,876	483	1,717	22,722	4,344	5,949

Note: If the modelled flow at Katherine Railway Bridge on 1 Nov is less than 2 cumecs, it is assumed there is no measurable inflow from the Katherine River upstream of Ironwood gauging station.

Extraction limits for groundwater extraction licences in this source will be determined first in accordance with Table 3; with extraction limits for surface water extraction licences in the Katherine River within the Plan Area determined subsequently to preserve Other Public Benefit Outcomes within the remaining available river flows.

Clause 34. Water Trading

The National Water Initiative recognises that "Trade is the key mechanism through which water resources are able to be reallocated among competing users and uses. Through trade, markets create incentives for participants to use water more efficiently, responding to price signals which are transparent and responsive to fluctuations in demand."

Incorporation of this definition of trade into Schedule 1 of the Plan (Glossary of Terms) is recommended.

The Committee considers that the lack of information in the Plan on how the trading process operates may have contributed to negligible trading activity to date. Explaining that trade may occur from one licence holder to either another licence holder or to an entity not currently licensed, and also explaining why total extraction from Zone 1 is limited to 15% of the annual extraction limit would also assist in clarifying the operation of clause 34.

Whilst supportive of the concept of trade, the Committee considers that trade need not necessarily be on a commercial basis and that cooperative trading between licence holders may be more appropriate.

The recommended wording is as follows:

(i) Water management zones

a. The following water management zones have been defined for this water source:

i. Zone 1 – extraction from this source in zone 1 will impact on flows in the Katherine River within 1 year; and

ii. Zone 2 – extraction from this source in zone 2 will impact on flows in the Katherine River more than 1 year later.

b. The locations of these zones are shown in Schedule 5.

(ii) Temporary trade

a. Temporary trade is the transfer of water entitlement and associated security level from one licence to another licence within, and for the maximum duration of, one water allocation year only.

b. A temporary trade can be up to 100% of the water entitlement and associated security level made available in the water accounting year for the licence from which trade occurs.

(iii) Permanent trades

a. Permanent trade is the transfer of water entitlement and associated security level from one licence to another licence for the full remaining term of the licence from which the transfer is made.

b. A permanent trade can be up to 100% of the maximum water entitlement and associated security level specified in the licence from which the transfer is made.

Note: The licence to which a temporary or permanent trade is made can be either an existing licence that had been granted before the trade was approved or it can be a new licence granted in accordance with clause 34 (vi) of this Plan.

(iv) Zone 1 Trading

a. Extraction from this source in zone 1 will reduce flow in the Katherine River within one year and, therefore, only 15% of the total extraction from this source (see clause 30; Table 3) is permitted from zone 1 in order to protect environmental flows in the river.

b. Temporary and permanent trades within zone 1 and from zone 1 into zone 2 can only occur on the provisos that:

i. there will be no unacceptable interference with water supply from any third party bore;

ii. the requirements of clause 25 of this Plan are met; and

iii. approval is sought and given in accordance with clause 34 (vi) of this Plan.

c. Temporary and permanent trade from water management zone 2 into water management zone 1 can only occur on the provisos that:

i. the resultant total of licensed extractions and unlicensed extractions for rural stock & domestic and other small groundwater uses in water management zone 1 is not greater than 15% of the annual extraction limit (see Clause 30, Table 3) for the water accounting year applying at the time of trade;

ii. there will be no unacceptable interference with water supply from any third party bore;

iii. the requirements of clause 25 of this Plan are met; and

iv. approval is sought and given in accordance with clause 34 (vi) of this Plan.

Note: Clause 34 (iv) c i means that a permanent trade into zone 1 can only occur if there has previously been nett permanent trade (or surrender of water entitlements) out of zone 1 of equivalent or greater volume to that sought with the permanent trade.

(v) Zone 2 Trading

a. Extraction from this source in zone 2 will not reduce flow in the Katherine River within one year and, therefore, up to 100% of the total extraction from this source (see clause 30; Table 3) can occur from zone 2 without risk to environmental flows in the Katherine River.

b. Temporary and permanent trades within zone 2 and from zone 1 into zone 2 can only occur on the provisos that:

   i. there will be no unacceptable interference with water supply from any third party bore;

   ii. the requirements of clause 25 of this Plan are met; and

   iii. approval is sought and given in accordance with clause 34 (vi) of this Plan.

c. Temporary and permanent trade from water management zone 2 into water management zone 1 can only occur on the provisos that:

   v. the resultant total of licensed extractions and unlicensed extractions for rural stock & domestic and other small groundwater uses in water management zone 1 is not greater than 15% of the annual extraction limit (see Clause 30, Table 3) for the water accounting year at the time of trade;

   vi. there will be no unacceptable interference with water supply from any third party bore; and

   vii. the requirements of clause 25 of this Plan are met; and

   viii. approval is sought and given in accordance with clause 34 (vi) of this Plan.

(vi) Approvals

a. An application for a groundwater extraction licence should be submitted by each trading party after they have agreed on the trade details.

Note: Trading in water entitlements can be undertaken on an agreed commercial basis between the trading parties or it can be undertaken on a non-financial basis as agreed between the trading parties. All trade negotiations are a matter for the trading parties alone and the commercial basis of any trade will be treated as confidential if requested by either trading party.

b. The application for the licence from which the water entitlement and associated security level is to be traded will request either a temporary or permanent reduction in licensed water entitlement and associated security level.

c. The application from the entity to which the water entitlement and associated security level is to be traded will request either a temporary or permanent increase in currently licensed water entitlement and associated security level or request the grant of a new licence.

d. The application to which the water entitlement and associated security level is to be permanently traded will include a property/business development plan that supports the requirement for the increased or new water entitlement and associated security level being sought.

e. Both applications will be processed jointly, including the requirement under the *Water Act* to advertise the applications for transfer of water entitlement and associated security level.

f. Subject to compliance with clauses 34 (iv) b, (iv) c, (v) b and (v) c of this Plan, new licences will be issued to the trading parties that reflect the agreed and/or approved transfer of water entitlements and associated security levels.

Clause 35. General

The Committee noted that Native Title Claim (NTD6002/00) is still outstanding and that, while amendment of the Plan to include 680ML/year for indigenous commercial development is not required as part of this review, provision should be made for the possible settlement of the claim over the remaining term of the Plan.

The recommended revised wording is as follows:

In accordance with section 22B of *the Act*, the Minister must ensure:

i. that a review of this Plan (hereafter **the review**) is conducted at intervals not longer than 5 years;
ii. that the review considers the extent to which the Plan has achieved its outcomes and objectives;
iii. that the provisions of section 18 of this Plan are fully carried out;
iv. that the review is informed by the outcomes of the monitoring program, and research findings as well as consultation with a relevant Water Advisory Committee and the broader Katherine Community; and
v. that all public submissions as well as any Territory or regional policies or agreements coming into force after the initial declaration and with relevance to this Plan are considered at the review.
vi. If the existence of Native Title (under application NTD6002/00) is recognised within the lifetime of this Plan, the relevant Parts of the Plan must be amended to include 680ML for Indigenous commercial development (through grant of licences upon application), including:
    a. Licence Security Categories and Reliability defined in Part 6 of the Plan;
    b. Limits to Licences defined in Part 6 of the Plan.
    c. The maximum extraction Limit defined in Part 7 of this Plan.

Note: There will be no reduction to environmental allocations described in Part 4 of this Plan if water is required to be allocated as described in Clause 35 (vi). If water for Indigenous commercial development is allocated, this will result in a small reduction in reliability for licence holders.

Clause 37. Rules for Amending and Renewing Licences

The Committee considers that whilst it was reasonable to include a process for reviewing actual on-ground development and water use against that proposed at the commencement of the Plan, the current wording of clause 37 is inflexible and fails to recognise that little ongoing consultation with licence holders has occurred over the last five years.

The Committee considers that the methodology specified in the Plan for reviewing licences is too onerous and alternative more appropriate mechanisms could include:

- Requiring all licensees with nil reported usage or on ground development to provide a written response to the Controller to justify their retention of the water extraction licence;
- Reducing the threshold for justifying continuation of licensed entitlements to 75% of annual water allocations rather than the currently applied 90% threshold, which does not adequately recognise climatic variability and growth cycles in new/emerging developments and which may also encourage excessive and unnecessary water extraction.

The recommended revised wording is as follows:

(i) The provisions of clause 37 at commencement of this Plan were assessed during the 5 year review and found to be too inflexible and onerous in the context of the current stage of water resource development utilising this water source and also in the context of emerging biosecurity threats.

(ii) Consequently, as soon as practicable following the completion of the 5 year review of this Plan:
   a) all groundwater extraction licences granted in this water source will be amended to provide uniform, specific conditions in regard to underutilisation or non-use of water entitlements (see Schedule 8); and
   b) holders of licences for which there has been no reported extraction, or who have not commenced on-ground development, since commencement of the Plan will be required to justify the retention of those licences in writing to the Controller of Water Resources.

(iii) Providing the requirements of the *Water Act*, Water Regulations and the licence conditions have been met, a licence expiring at the end of this Plan shall be renewed upon application by the licence holder.

New Schedule 8 – Template for Groundwater Extraction Licence

The Committee considers that improvement in understanding of the licensing arrangements for the Tindall Limestone Aquifer would be assisted through the addition of a new Schedule 8 to the Plan showing the template used for groundwater extraction licences granted in this water source.

The recommended wording for Schedule 8 is as follows.

NORTHERN TERRITORY OF AUSTRALIA
LICENCE TO TAKE GROUNDWATER
Pursuant to section 60 of the *Water Act*
Licence No:

Licence Holder:			
Address:			
Expiry Date:			
Groundwater Resource:	Tindall Limestone Aquifer, Katherine		
Bores:	RNXXXX and additional bore/s to be completed in the future (see additional condition 12h)		
Water Control District:	Daly Roper		
Management Zone:	Zone 1/ 2		
Property on which water is used:			
Beneficial Use of Water Entitlement	**Maximum Water Entitlement ML/year**	**Security Level**	**Licence Trading Allowed?**
Total Maximum Water Entitlement:			

Terms and Conditions:

1. This licence is valid until the expiry date stated on the licence, subject to terms 2, 3 and 4.
2. The licence holder can surrender or apply for modification of this licence at any time.
3. This licence may be revoked, suspended or modified at any time by the Controller of Water Resources, as provided for in section 93 of the *Water Act*.
4. Non-use or underutilisation of the water entitlement(s) conferred under this licence may result in full or partial revocation of the licence by the Controller of Water Resources.
5. No guarantee is given or implied by this licence that water will be available from the listed groundwater resource at any given time.
6. If a Water Allocation Plan is declared for the stated groundwater resource, the licensed water entitlement(s) may only be traded in accordance with the requirements of that plan.
7. The licence holder must take or use no more than the stated maximum water entitlement from the listed groundwater resource, subject to the *Water Act*, the Water Regulations and this licence.
8. Chemical and/or fertiliser injection systems shall not be installed into the pump discharge lines without the prior approval of the Controller of Water Resources
9. Extraction from the listed groundwater resource must be recorded by a meter or meters supplied, installed and maintained by the licence holder to the satisfaction of the Controller of Water Resources.
10. The record of extraction must be supplied to the Controller of Water Resources as stated in the additional conditions of this licence.
11. The water entitlement shown for each listed beneficial use must be used for no other purpose than that beneficial use without approval of the Controller of Water Resources.

The following additional conditions apply:

12a) The licence holder must not, nor permit any person to, tamper with any meter installed in accordance with this licence.

12b) Except as allowed by additional condition 12c), within two (2) weeks following the end of each month, the licence holder must supply the Controller of Water Resources with a record of total extraction from the listed bores or advise when that record will be supplied.

12c) The licence holder must ensure that no more than 3 months extraction records as required under additional condition 12b) are outstanding at any time during the term of this licence.

12d) Subject to additional conditions 12e) & 12f) below, the licence holder must ensure that total extraction from the listed bores over the term of this licence shall not exceed the following Entitlements:

Period	Entitlement

12e) Between [Date 1 and Date 2], the licence holder must ensure that total extraction from the listed bores in each 12 month period ending on 30 April does not exceed the Extraction Limit, which is determined as follows:

- Extraction Limit (ML/yr) = Entitlement (ML) x Announced Allocation (%); and
- Announced Allocation is notified on 1 May each year thereafter in writing to the licence holder by the Controller of Water Resources as the factor by which the relevant Entitlement shown in additional condition 12d) must be adjusted in order to maintain an appropriate level of environmental protection and water supply security in regional water resources that are connected to the Tindall Limestone Aquifer, Katherine.

12f) The licence holder must ensure total extraction for the listed bores in any one month does not exceed 30% of the Extraction Limit unless approved by the Controller of Water Resources.

12g) In the event that the total extraction reported under this licence is less than 75% of the Extraction Limits determined for 3 consecutive 12 month periods by additional condition 12e), the licence holder must provide a written report upon request from the Controller of Water Resources that explains why the Extraction Limits were not reached and provides a projection of water requirements under this licence for the next three years or remaining term of the licence, whichever is the lesser.

12h) The licence holder must notify the Controller of Water Resources of any bore or bores, other than those listed on this licence, from which it is intended to extract water for the purpose of this licence and must not use that bore or bores until the licence is reissued with all extraction bores listed.

Controller of Water Resources.. Date: / /

5. LOOKING AHEAD TO THE 2019 REVIEW

The Committee feels that it is important to capture some of their thoughts and lessons learned during the review process to assist the Department of Land Resource Managements and the future Water Advisory Committee tasked with preparation of a new water allocation plan to supersede the current Plan.

The following points may be of assistance

- The five year review period is appropriate and should be retained as things change quickly.
- It's not all about the science, input from licence holders and the community is critical to ensure the operation of the Plan is easily understood and transparent.
- As demand on the Tindall Aquifer increases we need to manage its use collectively, including stock & domestic, to ensure we are maximising sustainable use and a healthy environment.
- At the 2019 Review, integrate the Katherine Tindall, Katherine River, Oolloo Aquifer and Daly River water allocation plans.
- As horticultural enterprises in the region develop, cropping information will become more sophisticated and water usage more predictable. Crop use tables should be reviewed during each review of the Plan.
- Water allocations need to be preserved for future requirements, flexible uses and economic stability.
- Consideration should be given to the inclusion of Water Extraction Licences being attached in the Administrative Interests in Lands Title System to allow property purchasers to easily find if a property has access to a water allocation.
- Mining and energy developments that have the potential to impact on the Tindall Aquifer or Katherine River need to be included as part of water allocation planning.
- The process of applying for water returned to the consumptive pool needs to be transparent and easily administered.
- Consideration should be given in the formulation of the next Plan to strategies to encourage the installation of rainwater tanks on rural lots for domestic purposes to reduce demand on the aquifer.
- Introduction of metering of all bores for rural stock and domestic and other small volume groundwater users should be required to ensure accurate accounting of groundwater use, and to act as a demand management strategy as it encourages all users to monitor and moderate their consumption.
- Develop a simple system to encourage and facilitate water trading.
- Consider setting up an online system to allow licence holders to put any licenced allocation following the announced annual allocations not required for that year into a temporary annual pool and allow those interested in additional water to request additional water.

- Consider removing the requirement for public notification of licence increases arising from trading as it adds to the 'red tape' burden for licence holders and stalls the trading process.
- At the 2019 Review, planning for surface water and groundwater should be integrated.
- RAAF Base Tindal bores are not licensed (hence there is no record of the amount of water used) and this should be considered in the next Plan.
- The Committee acknowledges the baseline water quality monitoring and supports continuation of this to inform future management and protection of the resource.

Annex 1

WATER USAGE BY LICENCE HOLDERS

The Committee reviewed the 2013/14 pumpage figures reported to the Department of Land Resource Management and noted the following.

Source	Licensed Volume	2013/14 Pumpage	Average % Allocation Used	Number of Licences with no reported usage
Tindall Aquifer Zone 1	5,581 ML/year	864 ML/year	15%	7
TIndall Aquifer Zone 2	28,313 Ml/year	8,655 ML/year	31%	16
Katherine River	6,470 ML/year	1,801 ML/year	28%	8
Oolloo Aquifer	24,636 ML/year	9,434 Ml/year	38%	7
Jinduckin Aquifer (Katherine)	7,723 ML/year	257 Ml/year	3%	7

Annex 2

S&D BORES DRILLED: JANUARY 2009 - MARCH 2015

Zone	Bore Number	Completed Date	Purpose
Zone 1	RN036500	21/04/2009	Stock & Domestic
Zone 1	RN036794	18/09/2009	Stock & Domestic
Zone 1	RN036797	25/09/2009	Stock & Domestic
Zone 1	RN037697	16/12/2011	Stock & Domestic
Zone 1	RN037668	17/12/2012	Stock & Domestic
Zone 1	RN022663	10/07/2013	Industry <5ML
Zone 1	RN038394	12/01/2014	S&D & Industry <5ML

7 bores x 5 ML / year / property = increase of 35 ML/year

Zone	Bore Number	Completed Date	Purpose
Zone 2	RN036502	19/04/2009	Stock & Domestic
Zone 2	RN036540	14/05/2009	Stock & Domestic
Zone 2	RN037030	11/03/2010	Stock & Domestic
Zone 2	RN037242	1/10/2010	Stock & Domestic
Zone 2	RN037695	10/12/2011	Stock & Domestic
Zone 2	RN037696	8/12/2011	Stock & Domestic
Zone 2	RN037465	12/02/2012	Stock & Domestic
Zone 2	RN037535	20/02/2012	Stock & Domestic
Zone 2	RN037435	27/07/2013	Stock & Domestic
Zone 2	RN038853	9/11/2014	Stock & Domestic

10 bores x 5 ML / year / property = increase of 50 ML/year

Total increase in Stock & Domestic Extraction: 85 ML/year

To allow for continuing increase in Stock & Domestic Extraction for the remaining 5 years of the Plan, amend the current allocation from current 1,128ML/year to 1,300ML/year

FOR GOVERNMENT USE ONLY

Legend

- S&D Bores : Zone 2
- S & D Bores: Zone 1
- Tindall Limestone Aquifer (Katherine) Planning area
- Cadastre

Map compiled by
Water Management Branch
Department of Land Resource Management
Northern Territory of Australia.

Water Control District:
Daly Roper Water Control District

Water Allocation Planning Area:
Tindall Limestone Aquifer (Katherine)

Date: 13/03/2015
Time: 9:39:31 AM

0 5 10 20
Kilometers

N

Annex 3

Report provided by Water Monitoring Unit, Water Resources Division
Department of Land Resource Management

Katherine Tindall Water Allocation Plan Monitoring Program Status Report – May 2015

Appendix 2 of the Katherine Tindall Water Allocation Plan refers to a monitoring program undertaken by the DLRM Water Monitoring Group.

According to the Plan, the performance indicator is to be measured by:

1. Stream flows at gauging stations located at Ironwood and Wilden Stations; and
2. A Network of monitoring bores comprising bores fitted with continuous loggers and others monitored manually.

The following report aims to provide details of the monitoring undertaken in relation to these performance indicators.

Stream flows

Measurement of stream flows at Katherine River at Ironwood (G8140535) and Katherine River at Wilden (G8140536).

Due to the technological difficulties of continuously measuring flow, the hydrographic convention in Australia is to continuously measure river height then use a look up table (rating table) to convert height values to flow.

A rating table is created by measuring flow as a discrete measurement at a specific river height. This activity, called a flow gauging, is repeated for a range of river heights until there is sufficient data to create a relationship between river height and flow. Determining the flow during a gauging requires determining the rivers cross section area and velocity for a given location.

$$\text{Flow} = \text{Area} \times \text{Velocity}$$

Rivers being dynamic erode and deposit changing the cross section area and bed profile on a regular basis. These changes impact on the relationship between height and flow, therefore regular gaugings are required to update and verify the rating table.

The more stable the control; the defining section of the river where flows cease as the water level drops; the less variation there is in the low flow section of the rating table.

History of Establishment and Operation

Construction of gauging stations at Ironwood and Wilden was funded by the Commonwealth Watersmart Program; a National Water Initiative that provided resources to improve the resolution of monitoring infrastructure in support of Water Allocation Planning. These additional gauging stations were strategically located to determine flow rates at the beginning and end of the reach where the Katherine River intersects the Tindall aquifer. This represents the groundwater discharge zone; the length of the river where groundwater springs and seepage occurs.

Ironwood

Flows at Ironwood (G8140535), represent the water from upstream catchment run-off only. Continuous river height and rainfall data has been logged at the site since 12th December 2008. The site has a stable control consisting of a concrete crossing (Knotts Crossing) 1.8km downstream and a cease to flow gauge height of 1.09m.

Wilden

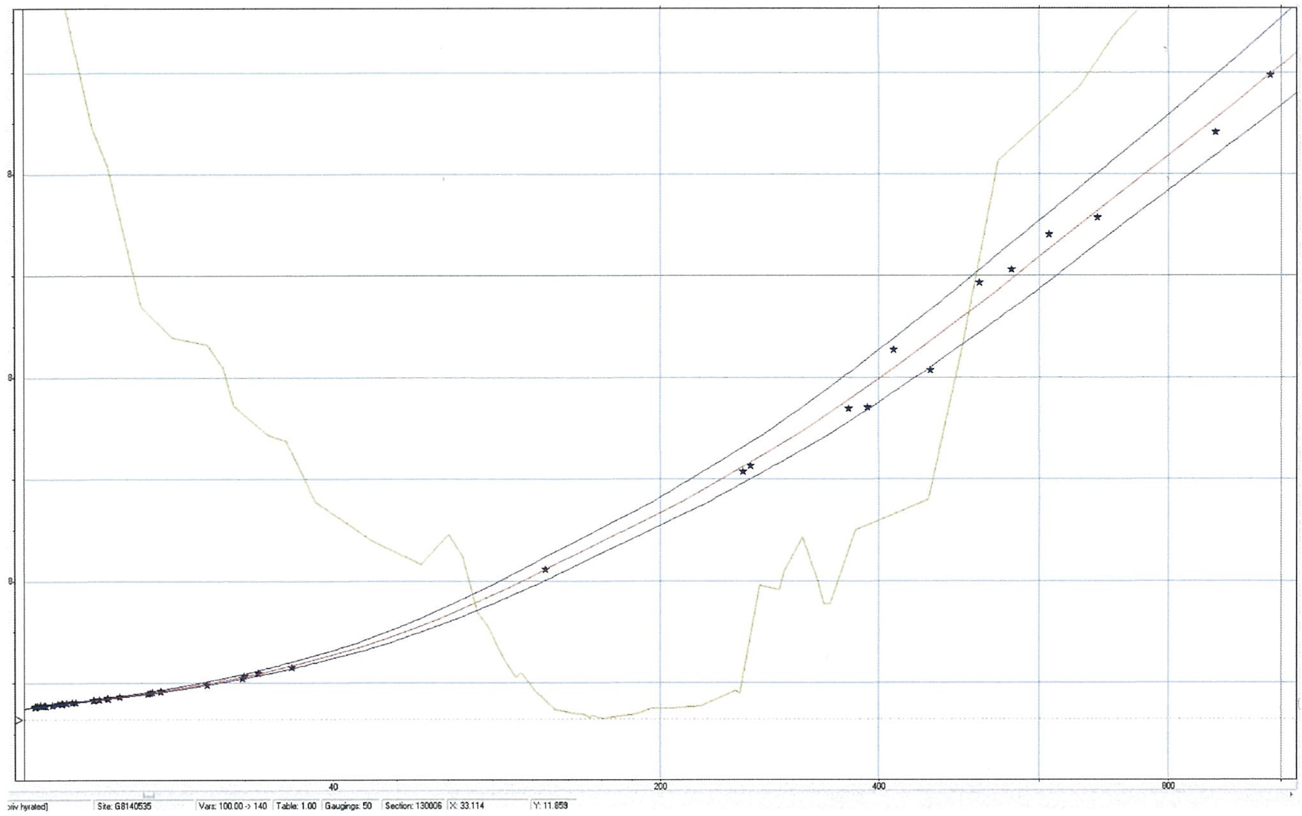
Flows at Wilden represent (G8140536), represent the water from a combination of upstream catchment run-off and spring flow. Continuous river height data has been logged at the site since 8th August 2008 with rainfall added in December 2008. The site has a reasonably stable control consisting of a natural rock bar 80m downstream of the gauging station and a cease to flow gauge height of 0.206m.

Range of flows that have occurred since establishment

Ironwood

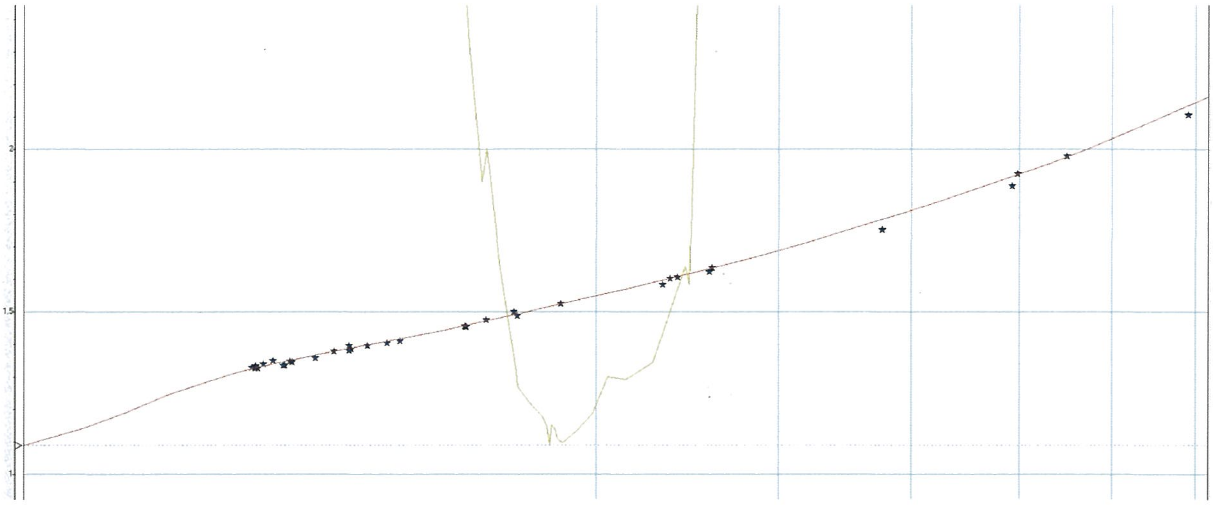
Between June 2008 and March 2015, 50 gaugings have been performed from 0.5 m3/s to 980 m3/s, and a single rating table developed.

In plot 1 the vertical scale is river height and the horizontal scale flow, the red line represents the rating curve; the line of best fit through the gaugings (blue stars). The blue lines represent +/- 10% quality boundaries, as an indicator of how much variation there is between the rating curve and the gaugings it is based on. The brown line in the background is the cross section through the control.



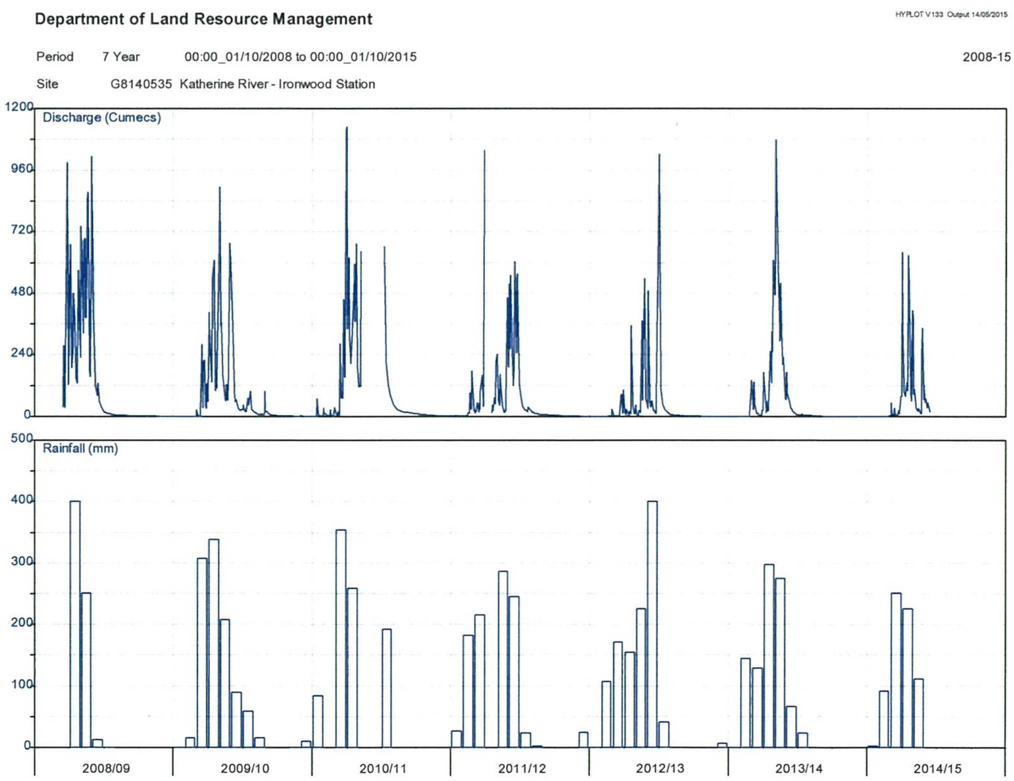
Plot 1 Ironwood Rating

The cease to flow height has been determined by survey. Flows between zero and 0.5m3/s are not based on gaugings but are extrapolated from the rating curve with the quality code attached to the data downgraded accordingly, see plot 2. Similarly flows above the highest gauging are extrapolated, but only within the confines of the measured cross section. Flows beyond the cross section are not generated.



Plot 2: Ironwood Low Flow Rating

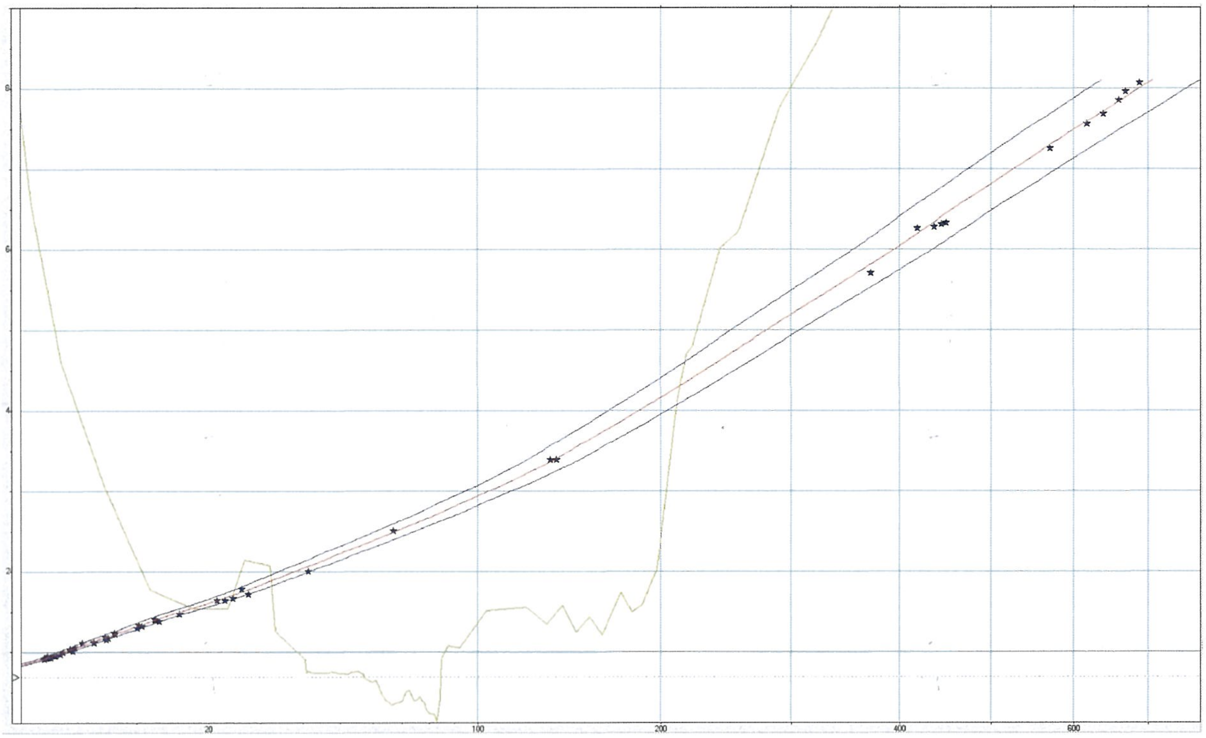
The lowest recorded river since commissioning was a gauge height of 1.30m on 23rd November 2014 approximately 0.37 m3/s. The highest recorded river height was 15.00m on the 17th March 2013 for a rated flow of 1127 m3/s. See plot 3



Plot 3: Ironwood Flow versus Rainfall

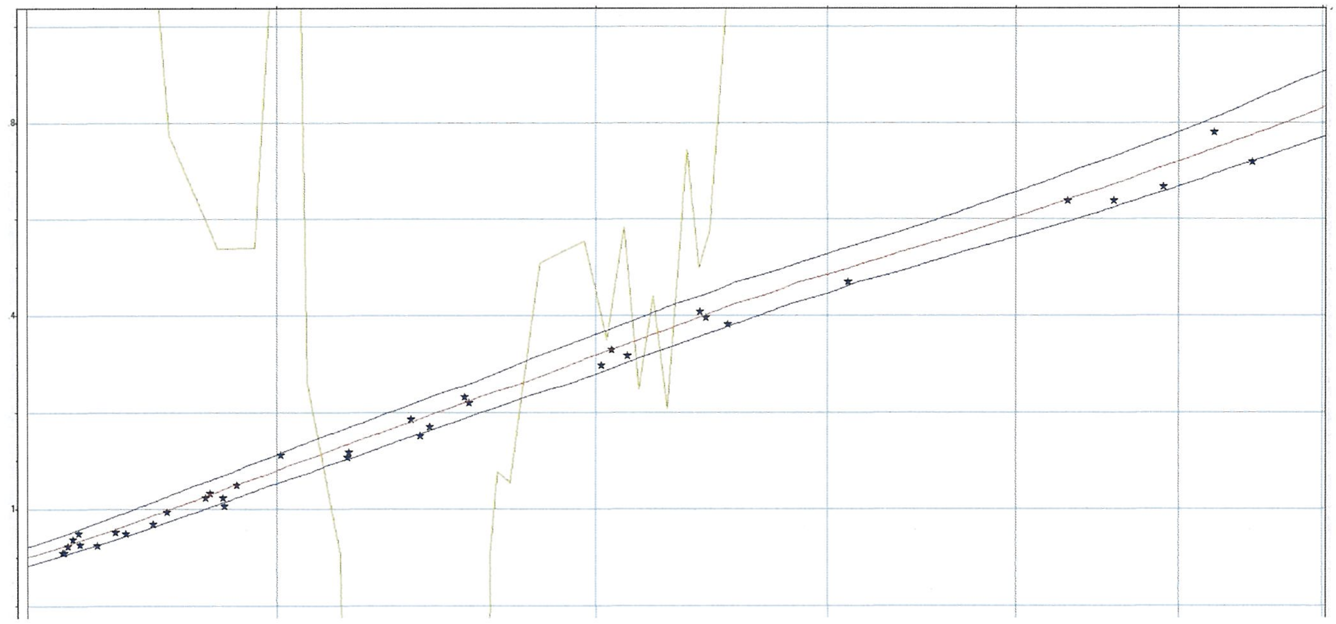
Wilden

Between June 2008 and March 2015, 51 gaugings have been performed from 2.7 m3/s to 688 m3/s, and a single rating table generated. The rating is extrapolated between the lowest gauging and the cease to flow gauge height, but has not been extended beyond the highest gauging as the focus for this site is the measurement of low flows only. See plot 4.



Plot 4: Wilden Rating

The number of gaugings and the correlation between the gaugings and the rating curve between 2.7 and 25 m3/s shown in plot 5, result in a reasonable quality code and confidence in low flow data.



Plot 5: Wilden Low Flow Rating

The lowest recorded river height since commissioning was a gauge height of 0.89m on 28th October 2014 approximately 2.29 m3/s. The highest recorded river height was 12.38m on the 19th March 2013 which exceeded the rating curve.

Quality of rating at each station and on-going work to improve ratings.

The quality of a rating is dependent on all elements, the logged river height data, the gaugings, section surveys and the rating generation process itself.

Standard quality assurance protocols require logger data to be checked against the water level on the gauge board during all site visits. This provides a calibration point if there has been any drift in the sensor values or logger clock. Logger data is quality coded based on whether timeseries data needs modification to comply against the calibration values.

Each gauging is undertaken to a strict set of quality assurance protocols. On completion of the gauging, the result is compared against the rated flow; if there is more or less than 10% difference between the rated flow and the gauged flow, the exercise is repeated. Where there is delineation from the rating, additional gaugings are performed at a range of river heights to determine the heights where a new rating curve will need to be developed.

As rating tables are derived from a large number of data and metadata elements, it is critical that a data review is conducted prior to any rating review. On completion of a rating creation or modification a number of mathematical tests are run to ensure there is no curve bias based on value, sign (+ive or –ive), stage and time. Based on these tests, sections of the curve are quality coded, good, satisfactory or poor.

Ironwood

The initial rating for Ironwood was developed on May 2011 based on the 22 gaugings that had been conducted up till that time.

A full data review for Katherine River at Ironwood was conducted in November 2013. This exercise included checking of gauging results, cross section, cease to flow and gauge board surveys and an assessment of the timeseries river height data. The subsequent rating review was based on additional data, allowing the curve to be better defined. The high end of the rating, beyond the highest gauging, was extrapolated using the average of two standard methods (Stevens and Manning's) as this gauging station is also used for flood forecasting purposes.

After review, the current rating table is quality coded as follows.

Table	Stage Range		Quality	Comments
	Start	End		
1.00	-1.000m	1.314m	91	Satisfactory rating. No gaugings in stage range. Shape of curve based on low flow gaugings.
1.00	1.314m	2.089m	41	Good rating. Good spread of gaugings.
1.00	2.089m	6.719m	91	Satisfactory rating. Only a few gaugings in this range.
1.00	6.719m	13.773m	41	Good rating. Good spread of gaugings.
1.00	13.773m	15.400m	95	Satisfactory rating extrapolated.

Additional works that have been identified to improve the rating include

- Cross section at the recorder or through the large rock bar required for more accurate high flow extrapolation.
- Additional gaugings between 2.5m and 7.5m and above 10m.
- Low flow gaugings below 1.5m.
- Repair or replace primary benchmark.

Wilden

The initial rating for Ironwood was developed on May 2011 based on the 27 gaugings that had been conducted at that time. In November 2013 a full data assessment and rating review was conducted over the same stage range. An additional 18 gaugings were used to refine and generate a new rating version (1.01).

This revised rating is yet to be archived however once signed off the new rating curve will be quality assured as follows.

Table	Stage Range		Quality	Comments
	Start	End		
1.01	-1.000m	0.903m	91	Satisfactory rating. Shape of curve defined by low flow gaugings.
1.01	0.903m	1.788m	41	Good rating. Good spread of gaugings in range.
1.01	1.788m	5.573m	91	Satisfactory rating. Low number of gaugings in this range.
1.01	5.573m	8.070m	41	Good rating. Good spread of gaugings in range.

The new rating has not been extended beyond the maximum gauged range.

Additional works that have been identified include

- Installing a new benchmark further away from the river, to eliminate any impacts from river bank movement,
- Increased gaugings particularly below 1.7m gauge height,
- Further surveys to more accurately locate the exact cease to flow location and value,
- Additional control cross section surveys to determine if erosion of the rock bar is occurring and if so what the impact is on the rating table.

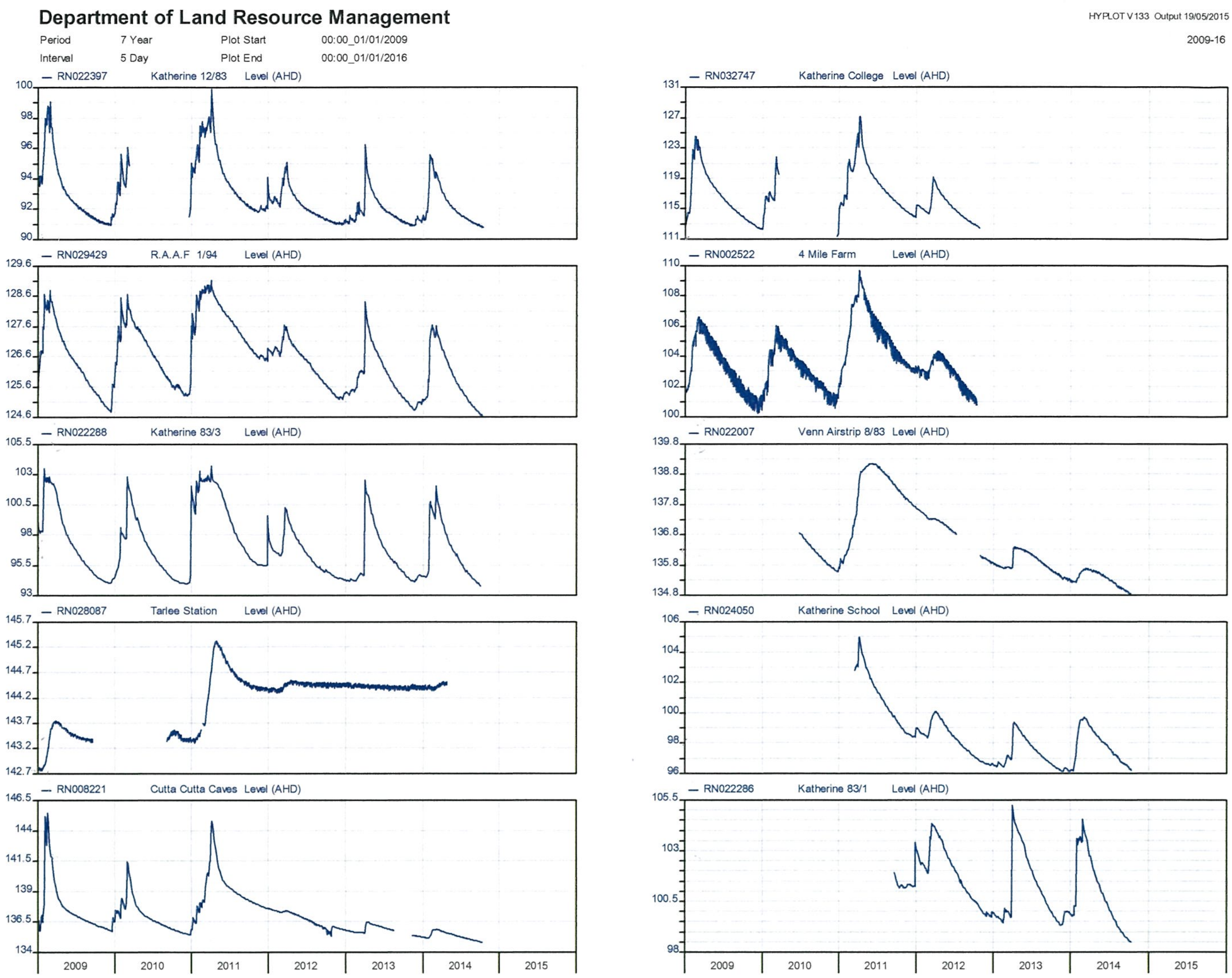
Groundwater and Rainfall

The Katherine Tindall Water Allocation Plan Groundwater Monitoring Program currently consists of 41 monitoring bores, of which 24 have data loggers installed. The remaining 17 are plopped at least twice a year during March and October to establish the highest and lowest points in the annual aquifer stage range.

Site	Name	Management Zone	Logger or SWL Only
RN002522	No.1 C.S.I.R.O. 4 Mile Farm Katherine	2	SWL
RN005032	Rural College 450 Stuart Hwy	2	Logger
RN007821	A=71/106 Mataranka Stn	2	SWL
RN007838	D.B. 30 A Manbulloo	2	Logger
RN008221	Cutta Cutta Caves 1/73	2	Logger
RN021694	Hickey K 2920 Zimin Drive	1	Logger
RN022002	Water Resources 3/81 Venn Airstrip	2	SWL
RN022006	83/7 Venn Airstrip	2	SWL
RN022007	8/83 Venn Airstrip	2	Logger
RN022286	Wr 83/1 Katherine	2	Logger
RN022287	Wr 83/2 Katherine	1	SWL
RN022288	Wr 83/3 Katherine	1	Logger
RN022289	Wr 83/4 Katherine	2	Logger
RN022390	5/8b Katherine Inv. Katherine	2	SWL
RN022391	6/83 Katherine Inv. Katherine	2	SWL
RN022392	Wr 83/7 Tindal	2	SWL
RN022394	Wr 83/9 Uralla	2	Logger
RN022397	12/83 Katherine Depot Bore	2	Logger
RN022474	Wr 83/19 Katherine	2	SWL
RN022475	20/83 Katherine Katherine Golf	1	Logger
RN022478	Wr 83/22 Katherine	1	Logger
RN023424	84/1 King River Katherine	1	SWL
RN023427	84/4 King River Katherine	2	SWL
RN023648	David R 1787 Zimin Drive	1	SWL
RN024050	Water Resources 1/85 Katherine	1	Logger
RN025126	Wr 87/2 Binjaree	1	Logger
RN027286	Mcmahon (Novus Quarry) Limestone Creek Victoria Highway	1	SWL
RN028087	Tarlee Station Western Creek		Logger

Site	Name	Management Zone	Logger or SWL Only
RN028782	R.A.A.F. Base Site 2 Tindal	2	SWL
RN029243	B.T. Tomlin No.2 Bore N.T.Por.2143 T=Katherine	2	SWL
RN029429	Tindal R.A.A.F N.T. Government	2	Logger
RN029430	Tindal R.A.A.F. N.T. Government Bore No 2/94	2	SWL
RN030695	A.W. & J.H. Thomas Bore No 1		Logger
RN032747	No 1/00	2	SWL
RN034594	N.T. Government (Ballongilly 1/05)	2	Logger
RN034597	[Mon] Cretaceous [Logger]	2	Logger
RN036473	N.T. Government (Manbulloo	2	Logger
RN036474	N.T. Government (Manbulloo	2	Logger
RN037410	N.T. Government (Katherine)	1	Logger
RN037411	N.T. Government (Katherine)	1	Logger
RN037412	N.T. Government (Katherine)	1	Logger

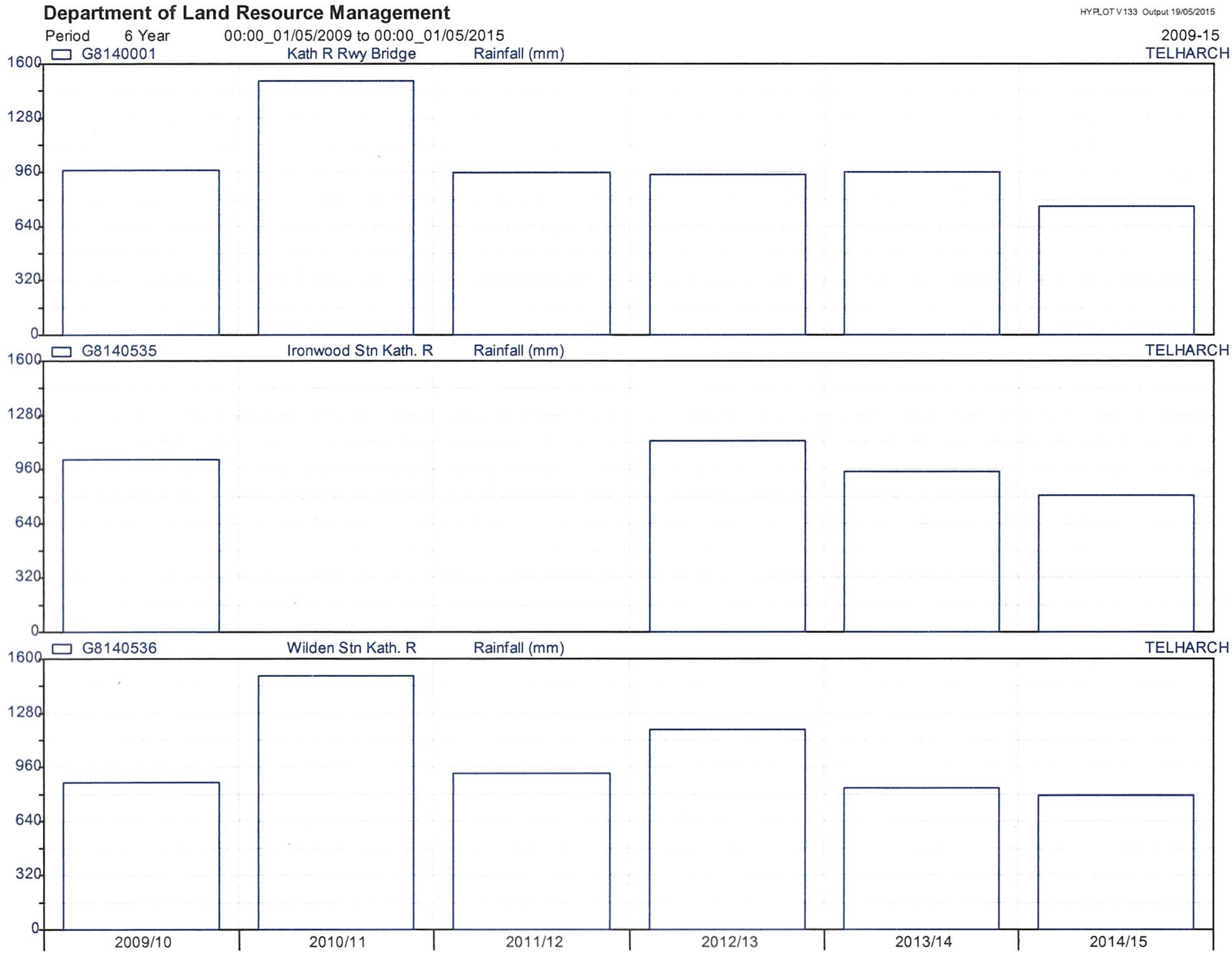
In addition to the above routine work, an intensive ground and surface water quality program is programmed for October 2015, to determine background nutrient, metals, herbicide and pesticide concentrations. The outcome of this exercise will allow more focussed long term water quality programs to be developed.



Plot 6: Hydrographs from bores with the longest continuous record.

As shown above, whilst the groundwater level trend varies from site to site, recharge was significant in 2011 but generally less in the following 3 years. The more complete datasets show that annual minimum groundwater levels have fallen in the last couple of years.

This is to be expected when viewed in conjunction with the total annual rainfall for the same period, see plot 7. Rain gauges at 3 Katherine River gauging stations show nearly 1500mm of rain in the 2010/11 wet season but a steady decline to 700mm this wet season.



Plot 7: Annual Rainfall at Katherine Gauging Stations

Appendix

G8140535 Gaugings

GAUGING DATE	GAUGING NUMBER	MEAN GAUGE HEIGHT	FLOW	DEVIATION FROM RATING	QUALITY CODE	QUALITY DESCRIPTION
18/06/2008	1	1.5	3.4	-6	11	Good Gauging
14/08/2008	2	1.396	1.2	-10	11	Good Gauging
10/02/2009	3	10.943	685.0	2	11	Good Gauging
11/02/2009	5	9.665	519.0	-7	11	Good Gauging
11/02/2009	4	9.921	562.0	-3	11	Good Gauging
12/02/2009	6	8.343	416.0	-6	11	Good Gauging
01/04/2009	7	1.925	19.9	0	11	Good Gauging
24/04/2009	8	1.636	8.0	-1	11	Good Gauging
20/08/2009	9	1.397	1.4	2	61	Satisfactory Gauging
28/09/2009	10	1.35	0.6	-13	61	Satisfactory Gauging
02/11/2009	11	1.34	0.6	-10	11	Good Gauging
01/02/2010	12	10.613	613.0	-4	61	Satisfactory Gauging
04/02/2010	14	7.175	367.0	4	61	Satisfactory Gauging
04/02/2010	13	7.213	387.0	9	61	Satisfactory Gauging
09/02/2010	15	4.018	127.0	0	11	Good Gauging
09/02/2010	16	4.018	127.0	0	11	Good Gauging
08/04/2010	17	1.98	22.5	0	11	Good Gauging
21/07/2010	18	1.454	2.6	4	11	Good Gauging
21/07/2010	19	1.454	2.6	5	11	Good Gauging
24/08/2010	20	1.379	1.1	0	11	Good Gauging
23/09/2010	21	1.348	0.7	5	61	Satisfactory Gauging
05/04/2011	22	13.733	980.0	0	11	Good Gauging
06/04/2011	23	12.616	880.0	4	11	Good Gauging
25/07/2011	24	1.602	6.8	0	11	Good Gauging
19/09/2011	25	1.456	2.6	2	11	Good Gauging
01/11/2011	26	1.475	2.9	-2	11	Good Gauging
15/02/2012	27	2.106	29.6	5	11	Good Gauging
20/03/2012	29	5.947	266.4	3	11	Good Gauging
20/03/2012	28	6.063	272.7	2	11	Good Gauging
22/03/2012	30	7.934	458.4	11	61	Satisfactory Gauging
30/04/2012	31	1.888	19.6	8	61	Satisfactory Gauging
04/06/2012	32	1.623	7.9	5	11	Good Gauging
07/06/2012	33	1.606	7.0	1	11	Good Gauging
25/07/2012	34	1.488	3.5	4	11	Good Gauging
04/09/2012	35	1.405	1.6	6	11	Good Gauging
15/10/2012	36	1.358	0.9	15	61	Satisfactory Gauging
27/05/2013	37	1.525	4.3	0	11	Good Gauging
30/07/2013	38	1.386	1.2	4	111	Poor Gauging
31/07/2013	39	1.382	1.2	8	61	Satisfactory Gauging
10/09/2013	40	1.347	0.8	8	61	Satisfactory Gauging
14/10/2013	41	1.327	0.5	1	61	Satisfactory Gauging
14/10/2013	42	1.327	0.5	4	11	Good Gauging
07/04/2014	43	1.584	6.6	7	11	Good Gauging
02/06/2014	44	1.411	1.8	8	11	Good Gauging
10/09/2014	46	1.335	0.7	18	11	Good Gauging
10/09/2014	45	1.335	0.7	20	61	Satisfactory Gauging
03/10/2014	47	1.329	0.5	-6	61	Satisfactory Gauging
14/10/2014	48	1.334	0.5	-10	61	Satisfactory Gauging
14/10/2014	49	1.333	0.5	-7	61	Satisfactory Gauging
17/03/2015	50	1.752	13.8	11	11	Good Gauging

G8140536 Gaugings

GAUGING DATE	GAUGING NUMBER	MEAN GAUGE HEIGHT	FLOW	DEVIATION FROM RATING	QUALITY CODE	QUALITY DESCRIPTION
19/06/2008	1	1.17	7.138	9999.99	11	Good Gauging
13/08/2008	2	1.023	4.34	6.13	11	Good Gauging
12/11/2008	3	0.923	2.76	1.76	11	Good Gauging
03/12/2008	4	1.186	6.85	-1.75	11	Good Gauging
01/04/2009	5	1.717	27.5	10.56	11	Good Gauging
23/04/2009	6	1.395	12.226	1.33	11	Good Gauging
25/05/2009	7	1.232	7.689	-3.25	11	Good Gauging
21/08/2009	8	1.023	4.14	1.24	11	Good Gauging
30/09/2009	9	0.949	2.86	-6.48	11	Good Gauging
03/11/2009	10	0.937	2.804	-3.26	11	Good Gauging
02/02/2010	11	8.07	688	-1.76	11	Good Gauging
02/02/2010	12	7.958	668	-1.85	11	Good Gauging
02/02/2010	13	7.847	659	-0.4	11	Good Gauging
02/02/2010	14	7.677	638	0.76	11	Good Gauging
02/02/2010	15	7.552	616	0.78	11	Good Gauging
03/02/2010	16	6.264	418	-2.14	11	Good Gauging
03/02/2010	17	6.279	436	1.65	11	Good Gauging
03/02/2010	18	6.308	444	2.68	11	Good Gauging
03/02/2010	19	6.329	449	3.24	11	Good Gauging
09/02/2010	20	3.386	135	-1.39	11	Good Gauging
09/02/2010	21	3.386	138	0.8	11	Good Gauging
06/04/2010	22	1.78	26.2	-5.68	11	Good Gauging
28/05/2010	23	1.408	12.1	-2.53	61	Satisfactory Gauging
20/07/2010	24	1.111	5.05	-8.92	11	Good Gauging
25/08/2010	25	0.994	3.72	1.34	11	Good Gauging
23/09/2010	26	0.952	3.196	3.15	11	Good Gauging
10/02/2011	27	7.251	569.858	1.1	11	Good Gauging
30/05/2011	28	1.667	24.5	7.91	11	Good Gauging
22/09/2011	29	1.118	5.95	5.09	11	Good Gauging
31/10/2011	30	1.107	5.93	8.25	11	Good Gauging
14/02/2012	31	1.998	41.4	9.36	11	Good Gauging
22/03/2012	32	5.704	371.4	3.59	61	Satisfactory Gauging
01/05/2012	33	1.638	22.9	6.99	61	Satisfactory Gauging
01/05/2012	34	1.638	21.5	0.45	61	Satisfactory Gauging
05/06/2012	35	1.329	10.3	0.21	11	Good Gauging
07/06/2012	36	1.317	10.6	6.3	11	Good Gauging
25/07/2012	37	1.152	6.98	11.29	11	Good Gauging
04/09/2012	38	1.032	4.186	-0.8	11	Good Gauging
19/10/2012	39	0.969	3.572	7.44	11	Good Gauging
16/01/2013	40	1.381	12.7	8.8	11	Good Gauging
11/04/2013	41	2.505	66.831	-1.8	11	Good Gauging
30/05/2013	42	1.219	7.76	1.27	11	Good Gauging
01/08/2013	43	1.006	4.36	13.46	11	Good Gauging
12/09/2013	44	0.95	3.3	7.43	11	Good Gauging
16/10/2013	45	0.925	3.03	10.63	11	Good Gauging
08/04/2014	46	1.297	10.094	6.1	11	Good Gauging
05/06/2014	47	1.05	4.506	0.27	11	Good Gauging
11/09/2014	48	0.926	2.872	4.36	11	Good Gauging
03/10/2014	49	0.91	2.712	6.81	11	Good Gauging
16/10/2014	50	0.91	2.724	7.28	11	Good Gauging
19/03/2015	51	1.47	15.5	7.88	11	Good Gauging

Annex 4
Report provided by Aquatic Health Unit, Water Resources Division
Department of Land Resource Management

Monitoring & Research by DLRM and partners of the Katherine River: 2009-2014

Background:
Most of the flow in the Katherine River downstream of Knotts Crossing is supplied form the Tindall Limestone Aquifer. Extraction from the aquifer will reduce dry season flows (relative to natural flows). A maximum of 20% reduction in flows is being managed for, within the context of the Erskine recommendations. Under this scenario, flows will not cease, and the reduction in dry season, groundwater-fed flow will in some or most years be within the natural range of flows. Thus, the ecological implications of water extraction may be subtle. Their understanding is hampered by an understanding of dry season river ecology and importantly its link to wet season ecology. The dry season cannot be examined alone. Moreover, the ecological impact of reduced dry season flows needs to be placed within a broader environmental monitoring context.

Monitoring and research activities

- **Improving our understanding of the impact of anthropogenically induced low dry season flows on river ecology.**

To better understand the ecological implications of anthropogenically induced low flows for tropical monsoon rivers, and in partnership with researchers from Charles Darwin University & Griffith University, a scientific paper has been published (see Attachment 1). The paper addresses the wet-dry transition, dry season and dry-wet transition, and is applicable to the Katherine River. This paper has helped provide a basis and direct research effort to address the general issue of ecological impact of "anthropogenic low flows", and the authors hope will generate discussion.

- **Pesticide and herbicide assessment of the Katherine River**

Agricultural and other land-uses over the Tindall Limestone Aquifer have the potential to pollute the aquifer. To first assess whether contaminants are present in the river, special samplers were deployed in the river for a one month period during the 2011 dry season when the river is groundwater-fed (Attachment 2). The samplers are able to detect very low levels of chemical contaminants.

Of the 188 chemicals tested, 15 were detected in the Katherine River downstream of Knotts Crossing, including 4 herbicides, 2 pesticides, 3 chemicals common in personal care products (e.g. perfumes, shampoos, lotions and sunscreens) and 5 hydrocarbons (oils). All of these chemicals were present at very low concentrations and did not exceed ANZECC national water quality guidelines for the protection of aquatic ecosystems.

This assessment will be followed up with a Tindall groundwater assessment of herbicides, pesticides and nutrients between September and November 2015.

- **Fish diversity and abundance (numbers) research**

Charles Darwin University has led, with NT Government and Griffith University, a research program into fish diversity and population numbers (abundance) for the Daly Rivers and its tributaries. It is known as the "Daly Fish & Flows" project (Attachment 3). The program is directed at addressing broad catchment and season scale patterns of fish, and has a focus on the effect of inter-annual variability of the flow (especially the wet season) on fish during the dry season. It has not been designed to monitor "environmental flows", but has the potential to provide some contextual and basic ecological information for the Katherine River.

In 2014, the program was in its 9th year, and has continued into its 10th year in 2015. One site, downstream of Galloping Jacks, was sampled in 2014, and in the earlier years a second site was surveyed for fish but is no longer included owing to logistic reasons of boat access caused by low river flows.

In October 2012, a fish-kill was recorded along the study reach. At least a thousand fish died. These events are important to know about because fish populations are clearly not just affected by flow but also water quality. It highlights "environmental flow" monitoring needs to be within the context of a broader environmental monitoring program, and distinguish the various anthropogenic and natural effects on fish populations. The event was primarily natural, though land-use may have had an influence. Similar events have occurred previously in the Katherine River (see Attachment 4).

- **The relationship between fish habitat and dry season flow in the Katherine River**

This research has made use of the Daly Fish & Flows data for the Katherine River sites, and a hydrodynamic model developed in 2007 for a 10 km reach of the Katherine River immediately downstream of Galloping Jacks. The research has the potential to identify which fish species are either disadvantaged or advantaged by low river flows, whether this natural or otherwise. A draft DLRM report has been written, but requires major editing.

- **Water quality**

Water quality has been measured and tested in the Katherine River on a project basis during 2009-2014. The Daly Fish & Flows project, for example, measures basic water quality parameters (e.g. dissolved oxygen which was nearly absent during the 2012 fish kill).

The pesticide assessment project collected water quality data too, as has the DLRM Water Allocation Plan early and late dry season stream gauging monitoring. All this data helps to contribute baseline data that can be used to assess pollution.

A water quality meter was deployed in December 2015 to monitor wet season conductivity (salt content) which varies with groundwater-surface proportions, but only recorded for a few days before being stolen. A meter will be deployed again for the 2015/16 wet season but be much better hidden.

Future research and monitoring

The Katherine River has been identified as a priority river for environmental monitoring. In 2016, resources permitting, DLRM will undertake an inventory of the river biota, habitats, water quality and geomorphology of the river downstream from Galloping Jacks (or Knotts Crossing) to the junction with the Flora River. This will provide a basis for the development of a research and monitoring program.

Implications of water extraction on the low-flow hydrology and ecology of tropical savannah rivers: an appraisal for northern Australia

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Abstract: Balancing the freshwater needs of humans and ecosystems is a fundamental challenge for the management of rivers worldwide. River regulation and water extraction can affect all components of the natural flow regime, yet few studies have investigated the effects on the low-flow end of the hydrograph. Low-flow periods are hydrologically distinctive and ecologically important, varying in nature among climatic zones. Tropical savannah rivers are characterized by highly seasonal and predictable flow regimes, but with high interannual variation in the magnitude, timing, and duration of low flows. Many tropical savannah rivers are relatively intact, especially in northern Australia, but many are now receiving increasing attention for water-resource development through surface- and groundwater extraction. We identified the hydroecological effects of water extraction on 3 phases of the seasonal flow regime: the wet–dry transition, dry season, and dry–wet season transition for perennial and intermittent rivers in tropical savannah climates. We propose a conceptual model and 7 predictions that describe the ecological implications of dry-season water extraction in tropical savannah river systems worldwide. The predictions address: 1) connectivity, 2) availability of in-stream habitat, 3) dry-season persistence of in-channel refugia, 4) water quality during dry–wet and wet–dry transition periods, 5) decoupling of wet- and dry-season flows, and the cumulative effects on 6) groundwater-dependent species and 7) whole-ecosystem shifts. We used northern Australia as a case study to review the current level of evidence in support of these predictions and their potential ecological consequences, and used this review to propose key priorities for future research that are globally applicable.

Key words: wet-dry, tropics, water extraction, dry season, savannah landscapes, flow alteration

Fresh waters are the most threatened ecosystem on the planet and exhibit the highest extinction rates of any ecosystem (Dudgeon et al. 2006). Balancing the freshwater needs of humans and ecosystems is a fundamental challenge, with most riverine ecosystems throughout the world highly degraded because of human activity (Nilsson et al. 2005, Vörösmarty et al. 2010, Tedesco et al. 2013). Alteration of natural flow regimes is one of the most significant threats to the ecological health of rivers (Bunn and Arthington 2002, Vörösmarty et al. 2010). Water-resource development can affect all components of the flow regime, but our knowledge of the ecological effects of flow alteration is based largely on studies of changes to medium- and high-flow events (Lake 2000, Poff and Zimmerman 2010). Despite the inherent vulnerability of the low-flow end of the hydrograph to human-induced flow change (Smakhtin 2001), the hydrological and ecological consequences of changes to low flows remain highly uncertain (Lake 2003, Niu and Dudgeon 2011, Walters and Post 2011).

Low-flow periods are distinct and ecologically significant components of the hydrological cycle of all river systems. Rolls et al. (2012) identified 6 ecologically relevant hydrological attributes of low flows (antecedent conditions, duration, magnitude, timing and seasonality, rate of change, and frequency), which vary between climatic regions and river types. They also proposed 4 generalized principles that

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describe the mechanistic links between the low-flow attributes and the ecological responses in riverine ecosystems. The synthesis by Rolls et al. (2012) included studies from all river types (perennial to ephemeral) and considered all types of low-flow regimes, including: predictable seasonal low flows, such as dry-season flows in tropical savannah regions; summer low-flow periods in temperate or mediterranean systems; and abnormal and extended low-flow periods, such as the recent severe 'Millennium' drought in southeastern Australia (van Dijk et al. 2013). However, most of the emphasis by Rolls et al. (2012) was on temperate rivers, and they cautioned that generalizing ecological responses to low flows to other climatic or biogeographic regions is problematic.

For many tropical-river systems, low flows during the dry season are a distinct and predictable period of reduced discharge (Lewis 2008, Warfe et al. 2011). The rivers in the tropical savannah climate region (Peel et al. 2007), also called the wet–dry tropics (e.g., Warfe et al. 2011), display extreme seasonality and predictability, with most of a river's discharge occurring in only a few months because of monsoonal rainfall in the wet season, and low- or zero-flow periods occurring for several months during the dry season (Petheram et al. 2008, Warfe et al. 2011). In these rivers, seasonal low flows result in contraction, and potentially disconnection, of aquatic habitats and changes in the availability and quality of resources for aquatic biota.

Tropical savannah regions are the 2nd-most-common global climate type. They cover 11.5% of the world and occur across large parts of Australia, Africa, South America, India, and southeastern Asia (Peel et al. 2007; Fig. 1). Many tropical savannah river systems, such as in India and southeastern Asia, are already among the most threatened river systems on the planet (Vörösmarty et al. 2010), largely because of the effects of groundwater pumping (Aeschbach-Hertig and Gleeson 2012) and high levels of river regulation (Lehner et al. 2011). In contrast, other savannah regions, such as northern Australia, currently have some of the lowest levels of surface- or groundwater extraction in the world (Lehner et al. 2011, Aeschbach-Hertig and Gleeson 2012) and relatively low threats to riverine biodiversity (Vörösmarty et al. 2010). However, interest is growing in developing the water resources to sustain expanded agriculture in northern Australia (Loughnane 2013, Commonwealth of Australia 2014), and much of this expansion will rely on dry-season water extraction.

Over-exploitation of ground water is a global issue (Aeschbach-Hertig and Gleeson 2012), and understanding how river ecosystems will respond to the alteration of seasonal low flows is increasingly important (Smakhtin 2001,

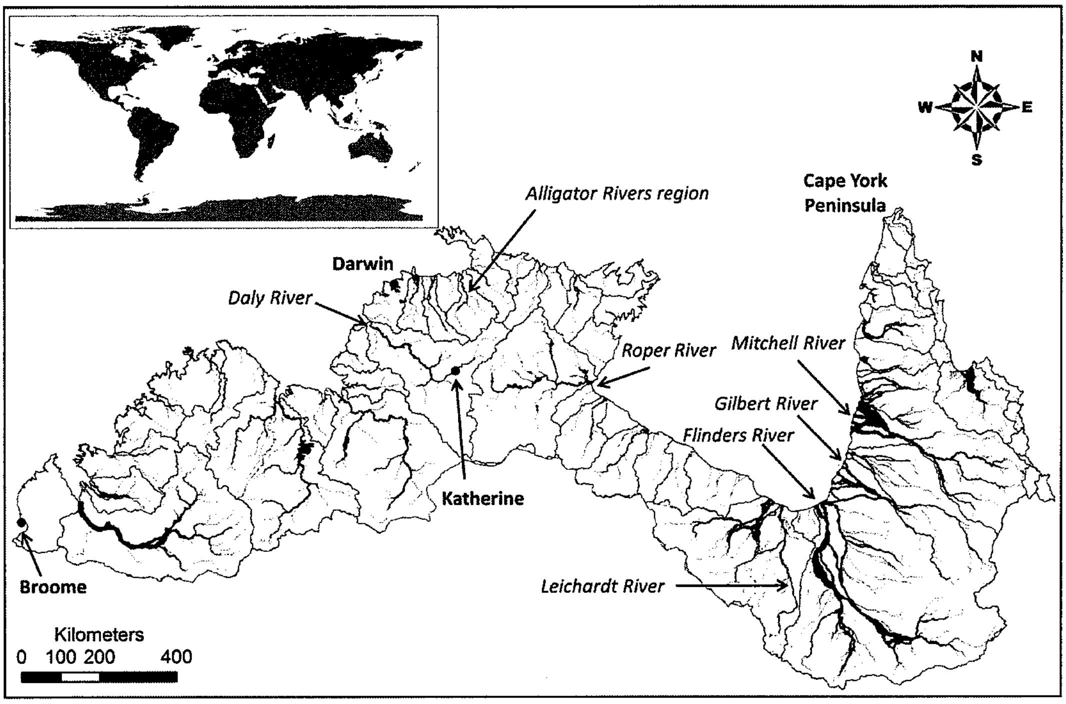

Figure 1. Map of northern Australia showing locations mentioned in the text. Inset map shows the global distribution of the Tropical Savannah Köppen–Geiger climate type Aw highlighted in dark gray (Source: Peel et al. 2007).

Rolls et al. 2012). The hydrological and ecological effects of water extraction in tropical savannah regions have received little scientific attention, but are likely to be substantial (Benstead et al. 1999, Niu and Dudgeon 2011). For example, Benstead et al. (1999) estimated between 34 and 62% daily mortality of migrating shrimp larvae that were entrained in surface-water pumps from a tropical river, with mortality increasing to 100% during low-discharge periods. Niu and Dudgeon (2011) recorded significant declines in macroinvertebrate species richness and compositional metrics in Hong Kong streams with high levels of dry-season water extraction. The ecological effects of droughts and low flows across a range of river types have been explored in many studies (in particular see review by Rolls et al. 2012), and some studies have been made of the effects of direct water extraction on unregulated rivers (see, for example, Castella et al. 1995, McKay and King 2006), but little specific information exists on the likely ecological responses to low-flow alteration in tropical savannah rivers. This key knowledge gap is currently impeding environmental flow management and sustainable water planning in many tropical parts of the world, including in northern Australia (Douglas et al. 2011).

We predicted the hydrological and ecological effects of water extraction on 3 phases of the seasonal flow regime: the wet–dry transition, dry season, and dry–wet season transition periods (sensu Warfe et al. 2011) for perennial and intermittent rivers in tropical savannah climates. We deliberately focused on the effects of surface- or groundwater extraction, and we do not discuss the effects of river regulation, i.e., dam and weir construction and operation, which have received much more attention in the literature (e.g., Dudgeon 2000, Bunn and Arthington 2002, Hart 2004). We reviewed relevant literature on low-flow hydrology and ecology from tropical savannah rivers from northern Australia and elsewhere. We used a conceptual model that describes the mechanistic links to present specific predictions on the hydrological effects of water extraction in tropical savannah rivers worldwide. We critically evaluated the current level and quality of evidence in support of each prediction, assessed their potential ecological consequences, and used this evaluation to identify key priorities for future research. We focused on knowledge derived from rivers of the tropical savannah region of Australia because they are: 1) currently relatively unaffected by humans and, therefore, are useful model systems, and 2) they are under imminent threat from water development. However, we think our predictions are relevant to other tropical savannah rivers throughout the world.

AUSTRALIA'S TROPICAL SAVANNAH RIVERS AND POTENTIAL FUTURE WATER DEVELOPMENT

Australia's tropical savannah region has one of the largest aggregations of free-flowing rivers in the world (Reidy-Liermann et al. 2012) and supports highly productive and diverse ecosystems of great social, cultural, and economic value (Pusey et al. 2011). The region extends over ~1.3 million km^2, from Broome in Western Australia, across the northern part of the continent to the tip of Cape York in Queensland (Fig. 1). The region has low population densities and very small areas of intensive land use. The rivers of northern Australia are considered the most biologically diverse and healthy aquatic systems in Australia, and among the least threatened globally by current human activities (Vörösmarty et al. 2010, Pusey et al. 2011). Approximately 30% of the region's land mass, and many aquatic ecosystems of high conservation value, are owned by indigenous people, with some river catchments entirely within Aboriginal-owned land (Jackson et al. 2011). However, Australia's savannah rivers are not pristine. Two-thirds of the total land area of the region supports a low-intensity cattle-grazing industry and other land uses, such as forestry, cropping, horticulture, and mining, which are largely focused around permanent water sources (Woinarski et al. 2007). The region accounts for more than half of Australia's river discharge, but the currently low anthropogenic water demand means that few rivers are impounded, and only 23 water storages have >1 GL capacity (Cresswell et al. 2009). Ground water also is largely undeveloped across the region, except for the Daly River, the Darwin–Howard East area near Darwin, and the Western Cape York region (CSIRO 2009a; Fig. 1).

The past decade has seen increasing interest in developing the water resources of the region for agriculture and other human uses (Pusey et al. 2011, Loughnane 2013). Proposals for smaller-scale developments using direct surface- and groundwater extraction are increasing. Large numbers of new dams are unlikely because of the generally low relief, the declining rainfall gradient from the coast inland, variable wet-season rainfall, and high evaporation rates (CSIRO 2009a). However, potential dam sites, off-stream storages, and increased groundwater extraction are being assessed in specific watersheds across the region (e.g., CSIRO 2013, Petheram et al. 2008, 2013).

Governments in the region are actively undertaking water-resource assessment and planning, with the aim of equitable allocation of the available water resource, while conserving the environmental values of the system. For example, in the Daly watershed (Fig. 1), most ground water for the lower Katherine River is reserved for environmental purposes. Seventy percent of ground water discharging into the Katherine River is allocated to the environment during normal-to-wet years and 87% in very dry (low flow) years (DNREAS 2009). The Mataranka draft Water Allocation Plan for the Roper River (Fig. 1) allocates a maximum annual extraction for consumptive purposes of 15% of the long-term annual average modeled recharge (20 GL; DLRM 2011). Other groundwater extraction limits have been set as annual volumes (e.g., 10 GL from the Cape York region; CSIRO 2009b), but are not explicitly linked to maintenance of stream flow. Direct surface-water extractions during the dry season from intermittent and perennial rivers are currently negligible on a watershed or regional scale, but could be significant at a local scale and could increase in the future (Table 1).

FLOW REGIMES AND HYDROLOGICAL CONSEQUENCES OF WATER EXTRACTION IN TROPICAL SAVANNAH RIVERS

The tropical savannah region of northern Australia has strongly seasonal monsoonal rainfall, with >90% of annual rainfall occurring during the wet season from November to April, and a marked gradient from maxima of 2000 mm on the coast to 300–400 mm 400 km inland (Warfe et al. 2011). Very little rain falls during the dry season, and river flows recede such that most rivers cease to flow or dry completely before the following wet season, but several iconic perennial rivers in the region rely on significant groundwater input to maintain flows. Despite the relatively high wet-season rainfall, the region is essentially water-limited because of high temperatures and high evaporation rates (Cresswell et al. 2009).

Tropical savannah rivers have a distinct and predictable hydrologic seasonality reflecting the wet–dry climate and can have either permanent or intermittent flows (Kennard et al. 2010, Warfe et al. 2011; Fig. 2A, C). In northern Australia, intermittent flow regimes are the most common hydrological type, but the degree of intermittency varies depending on climate, latitude, and underlying geology, and rivers can cease flowing for up to several months (Kennard et al. 2010; Fig. 2C). Perennial streams and rivers are much less common but do occur in areas with strong surface-water–groundwater connectivity, such as in the Daly and Roper River basins (Petheram et al. 2008, Kennard et al. 2010; Fig. 2A).

Warfe et al. (2011) recognized 4 hydrological periods for the tropical savannah rivers: 1) transition from dry to wet season, 2) wet season, 3) transition from wet to dry season, and 4) dry season (Fig. 2A). Wet-season flow is supplied mainly by surface runoff and shallow subsurface flow from monsoonal rainfall (Fig. 2A), although cyclonic weather and convective storms also contribute. A small proportion of the rainfall, ~10% annually (Cook et al. 1998), recharges aquifers and raises water tables often by several meters until they fill to capacity and then slowly drain through springs, seepages, and directly into the river, and supply water for the evapotranspiration of deep-rooted trees. Dry-season flows are predominantly groundwater-fed (Fig. 2A) because storm-runoff events are infrequent. The transition from wet to dry season is marked by a gradual shift from surface-dominated flow to groundwater-dominated flow (Fig. 2A). The converse occurs during the dry-to-wet transition (Fig. 2A) when groundwater-fed flow is diluted by episodic storm-runoff events before major wet-season flows. The seasonality of flow in tropical savannah rivers is highly predictable, but the precise timing of these 4 seasons can vary from year to year. Even less predictable is the interannual variation of the magnitude of wet- and dry-season flows (Kennard et al. 2010).

The magnitude of dry-season low flows is linked to the height of groundwater tables and aquifer discharges, which can vary naturally among years in response to wet-season rainfall total and the temporal and spatial distribution of rainfall over the recharge area. Intermittent rivers cease to flow in the dry season because the groundwater supply to the river channel is exhausted (Fig. 2C). In some intermittent systems, the river dries completely, but many decrease to a series of disconnected in-channel pools of highly variable depth (up to 5 m), length (up to several kilometers), persistence (weeks to months), and spatial distribution in the systems. The duration of the dry-season low-flow period is determined by the timing of the wet-to-dry transition, and the beginning of the transition to the wet season (Fig. 2C).

Groundwater extraction from bores and wells can significantly reduce river flow by removing water that would have naturally travelled to a river or stream and, therefore, can alter the natural flow regime of perennial and intermittent rivers. This alteration occurs predominantly during the low-flow dry season and shouldering transition periods when water extraction is more likely to occur, and when the river flow is at its lowest and any reduction in flow is more significant (Fig. 2B). The effect of groundwater extraction on stream flow depends on the volume extracted, the travel time between the point of recharge and stream, and the effect of reduced groundwater inflow on stream flow. For example, the number of zero-flow days will increase significantly from historical numbers under theoretical implementation scenarios of the full use of current water allocations (including groundwater and surface water extractions) in many parts of the Leichardt, Flinders, Gilbert, and Mitchell Rivers in Queensland (Close et al. 2012; Fig. 1). The effect of groundwater extraction on river flow may not be apparent for decades because of slow groundwater travel times. This effect is in contrast to the immediate impact of direct surface-water extraction from the river. Groundwater discharging into the Daly River is ≥50 y old (Cook et al. 2003). Dry-season flow reduction caused by groundwater extraction is predicted to occur for the Katherine and Roper Rivers in the next 5 to 50 y and in the Darwin region in the next 5 y (SKM 2012). Groundwater extractions that exceed the annual wet-season recharge will result in a gradual long-term lowering of the water table and a depleted aquifer to supply not only stream flow, but also anthropogenic uses. The incremental decline in flow over decades, overlying natural flow variability, could be considered a ramp disturbance, which is defined by the gradually increasing magnitude of the disturbance temporally and spatially (Lake 2000).

Table 1. Assessment of relative hydrological impacts of groundwater and surface-water extraction in perennial and intermittent tropical savannah rivers. Relative hydrological impact of extractions are interpreted from the authors' expert assessment and review of the literature and considers the hydrological impact with respect to ecologically important components of the flow regime (e.g., magnitude, frequency, duration, timing, and rates of change in flow events) and the relative contribution of ground water to total discharge (see Fig. 2). Hydrological impact is defined as High: predicted to be a substantial change in a number of flow components of the flow period; Moderate: predicted to be a substantial change to 1 flow component or lesser effects on several flow components of the flow period; and Low: predicted to be a minor change to a single flow component of the flow period only.

Flow regime type	Relative hydrological impact of extraction on flow period			
	Wet–dry transition	Dry-season base flow	Dry–wet transition	Seasonal flow
Perennial	Possible extension of wet–dry transition period because of delayed commencement of clear groundwater-dominated flows caused by the lower proportion of ground water relative to surface-water flow *Low hydrological impact*	Further lowers base flows and in extreme scenarios may result in flow cessation; decreased interannual variation in dry-season flow magnitude; potential shortening of dry season from extension of wet–dry transition and earlier commencement of wet–dry period *High hydrological impact*	Lower late-dry-season flows will increase the hydrological impact of early wet-season storm runoff on base flow; may result in apparently earlier start of dry–wet transition or wet phase because surface-water flow dominates total flows *Low hydrological impact*	Potential to decouple magnitude of wet-season flows and subsequent dry-season flows; high wet-season flows generally followed by high dry-season flows because of substantial groundwater recharge; extraction will cause lower-than-natural dry-season flows, following naturally high wet-season flows *Moderate hydrological impact*
Intermittent	Same as above *Low hydrological impact*	Further lowers base flows; earlier flow cessation and longer period of pool disconnection and evapotranspiration losses; reduced groundwater seepage to pools; shallow pools dry *High hydrological impact*	Smaller pool volumes because of longer period of evapotranspiration losses and reduced groundwater inputs; less buffer to early wet-season storm inflows, and longer period for river connectivity to resume *Low hydrological impact*	As above, except decoupling will be between wet-season flows and the volume and persistence of disconnected pools *Low hydrological impact*

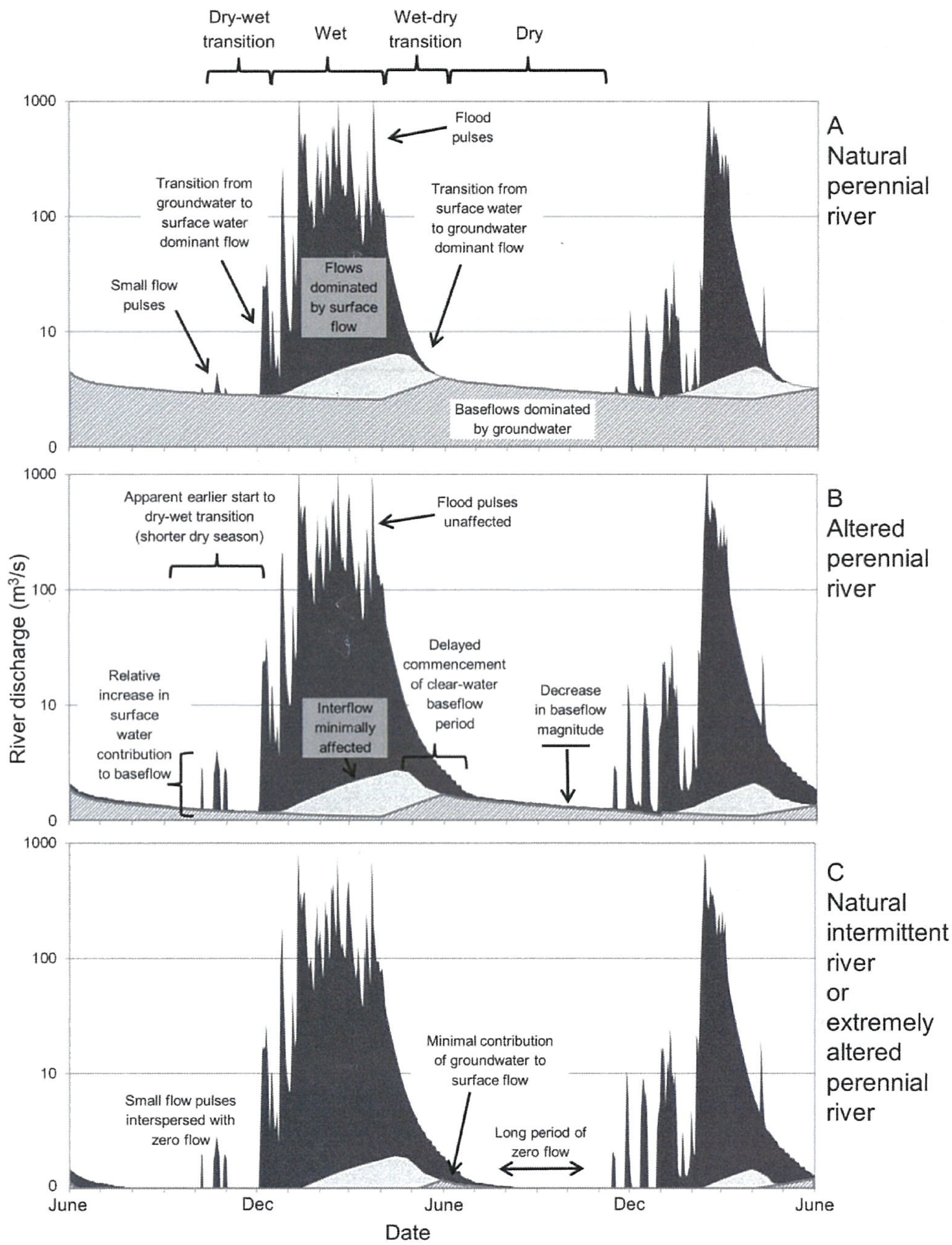

Figure 2. Conceptualization of daily variation in river discharge from surface flows (solid grey fill), interflows (dotted grey fill) and groundwater base flows (diagonal striped fill) for a naturally perennial river (A), a perennial river altered by water extraction (B), and a naturally intermittent river or a perennial river altered by significant water extraction (C). Extraction is assumed to be constant throughout the year and predominantly via ground water. Large surface-water extractions may contribute to other hydrological effects. Surface flow includes all overland flow and precipitation falling directly onto stream channels, interflow is the portion of the stream flow contributed by infiltrated water that moves laterally in the subsurface until it reaches a channel, and groundwater flow is the baseflow component contributed to the channel by ground water (Ramírez 2000). Key hydrologic characteristics and effects of water extraction also are shown. Contributions to river discharge from ground water may be more susceptible to groundwater extraction compared to interflow processes (Costelloe et al. 2014).

The effect of groundwater and surface-water extraction on the seasonal hydrograph will vary with natural flow-regime type, seasonal flow period, the volume extracted, proximity of extraction to the river, and the relative change in ground water as a proportion of total flow. We propose that water extraction will influence the hydrology of tropical savannah perennial and intermittent rivers in 6 ways (Fig. 2A–C, Table 1):

1. *A decrease in the magnitude of dry-season base flows in perennial rivers.* When groundwater resources are over-exploited and have water tables substantially lower than their natural range, the most significant effect for perennial rivers will be a decrease in dry-season flows, and in extreme circumstance, their cessation.
2. *Decoupling of wet- and dry-season flows.* A decoupling of wet- and dry-season flows is predicted to occur when wet-season flows remain nearly natural but are followed by dry-season flows with significantly lower flows than the natural flow regime.
3. *Altered connection periods in intermittent streams.* For intermittent streams, a shortened period of flow connection and an extended period of in-channel pool disconnection and reduced pool levels to buffer early wet-season storm runoff in the wet–dry transition is predicted.
4. *An extended dry–wet transition period.* A reduced riverine flow magnitude (for perennial rivers) and reduced pool volumes (intermittent rivers) to buffer early wet-season storm runoff in the dry–wet transition will result in the apparently earlier commencement of this transition period.
5. A *delayed commencement of dry-season base flow in perennial rivers.* The wet-to-dry season transition period is predicted to be extended because of delayed commencement of the clearly groundwater-dominated flow period because of the lower proportion of ground water contributing to total river flow during seasonal recession flow.
6. *Prolonged extraction will lead to long-term reductions in groundwater levels.* Prolonged groundwater extraction that exceeds aquifer recharge will progressively lower the groundwater table, potentially leading to long-term reductions in groundwater discharge to river flows. This decline can further reduce dry-season riverine base flows and, in extreme scenarios, dry-season flows in perennial rivers could cease.

Our assessment of the relative hydrological impact of dry-season water extraction of flows in perennial and intermittent rivers (Table 1) suggests that, although extraction will affect both dry-season flows and the shouldering transition-flow periods, the effects will be more significant in the low-flow dry-season phase.

PREDICTING THE ECOLOGICAL CONSEQUENCES OF WATER EXTRACTION

We propose a conceptual model (Fig. 3) and 7 broad, testable predictions to describe the probable ecological consequences of water extraction on tropical savannah rivers. These predictions are based on a critical review of the relevant ecological literature on tropical savannah rivers, particularly from northern Australia and the combined authors' expert knowledge and experience of these river systems. We used literature from other regions where appropriate, and we think these predictions are likely to be applicable to other tropical savannah rivers throughout the world. We focused on northern Australian rivers only to assess the quality of evidence supporting each of the predictions, the likelihood of significant impact, and its ecological consequence (Table 2).

Prediction 1. Water extraction will reduce the connectivity and movement of biota and materials during the dry season

The dry season is a period of naturally low flows, but water extraction will further reduce discharge and, therefore, the extent of longitudinal, lateral, and vertical connectivity. This reduction, in turn, could limit the transport of nutrients and organic matter and the movement of biota. Low flows reduce the suspension, mobilization, and transport of fine particulate organic matter (Jones and Smock 1991) and benthic organic matter, such as leaves and small woody debris (Dewson et al. 2007), and may reduce the sloughing of benthic algae (Townsend and Padovan 2005, 2009). Longer retention times in river pools and slackwaters will favor the growth and increased biomass of phytoplankton (Townsend et al. 2012). Australia's tropical savannah rivers are generally heterotrophic (Townsend et al. 2011, Hunt et al. 2012) and nutrient limited in the dry season (Webster et al. 2005, Ganf and Rea 2007, Townsend et al. 2008). Hence reductions in groundwater connection during the low-flow period could further restrict nutrient transport from sediments and the hyporheic zone (Rolls et al. 2012). However, the importance of these processes in the dry season relative to in the wet season is unknown (Brodie and Mitchell 2005).

Lower dry-season flows also may limit the longitudinal movement of aquatic biota. Many aquatic organisms, such as macroinvertebrates, early life stages of fish, and plant seeds are obligate drifters and require flow to facilitate dispersal and transport. Reduced discharge may decrease dispersal distance and rates and densities of drifting biota, potentially leading to wider consequences for higher trophic levels, such as limiting growth rates and productivity of predatory consumers (Rolls et al. 2012). Low flows also may

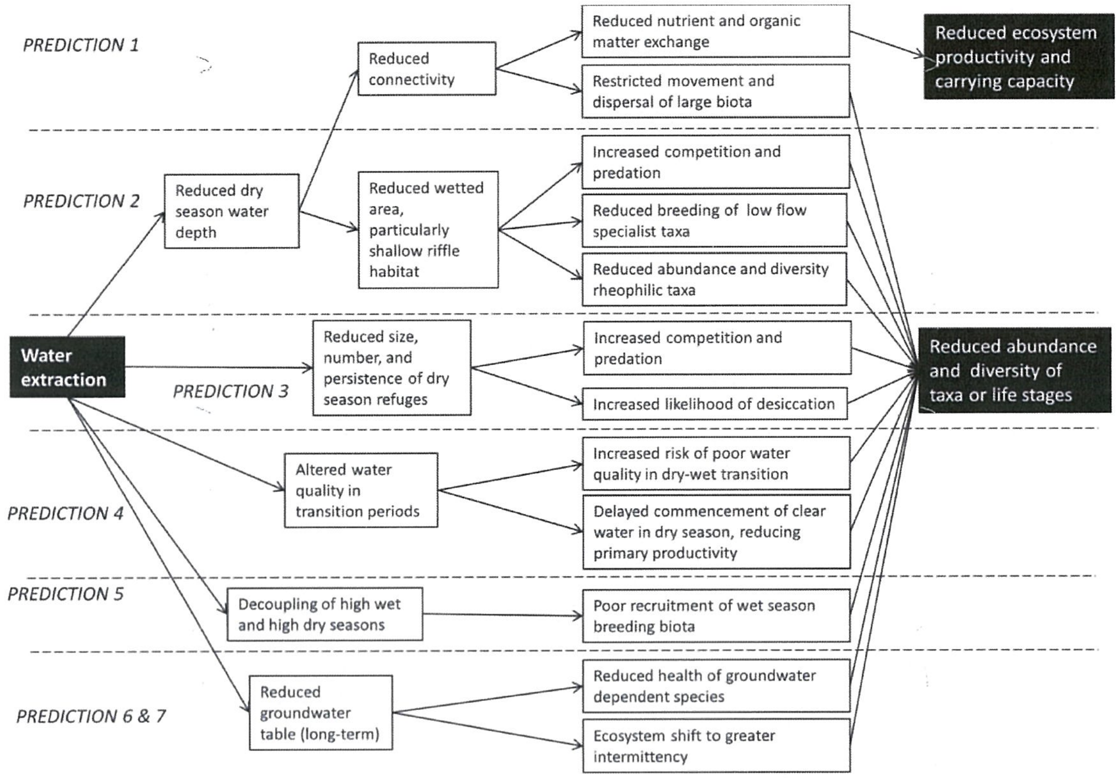

Figure 3. Proposed conceptual model describing mechanistic links between water extraction and potential physical and ecological outcomes in tropical savannah rivers.

trigger the movement of some biota to disperse or seek refuge during drier spells (Magoulick and Kobza 2003). For example, the annual contraction of intermittent and ephemeral rivers in the wet–dry transition period seems to force aquatic macroinvertebrates and fish to disperse, seek suitable dry-season refugia, and then recolonize once wet season flows begin (Bishop et al. 1995, Dostine et al. 1997). The behavioral and ecological responses to dewatering and declining flow conditions and the dispersal requirements of most aquatic biota during the dry season in tropical savannah rivers are poorly known.

Reduced dry-season flows over natural structures, such as rock bars or riffles, or anthropogenic features, such as road crossings and culverts, can create shallower and higher-velocity areas that could exceed swimming abilities, and therefore, could restrict the movement of larger biota (e.g., fish, turtles, sharks, and rays). Wet-season flows facilitate annual longitudinal and lateral connection of large fish through the catchment (Jardine et al. 2012b), but the movement requirements of large fish during the dry season in perennial or intermittent rivers are less clear. Anecdotal evidence indicates that recreational fisherman in northern Australia often target moving and aggregating Barramundi (*Lates calcarifer*) at culverts, road crossings, or natural rock bars as water levels recede (wet–dry) or rise (dry–wet). Some evidence suggests that juveniles of diadromous fishes (e.g., Freshwater Sole *Leptachirus triramus*, Ariidae catfish) and shrimp migrate upstream during the receding wet–dry transition period and very early dry season (Benstead et al. 1999, AJK and P. Novak [Charles Darwin University], unpublished data). Therefore, restrictions to free movement could reduce the densities of fauna migrating upstream and create high densities just below the barrier, thereby exposing them to higher levels of predation and competition for resources. Reduced connectivity also can restrict access to food resources for mobile wide-ranging species. For example, the pig-nosed turtle (*Carettochelys insculpta*) in the Daly River undertakes foraging movements covering >10 km of river during the dry season to maintain its body condition and, therefore, is highly susceptible to reductions in dry-season water levels (Georges et al. 2002). Further research in tropical savannah rivers is required on the importance of dry-season movements of biota, particularly whether bottleneck periods occur and whether in-stream barriers to movement are likely to influence metapopulation persistence.

Prediction 2. Water extraction will reduce the availability of some habitats during the dry season, reducing abundance and diversity of some specialized taxa and life stages

Lower flows reduce the volume, area, and depth of available aquatic habitat and change the instantaneous velocity of rivers (Rolls et al. 2012). Shallow, fast-flowing habitats (e.g., riffles) are the most vulnerable to reduced discharge in the low-flow period. Reduced densities of rheophilic (prefer to live in fast flows) taxa and life stages, and ultimately, local loss of species can occur with prolonged low flows that extend beyond their normal life span. Examples have been reported throughout the world (e.g., Castella et al. 1995, McKay and King 2006, Miller et al. 2007), but few examples exist that test rheophilic species' resistance and resilience to water extraction in tropical environments (but see Covich et al. 2003).

Riffles are important sites for benthic algae and invertebrate production, which in turn, provide important food resources for fish, birds, and reptiles in tropical savannah rivers (Douglas et al. 2005). The growth and density of benthic algae peaks during the middle of the dry season in the Daly River, then decreases sharply during the late dry season because of autogenic sloughing (Townsend and Padovan 2009). Townsend and Padovan (2009) predicted that reduced dry-season flows would decrease the area of favorable hydraulic conditions for the growth of *Spirogyra* sp. and, therefore, would limit energy transfer to higher organisms. Similarly, macroinvertebrate diversity is at its highest early in the dry season (with more sensitive and rheophilic taxa occurring), rather than in the late dry season when fewer taxa that are generally resistant to changing water levels and quality occur (Garcia et al. 2011, Leigh 2013). The biota are undoubtedly adapted to natural and seasonal periods of low flows, but flow alteration that increases the likelihood of flow cessation would alter the resistance and resilience of assemblages, such that early wet-season recovery after the dry season may not be reliable (Leigh 2013). Riffles are the preferred habitat for juveniles of many fish species in northern Australian rivers, including Sooty Grunter (*Hephaestus fuliginosus*) and Butler's Grunter (*Syncomistes butleri*) (Pusey et al. 2011). Chan et al. (2012) demonstrated that the availability of shallow, fast-flowing riffles in the Daly River is very sensitive to variation in dry-season discharge. Hence, reductions in riffle availability caused by dry-season water extraction could have severe consequences for recruitment and population persistence of these riffle-dependent species.

In tropical rivers, breeding of most biota is thought to occur during the resource-rich wet season. For example, most freshwater fish in northern Australia are thought to breed during the wet or shoulder transition phases (Bishop et al. 2001, Pusey et al. 2004). A reduction in low-flow discharge could reduce the availability of breeding and rearing habitats for species that preferentially breed during the dry season. Known dry-season breeders include freshwater crocodiles (*Crocodylus johnstoni*) (Compton 1981) and pig-nosed turtles (Doody et al. 2001). The low-flow period is an important spawning and recruitment period for some fish species in temperate floodplain rivers (see Humphries et al. 1999, King 2004), and recent evidence suggests that dry-season spawning and recruitment does occur for some species in Australian tropical rivers (Pusey et al. 2002, 2004, Doidge 2014). Further research is required in tropical savannah rivers to understand the breeding and nursery habitat requirements of dry-season breeding biota, their susceptibility to low-flow alteration, and the resulting consequences for recruitment.

Prediction 3. Water extraction will reduce the size, number, persistence, and quality of in-channel refugia available during the dry season, particularly in intermittent systems

Intermittent rivers are the most common river type in northern Australia (Kennard et al. 2010). These rivers often contract to a series of isolated within-channel or floodplain waterholes during the dry season. The waterholes, or refugia, are critical for the survival of aquatic biota during the dry season and are important sources of recolonizing biota during the dry–wet transition phase, when isolated refugia reconnect and biota can move to more favorable environments (Dostine et al. 1997, Pettit et al. 2012). As the dry season progresses, smaller disconnected waterholes are often harsh environments, where habitat area and water quality decline markedly and the limiting effects of competition and predation play an increasing role (Pettit et al. 2012). Deeper waterholes or refugia with constant groundwater connections typically retain habitat and water quality, sustaining high biodiversity throughout the dry season (Townsend 2006). Dostine et al. (1997) proposed that the significance of dry-season refugia for macroinvertebrate recolonization of temporary streams in the wet season is governed by 3 factors: the nature of the substrate (with sandy substrates acting as a significant refuge for resting stages of microcrustacea), the severity of the dry season (described by its duration and the number of refugia remaining), and the proximity of permanent refugia to the temporary stream. The location of refugia within the landscape also is critical for biotic recovery when high flows return (Beesley and Prince 2010).

As the dry season progresses, the ecological stability of isolated, smaller refugia declines. As resources become more limited, the breadth of fish diets may narrow and become poorer in quality (Balcombe et al. 2005, Winemiller et al. 2008) as they become more dependent on localized food sources (Jardine et al. 2013). In Neotropical rivers, the potential for competition and predation in refugia can increase as the dry season progresses (Winemiller 1996, Rodríguez

Table 2. Quality of evidence, likelihood of significant impact, ecological consequence, and critical knowledge gaps for each ecological prediction for the Australian tropical savannah rivers. This qualitative assessment is based on the authors' collective expertise and experience and review of the literature. Quality of evidence incorporates the type, amount, quality, consistency, and agreement between studies and is based on an assessment of the literature and authors' opinion: low (e.g., <5 studies, inconsistency between studies), medium (e.g., 5–10 studies, some consistency between studies), and high (e.g., >10 studies, mostly consistent). Likelihood of significant impact: authors' expert assessment of the likelihood that the prediction will have a significant effect on the ecological functioning and biodiversity of the wet–dry tropics rivers. Likelihood is expressed in probabilistic terms (unlikely: <33%, equal chance: 33–65%, likely: >66%, very likely: >90%; following Mastrandrea et al. 2010). Ecological consequence: authors' expert assessment and rating of ecological significance if the prediction is true: low (e.g., processes/abundance reduced but maintained), medium (e.g., probable localized species loss), high (e.g., probable ecosystem shift, species extinction).

Prediction	Quality of evidence	Likelihood of significant impact	Ecological consequence	Critical knowledge gaps
1. Water extraction will reduce the connectivity and movement of biota and materials.	*Organic materials: low* Few studies *Biotic: low* Few studies	*Organic materials: unlikely* Most material movement occurs in wet season *Biotic: equal chance–likely* Biotic movement unconstrained during wet season; high likelihood of dry-season movement important for some biota for breeding and feeding; impact expected to be species specific, and most significant for fish and turtles	*Low–medium* Reduced abundance of key higher-trophic-level biota.	Movement requirements of key biota during dry season and dry–wet–dry transition periods
2. Water extraction will reduce the availability of some habitats (e.g., shallow, fast-flowing habitats) during the dry season.	*Use of riffle habitats: medium* Few studies, but consistent *Dry-season breeding: low* Few studies	*Likely* Number of species that favor riffle habitats or breed during dry season	*Medium–high* Reduced abundance and diversity of rheophilic taxa and life stages; potential for localized extinction of a number of species; broad foodweb and dry-season productivity implications	Mechanism and flexibility of use of riffle habitats; productivity and foodweb importance of riffle habitats; breeding requirements during dry season
3. Water extraction will reduce the size, number, persistence, and quality of in-channel refugia (pools) available during the dry season, particularly in intermittent streams.	*Medium–high* Many studies consistently confirm importance of refugia	*Likely* Good level and quality of evidence; shallow refugia of intermittent streams most vulnerable	*Medium–high* Intermittent streams common; high potential for localized species extinction	Model number, persistence, and location of refugia under various water extraction scenarios; assess effects of compounding threats, (e.g., grazing, weeds) for persistence and resilience of biota in refugia

4. Water extraction will increase the risk of poor water quality during the dry–wet transition phase and extend the duration of high-turbidity flows during the wet–dry transition phase.	*Dry–wet transition: low* Few studies confirm occurrence and immediate impact on fish, but not mechanism *Wet–dry transition: low–medium* Few studies, but all confirm a change from low-to-high water clarity during wet–dry transition	*Dry–wet transition: equal chance* Poor water-quality events are a natural feature, but if frequency and severity increases then biological impact would increase *Wet–dry transition: low* Evidence base very small	*Dry–wet transition: low–medium* Depends on scale of impact on ecological processes and population persistence *Wet–dry transition: unlikely–equal chance* May be countered by shallower depths and higher light intensities at the river bed	*Dry–wet transition*: Predicting frequency and severity of events under various water-extraction scenarios, understanding ecological triggers of poor water quality; significance of fish kills for population persistence; understanding water-quality tolerances of key biota. *Wet–dry transition*: Physical mechanisms driving water clarity, light intensity to trigger benthic primary production; significance of the timing of the accumulation of dry-season benthic plant biomass
5. Water extraction will result in lower dry-season flows, which are less influenced by the magnitude of the preceding wet season lowering survival and recruitment for wet-season breeding biota.	*Low* Few studies	*Equal chance* Evidence base very small	*Low–medium* Depends on scale of impact on survival and recruitment	Elucidate the strength of ecological links between wet and dry seasons, and whether relevant thresholds exist
6. Cumulative impacts of prolonged water extraction may result in a reduction in water-table levels over the longer term, thereby affecting the survival and persistence of groundwater-dependent species.	*Low* Few studies	*Equal chance* Evidence base very small	*Low–medium* May result in local change in species composition of riparian trees or species loss if dependence is strong	Establish dependence of key biota on groundwater flows
7. Cumulative impacts of water extraction could result in ecosystem shifts, whereby perennial systems move towards intermittency, and intermittent systems become drier for longer, resulting in altered community composition and potentially causing species loss.	*Low* Few studies	*Likely* Intermittent and perennial systems have different ecological communities; if hydrological regime shifts, so will ecological communities	*Medium–high* Localized extinctions and potential species extinctions, ecosystem shifts	Establish the form and nature of the relationship between ecosystem response and flow alteration

and Lewis 1997). Water quality, such as dissolved O_2 concentration, also can deteriorate (Pettit et al. 2012) and increase the likelihood of fish kills (Townsend 1994). Water extraction is likely to exacerbate these effects and may threaten population persistence of susceptible taxa (most likely those with limited dispersal capabilities) if suitable refugia become unavailable or are patchily distributed. For example, McJannet et al. (2014) suggested that under some drier climate-change predictions, reductions of >60% of in-stream refugia would be expected in the Flinders and Gilbert catchments, Queensland. Modeling the proportion and spatial location of refugia likely to be lost under future water-extraction scenarios and predicting which biota will be most heavily affected by stranding and desiccation is a research priority for northern Australia.

Prediction 4. Water extraction will increase the risk of poor water quality during the dry–wet transition phase and extend the duration of high-turbidity flows during the wet–dry transition phase

The dry–wet transition period is marked by numerous isolated storm events that generate pulses of surface runoff that fill and reconnect refugia and small dry or intermittent tributary streams (Fig. 2A). These first flush events are likely to have poor water quality because they inundate previously dry ground, carry a pulse of organic matter, sediment, nutrients, and (potentially) heavy metal concentrations, and often have very low dissolved O_2 concentrations (Townsend 1994, Warfe et al. 2011, Townsend et al. 2012). The poor water quality in some of these events results in severe fish kills, with large numbers and many species affected (Townsend et al. 1992, Townsend 1994, Townsend and Edwards 2003). These events do occur naturally in tropical savannah rivers, but water extraction could lead to more frequent, severe, and prolonged hypoxia or poor-water-quality events as the 'buffering' capacity of the main channel and refugial waterholes is reduced as a result of lower volumes to dilute poor-quality inflows. However, little is known about the capacity for tropical savannah rivers to recover from such events, particularly after the next wet-season high flows, and whether resilience can be sustained if the frequency of hypoxic events increases.

Changes in water chemistry also can cause major shifts in dry-season invertebrate community composition in perennial rivers. For example, sandstone aquifers in the upper reaches of the Katherine River, Northern Territory, provide low-alkalinity groundwater inputs to the river, whereas further downstream, a calcareous aquifer provides high-alkalinity ground water to the river. This chemical change corresponds to major differences in invertebrate community composition (Garcia et al. 2011). Changes in the source and mix of groundwater inputs leading to altered water chemistry are a potential consequence of groundwater extraction and, therefore, can alter macroinvertebrate assemblages.

Tropical savannah rivers are highly turbid during the wet season, but the water clears as flow becomes progressively dominated by ground water (Townsend and Padovan 2005, Webster et al. 2005), which has intrinsically low turbidity, though sometimes can be highly colored (Lewis 2008). The increased water clarity in the Daly River permits commencement of benthic primary production, initially dominated by microalgae and *Spirogyra* and later by Ribbonweed (*Vallisneria nana*) (Webster et al. 2005). This primary production provides a base for dry-season food webs (Jardine et al. 2012a) and habitat for aquatic biota. A delay in the commencement of clear, dry-season flows is predicted to delay commencement of benthic primary production with possibly wider ecological implications.

Prediction 5. Water extraction will result in lower dry-season flows, which are less influenced by the magnitude of the preceding wet season, thereby decreasing survival and recruitment for wet-season breeding biota

In years with higher-than-average rainfall during the wet season, higher river discharge and groundwater-recharge rates occur and result in higher flows during the subsequent dry season (Knapton 2009). Many northern Australian freshwater fish reproduce during the wet season (Bishop et al. 2001, Pusey et al. 2004). Large wet-season flows are likely to result in high recruitment pulses as a result of both high levels of spawning in the large wet-season flows, and higher juvenile survival as a result of the subsequent higher dry-season flows. For example, the recruitment strength of Barramundi and Sooty Grunter in the dry season is highly correlated to the preceding wet-season discharge (Staunton-Smith et al. 2004, Halliday et al. 2008, Stewart-Koster et al. 2011). However, significant water extraction could reduce dry-season discharge so that it is no longer correlated with the magnitude of the preceding wet season. This decoupling may result in competition among large numbers of juveniles for limited resources in the following dry season with lower flow conditions than expected. Very little is known about the mechanism of impact (e.g., increased predation, limited food resources), but future research could aim to elucidate the strength of ecological links between wet and dry seasons via examination of long-term, quantitative-catch data sets. Over the longer term, decoupling of wet- and dry-season flows would alter assemblage composition, favoring species more adapted to high inter- and intra-annual variability.

Prediction 6. Cumulative effects of prolonged water extraction may result in a reduction in water-table levels over the longer term, affecting the survival and persistence of groundwater-dependent species

Sustained water extraction could progressively and significantly lower groundwater levels (Sophocleous 2002). Predicting the longer-term ecological effect of systemic and declining groundwater levels is difficult. Close et al. (2012) suggested that, even allowing for the possibility of increased recharge under future climate scenarios, groundwater levels are likely to continue to decline in areas with significant groundwater extraction, such as the Darwin rural area. This groundwater decline is predicted to threaten a number of groundwater-dependent ecosystems in the area. Groundwater extraction may disturb subterranean and groundwater ecosystems, which may contain unique stygofauna (Hancock et al. 2005, Humphreys 2008). In addition, surface-dwelling groundwater-dependent species are at risk. For example, ground water is a significant source of water for many riparian tree species in the Daly River system during the dry season, potentially accounting for >50% of the water transpired during this time (Lamontagne et al. 2005, O'Grady et al. 2006). If the groundwater table falls below the root zone of some riparian tree species, then it is likely that the species composition of the riparian zone will change.

Prediction 7. Cumulative impacts of water extraction could result in ecosystem shifts, in which perennial systems move toward intermittency, and intermittent systems become drier for longer, resulting in altered community composition and potentially causing species loss

Long-term over-exploitation of available water resources will result in progressively lower water-table levels, which could disconnect normally connected reaches, shift the flow regime from perennial to intermittent (Pusey and Kennard 2009), and cause major ecological change. For example, macroinvertebrate and fish communities differ distinctly between lotic and lentic tropical savannah river systems (Leigh and Sheldon 2009, Pusey et al. 2011). An unnatural shift from one predominant flow state to the other could potentially cause the ecological community to change to suit the new conditions and could result in localized extinctions. A long-term study in the Alligator Rivers region, Northern Territory, suggested that macroinvertebrate communities changed from lotic- to lentic-dominated taxa over an 11-y period of below-average rainfall, and consequently lower dry-season flows (Dostine and Humphrey 2012). This change led to a change from high abundances of rheophilic taxa to near extinction of these taxa. Moreover, the change persisted well after the years of low flows and did not recover during wetter years. In particular, initially dominant taxa, including Leptophlebiidae and Baetidae, hydropsychid caddisflies, and hydrophilid beetles, declined in abundance, whereas Caenidae and Pyralidae increased in abundance.

Significant alterations to the flow regime also can cause shifts in life-history traits. For example, taxa in ephemeral systems tend to have higher proportions of taxa with short life spans, small body size, low fecundity, and multiple batch recruitment (Bonada et al. 2007, Chakona et al. 2008, Arscott et al. 2010). For example, Chakona et al. (2008) demonstrated that smaller-bodied macroinvertebrates and species with multiple batch recruitment were more abundant in ephemeral than intermittent streams in Zimbabwe. Similarly, catch rates of shrimp in a perennial rainforest stream in Puerto Rico declined during a severe drought and then recovered quickly, but the reproductive activity of 1 species remained low and did not recover for ≥3 y post drought (Covich et al. 2003).

SYNTHESIS AND IMPLICATIONS

Predicting the ecological responses to human-induced environmental change is a paramount challenge in science. Relatively intact rivers and their biota in northern Australia (Douglas et al. 2011) and other tropical regions throughout the world (Vörösmarty et al. 2010) are under increasing threat from anthropogenic changes associated with water-resource development. A major challenge for researchers and managers is to anticipate how these threats will influence ecosystem processes and biota so that appropriate strategies can be developed to respond to the threats. The Northern Australia Land and Water Taskforce (2009) highlighted the need for a greater understanding of surface-water–groundwater interactions so that the effects of water extraction on river ecology could be assessed. Similarly, an urgent call has been made for research and information on quantitative flow–ecology relationships to underpin water-allocation planning and future monitoring in northern Australian rivers (Douglas et al. 2011, Warfe et al. 2011).

Our conceptual model and predictions draw together the best information currently available on the potential hydrological and ecological effects of dry-season water extraction in tropical savannah rivers. These predictions will allow researchers and managers to consider the range of potential effects of dry-season water extraction, with a view to informing policy debates and helping to focus future research activities. We used northern Australian rivers as our primary reference point, but we think our predictions are very likely to be applicable in other regions. They are intended to spur discussion about rivers in tropical savannah regions throughout the world. Our predictions are testable, and we encourage further research that may support, refute, or review them.

Many of the predictions currently have low-to-medium quality of evidence supporting them, mostly because relatively few publications on these topics exist for savannah streams (Table 2). However, the high level of consistency among these findings means that the likelihood that water extraction could create a significant impact is generally medium to high. We also think that the scale of the ecological consequences is generally medium to high. Our analysis highlights a number of critical knowledge gaps (Table 2) that should be addressed to increase confidence in effective water planning and environmental-flow decision-making. A range of approaches would be appropriate to fill these knowledge gaps. These approaches include field-based sampling along spatial and temporal hydrological gradients, monitoring of ecological responses to experimental flow manipulations (Konrad et al. 2011, Olden et al. 2014), and modelling approaches such as Bayesian Belief Network modeling that has the capacity to combine different types of knowledge and data (e.g., Chan et al. 2012). However, each of these approaches has inherent strengths, weaknesses, and feasibility constraints in tropical savannah rivers. Constraints include issues of transferability of knowledge and data from one place to another, the feasibility and logistical constraints in undertaking field studies in remote areas that are highly seasonal, costs of undertaking research programs, and the constraints on human resources and scientific knowledge to undertake them.

We acknowledge that our review has focused only on the direct effects of water extraction on hydrology and ecology, and has largely ignored other concurrent effects that are likely to occur with increasing water development. For example, increasing agricultural and mining development may introduce multiple stressors on the aquatic environment. These stressors include changing landscape-scale patterns of land use, which would increase catchment erosion rates and, therefore, potential sediment input to waterways, thereby increasing concentrations of nutrients, pesticides, and other toxicants (Brodie and Mitchell 2005). Changes in land use also would increase road infrastructure and, therefore, the number of potential in-stream barriers (Douglas et al. 2011). Fresh waters are known to be at great risk of multiple-stressor effects (Ormerod et al. 2010), so it will be important to understand the relative effect of each of these potential stressors. The compounding influence of climate change on water-resource development also should be considered. Climate-change predictions are imprecise for northern Australia, but the likelihood of higher temperatures, evapotranspiration rates, and extreme storm events will increase (Morrongiello et al. 2011). These changes would result in greater flow variability in rivers, with decreases in flow or flow cessation occurring more frequently and peak flows during the wet season occurring more sporadically. Hence, our water-extraction predictions are likely to be further exacerbated under many potential climate-change scenarios. This likelihood highlights the critical need for ecologically sound water-resource planning and decision-making in northern Australia that incorporates all potential water-development effects and other significant confounding impacts.

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Trial monitoring of pesticides in the Katherine River

Key Findings

A pilot project monitoring pesticides at four sites in the Katherine River during the dry season in 2011 detected very low traces of some common herbicides, pesticides and polycyclic aromatic hydrocarbons (PAHs; atmospheric pollutants that are the by-products of fuel combustion) in the water. The concentrations of all chemicals were well below national guideline levels for ecosystem protection.

The Katherine River is still one of the cleanest in Australia with regards to pesticide, herbicide and PAH contamination. The current concentrations are very low; however, they are an indication that chemicals do leach into the groundwater and eventually reach the river, and that atmospheric toxicants can pollute rivers.

Method

Very low levels of chemicals are difficult to detect when a normal water sample is analysed. In this project a method called "passive sampling" was used. With this technique, samplers were left submerged in the river for four weeks. During this time they absorbed and concentrated chemicals from the water. Because the chemicals are concentrated they can then be detected with the usual laboratory analysis methods.

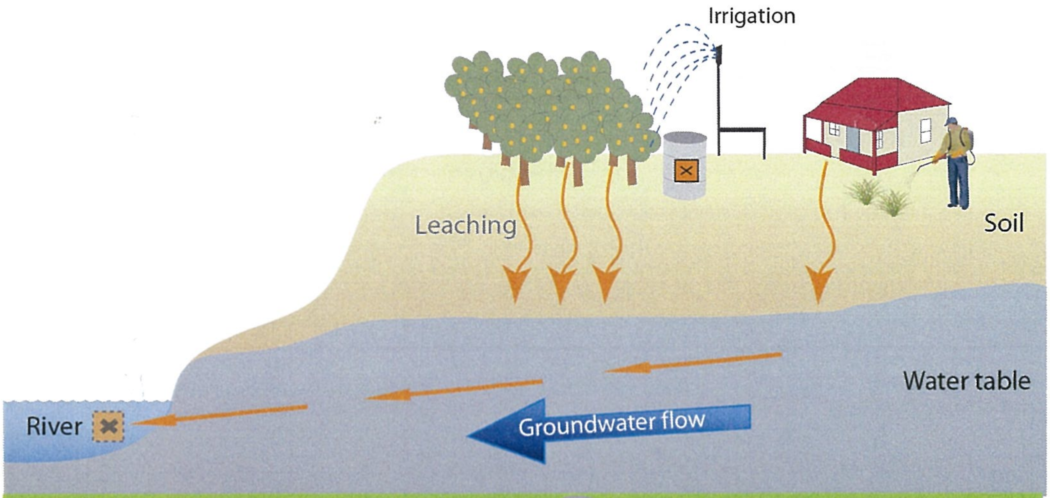
Pesticide sampling requires careful handling of samplers to avoid contamination.
Photo: J. Schult

Which chemicals were found?

Of 188 chemicals tested, only 15 were detected in the Katherine River. Five of these were common herbicides, two pesticides, one insect repellent (DEET), two chemicals common in personal care products, such as sunscreens, lotions and perfumes, and five PAHs.

How do these chemicals get into the river?

Some chemicals, including many herbicides, are easily dissolved in water. When they are applied to crops, pastures or roadsides, they can be transported by rain or irrigation through the soil to the groundwater table. Once they have reached the groundwater table, they can travel with the groundwater below the surface until they reach the streams through seepages or springs. Other chemicals can be transported attached to sediments in runoff from roads, pastures or cropland. Some of these chemicals can also accumulate in river sediments.



During the dry season, pesticides and herbicides can reach the river when they leach through the soil into the groundwater.

Further information

This fact sheet is based on information from the following report:

Schult, J. (2012). Trial monitoring of pesticides and PAHs in the Katherine River using passive samplers. Report 23/2011D, Department of Natural Resources, Environment, The Arts and Sport, Darwin.

Available online at: http://www.nretas.nt.gov.au/natural-resource-management/water/aquatic/publications.

Northern Territory Government

DEPARTMENT OF LAND RESOURCE MANAGEMENT

Trial monitoring for pesticides and PAHs in the Katherine River using passive samplers

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Report No 23/2011D

November 2012

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This report can be cited as:

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Cover photo:

Preparing passive samplers for deployment in the Katherine River. *Photo: J. Schult*

Contents

1. SUMMARY

Pesticides, herbicides, the chemical products of incomplete combustion known as polycyclic aromatic hydrocarbons (PAHs) and other toxicants were monitored at four Katherine River sites in the vicinity of the township of Katherine using passive samplers. Of the 188 chemicals for which analyses were undertaken, 15 were detected in the Katherine River, including 4 herbicides, 2 pesticides, 3 chemicals common in personal care products (e.g. perfumes, shampoos, lotions and sunscreens) and 5 PAHs. All of these chemicals were present at very low concentrations and did not exceed ANZECC water quality guidelines for the protection of aquatic ecosystems.

The water-soluble herbicides were only detected at Sites 2-4, downstream of the influence of the Tindall aquifer and Katherine township, indicating that there may be some very low level contamination of the Tindall aquifer with these herbicides. No herbicides were detected at Site 1 which is upstream of the town of Katherine and receives water from a different groundwater source. Pesticides were only detected at Sites 2-4, while DEET, a mosquito repellent, was present at all sites, as were a number of PAHs. Passive samplers provided a simple, easy-to-use method for the detection of toxicants in the Katherine River in the dry season, and are recommended for future monitoring.

The Katherine River is still one of the cleanest in Australia. Nevertheless, the results are a reminder that pesticide use has the potential to affect the health of the Daly river system.

2. INTRODUCTION

2.1 Background

The Katherine region is the most populated area of the Daly River catchment and contains the largest urban centre and one of the major agricultural areas. Pollution of the aquatic environment with anthropogenic chemicals is therefore most likely to be found in this part of the catchment.

Chemical pollutants in the river can originate from many sources, including the use of pesticides (herbicides, insecticides and fungicides) in agricultural areas, industrial areas, roadsides and urban and rural properties, or the use and burning of oils and fuels. Chemicals that are applied to roadsides, orchards, crops or pastures can pass through the soil and enter the groundwater. Water soluble chemicals have a higher risk of groundwater contamination because they are easily transported through the soil to reside in groundwater, while less soluble substances can be carried overland attached to sediments. The incomplete combustion of fossil fuels, wood and plant biomass, can generate toxicants known as polycyclic aromatic hydrocarbons (PAHs), which enter waterbodies from atmospheric pollution.

When chemicals leach into the groundwater or are carried with surface water runoff, they can enter streams and impact on their ecology. Many man-made chemicals are toxic to aquatic plants and animals and can affect aquatic food webs, or even be harmful to humans.

Pesticide residues have been found in other Australian tropical rivers (e.g. Davis et al. 2008, Lewis et al. 2009) but to date no studies have investigated pesticide contamination in the Daly River catchment.

2.2 Study aim

The aim of this study was to investigate

- whether any traces of common environmental toxicants including herbicides, pesticides, and polycyclic aromatic hydrocarbons (PAHs) could be detected in the Katherine River; and if found,
- whether their concentrations exceeded national guidelines for the protection of aquatic ecosystems (ANZECC/ARMCANZ 2000a); and
- whether the use of passive sampler technology was a suitable and practical method for the detection of toxicants in the river system.

3. METHODS

3.1 Study sites

Passive samplers were deployed at four sites in the Katherine region during the dry season (Figure 1). Site 1 was located at the inflow to Donkey Camp Pool, upstream of the township of Katherine. Dry season flows at this site are supplied from groundwater that originates from a Cretaceous sandstone aquifer and is characterised by low conductivity and low pH. This site is upstream of major developments and most of its catchment lies within Nitmiluk National Park. Tourism is the main human activity in the area upstream of this site.

Site 2 is situated within the area of Katherine township, downstream of a large unnamed spring that enters the river on the north bank.

Site 3 was downstream of the Springvale Spring, just upstream of Springvale Caravan Park and Site 4 was located at 'Galloping Jack's', downstream of the Florina Road agricultural region.

Sites 2-4 receive major groundwater inflows from the Tindall aquifer that underlies Katherine township and agricultural land. From Site 2 onwards, the influence of the Tindall aquifer increases, as indicated by rising conductivity and pH.

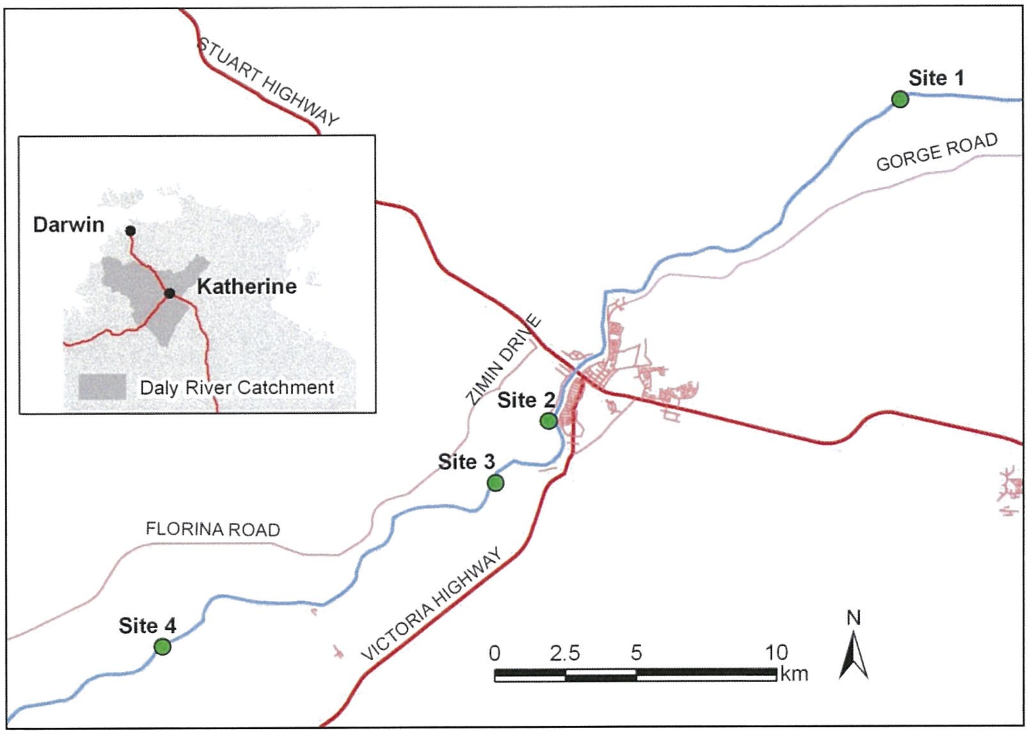

Figure 1. Map of passive sampler deployment sites on the Katherine River.

3.2. Passive Samplers

Passive samplers can detect very small traces of chemicals in water that would be impossible to detect by conventional water sampling because the concentration of the chemical is either too low (i.e. below detection limits) or varies over time and may be missed by conventional grab sample collection. Passive samplers are devices that can be deployed in a water body for a period of up to one month. During this time, the samplers absorb and accumulate the chemicals, so that the final concentration is high enough to be detected. (For a more detailed overview and introduction to the use of passive samplers see Alvarez (2010)).

A chemical flow estimation device is deployed at the same time and this allows an estimate of the average concentration of the chemicals over the deployment period.

Two different types of samplers were used in this study, one which accumulates, hydrophilic substances (i.e. water loving) and one which accumulates substances that are hydrophobic, meaning they are repelled by water.

Most herbicides belong to the first category of hydrophilic substances, while most pesticides and PAHs are hydrophobic.

3.3 Sampling methods

Samplers were supplied by the National Research Centre for Environmental Toxicology (EnTox) in Queensland. Each sampler array contained one Empore Disc sampler (ED) for hydrophilic substances, one polydimethylsiloxane (PDMS) sampler for hydrophobic substances and one passive flux meter (PFM) to estimate flow through the samplers. Duplicate EDs and PDMSs were deployed at Site 4 only.

The samplers were attached to a rope that was weighted at one end with a buoy attached to the other as in the diagram below (Figure 2). A guide rope was attached to a tree on the river bank so the samplers could be located for retrieval. Samplers had to be placed in the lower half of the water column to ensure passing boats would not get entangled as the water level dropped over the deployment period.

Sampler arrays were deployed for a total of four weeks, from 18 July 2011 to 15 August 2011. Upon retrieval, samplers were stored on ice and returned to EnTox for extraction, analysis and calculation of water concentration estimates. The chemical analyses were carried out by Queensland Health Forensic and Scientific Services.

During the initial sampler deployment, temperature, pH, dissolved oxygen, conductivity and turbidity were measured at each site using a Quanta multi-parameter probe. Water samples were collected at each site and analysed for total nitrogen (TN), total phosphorus (TP), nitrite (NO_2), nitrate (NO_3) and filterable reactive phosphorus (FRP). Triplicate samples were collected at Sites 1 and 4 and single samples at sites 2 and 3.

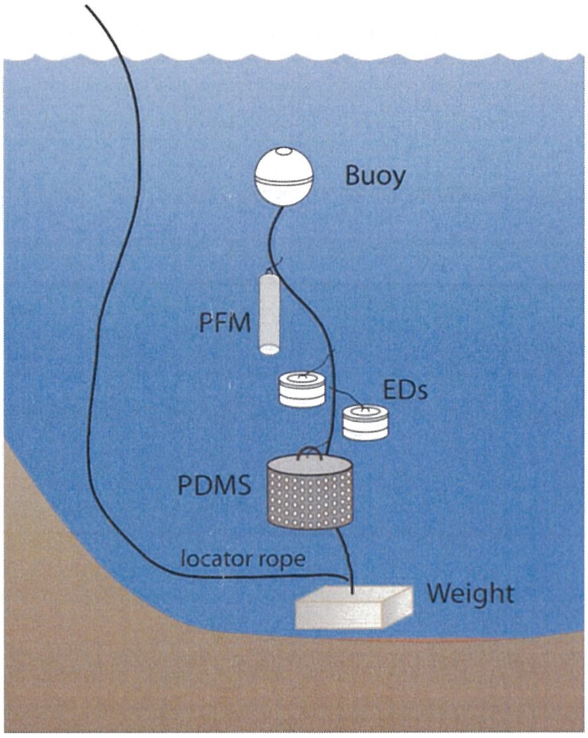

Figure 2. Diagram of passive sampler array

4. RESULTS

4.1 General dry season water quality

Water quality results are summarised in Table 1. Site 1 has a lower pH and lower conductivity than the other three sites due to the difference in water source. Conductivity increases downstream as the Tindall aquifer influence increases. Dissolved oxygen was high at all sites and turbidity low throughout.

Nitrate concentrations were below the detection limit of 1 µg/L at Site 1 and increased to over 60 µg/L further downstream where water from the Tindall aquifer enters the river. The increase in total nitrogen from upstream to downstream also reflects this increase in nitrate. Filterable and total phosphorus concentrations were similar across sites and ranged from 8-9 µg/L for FRP and 7-10 µg/L for total P. These concentrations were similar to those found in previous studies (e.g. Schult et al. 2007, Schult and Townsend 2012).

Table 1. Water quality at four Katherine River study sites, July 2011

Water Quality Parameter	Site 1	Site 2	Site 3	Site 4
Temp (°C)	23.2	24.9	26.4	25
pH	5.4	6	5.8	6.4
DO (%)	89	83	88	90
EC (µS/cm)	36	210	275	334
Tur (NTU)	2.3	4.7	3.4	4.2
NOx (µg/L as N)	2	69	79	79
FRP (µg/L)	9	8	8	9
TP (µg/L)	10	10	10	7
TN (µg/L)	90	150	160	170
No. of replicates	3	1	1	3

4.2 ED sampler results (Group 1)

Of the 19 herbicides (Group 1) for which analyses were undertaken, 5 were detected in the Katherine River. Traces were detected at three of the four sites sampled. There were no traces of any herbicide at Site 1, the site furthest upstream. Sites 2 to 4 showed low levels of five chemicals: atrazine, atrazine desethyl (a breakdown product of atrazine), hexazinone, simazine and tebuthiuron (Table 2).

The concentrations of all chemicals were very low and well within the ANZECC and ARMCANZ (2000a) recommended guideline values for slightly disturbed ecosystems.

Table 2. Estimated average water concentrations of herbicides (Group 1) in the Katherine River. All concentrations are given in ng/L. (N/A: not available)

Chemical name	Site 1	Site 2	Site 3	Site 4*	ANZECC Guideline Value**
Ametryn	0.00	0.00	0.00	0.00	
Atrazine	0.00	0.39	0.18	0.35	13000
Atrazine desethyl	0.00	1.48	1.10	0.65	N/A
Carbendazim	0.00	0.00	0.00	0.00	
Diazinon	0.00	0.00	0.00	0.00	
Diclofenac	0.00	0.00	0.00	0.00	
Diuron	0.00	0.00	0.00	0.00	
Fipronil	0.00	0.00	0.00	0.00	
Hexazinone	0.00	0.07	0.15	0.10	N/A
Irgarol	0.00	0.00	0.00	0.00	
Isoproturon	0.00	0.00	0.00	0.00	
Mecoprop	0.00	0.00	0.00	0.00	
Metolachlor	0.00	0.00	0.00	0.00	
Prometryn	0.00	0.00	0.00	0.00	
Simazine	0.00	0.11	0.07	0.10	3200
Sulfamethoxazole	0.00	0.00	0.00	0.00	
Tebuthiuron	0.00	0.38	0.30	0.24	2200
Terbutryn	0.00	0.00	0.00	0.00	
Terbutylazine	0.00	0.00	0.00	0.00	

*averages of two samplers

** Value for 95% ecosystem protection as recommended for slightly to moderately disturbed ecosystems

4.3 PDMS sampler results (Groups 2 and 3)

A suite of 152 pesticides and other chemicals (Group 2) were tested for, as well as 17 polycyclic aromatic hydrocarbons (PAHs, Group 3). A full list of analytes is provided in Appendix 1. Traces of eight of the pesticides and chemical compounds in Group 2 and 5 PAHs were detected in the Katherine River (Table 3 and Table 4).

At Site 1 only one Group 2 compound (DEET) and three PAHs (Group 3) were detected while Sites 2-4 showed traces of between 3 and 6 chemicals of Group 2 and 3-5 PAHs at each site.

Concentration estimates are provided wherever possible, however, not all concentrations could be estimated because these estimates require knowledge of water – sampler partitioning coefficients that are not currently available for all chemicals. For these compounds a total amount per sampler per day is provided. All concentrations were well below ANZECC/ARMCANZ guidelines for aquatic ecosystems.

Table 3. Estimated average water concentrations of pesticides and other chemicals (Group 2) in the Katherine River (ng/L). (N/A: not available)

Chemical name	Site 1	Site 2	Site 3	Site 4*	ANZECC Guideline Value
DEET	189.3	79.0	92.5	102.6	N/A
Chlorpyrifos	0.0	0.5	0.6	0.0	10
(ng/sampler/day)					
Galaxolide	0.0	0.0	21.1	22.3	N/A
Tonalide	0.0	3.1	6.2	3.1	N/A
Methamidaphos	0.0	42.0	0.0	0.0	N/A

*averages of two samplers

** Value for 95% ecosystem protection as recommended for slightly to moderately disturbed ecosystems

Table 4. Estimated average water concentrations (ng/sampler/day) of polycyclic aromatic hydrocarbons (PAHs) (Group 3) in the Katherine River. (N/A: not available).

Chemical name	Site 1	Site 2	Site 3	Site 4*	ANZECC Guideline Value** (ng/L)
Phenanthrene	2.1	1.7	1.7	2.8	600
Anthracene	0.0	0.1	0.0	0.0	10
Fluoranthrene	1.0	0.6	0.6	1.3	1000
Pyrene	0.3	0.3	0.3	0.8	100
Perylene	0.0	0.3	0.0	0.0	N/A

*averages of two samplers

** Value for 99% ecosystem protection. High reliability values are not available for these chemicals. Values used are low reliability guidelines (ANZECC/ARMCANZ 2000b).

5. DISCUSSION

5.1 Herbicides (Group 1)

Of the 19 chemicals tested, five were detected in the Katherine River. Four of these are herbicides that are commonly used in agriculture and on pastures in the Northern Territory and one, atrazine desethyl, is a break-down product of one of the other herbicides. Table 5 gives an overview of uses and risks associated with each of the herbicides.

Atrazine and its break-down product atrazine desethyl were present in the highest concentrations of the five herbicides found. Atrazine is one of the most commonly detected herbicides in Australian surface waters. It is highly water soluble and therefore has a high risk of leaching into the groundwater. It is used in maize and sorghum crops in the Katherine area (Malcolm Bennett, Department of Primary Industries and Fisheries, pers. comm.) but may also have other applications elsewhere. In the Northern Territory it has previously been detected in groundwater of the Darwin rural area in the 1990s (Wilson unpublished data as referenced in Waugh and Padovan 2004).

Hexazinone and Tebuthiuron are used for control of woody (tree) and broadleaf weeds in pastures in the NT. Tebuthiuron was listed as one of the highest use herbicides in the Darwin area by Waugh and Padovan (2004). Simazine is mainly used for citrus and other fruits.

Table 5. Uses and risks associated with herbicides detected in the Katherine River (information adapted from Waugh and Padovan 2004, APVMA 2011)

Atrazine (e.g. NUTRAZINE, FARMOZINE)	
Description	Systemic triazine herbicide, applied by ground spray and absorbed through roots
Uses	Control of grasses and broad-leaved weeds in orchards, plantations, crops and roadsides. Commonly used in maize and sorghum crops.
Risks and Effects	High risk of groundwater contamination. Relatively stable in water and persists in ground water with DT50 of > 100 days. Highly mobile and commonly detected in surface and groundwater samples in Australia De-registered in the EU due to groundwater contamination concerns. Disrupts sexual development of frogs (can result in intersex hermaphroditic condition)
Simazine (e.g. GESATOP, SIMAQUEST)	
Description	Systemic triazine herbicide. Absorbed through roots. Stable in water, decomposed by UV light, binds to soil.
Uses	Controls broad-leaf weeds in a variety of crops and at higher rates of application, grasses and broad-leaved weeds in other areas. Used in citrus and for non-crop weed control on roads, railways etc. First registered 1995.
Risks and Effects	High risk of groundwater leaching.
Hexazinone (e.g. VELPAR)	
Description	Contact herbicide, absorbed through leaves and roots.
Uses	Commonly used against a variety of weeds in tree plantations, commercial/industrial areas and rights-of-way. Broad-spectrum herbicide used to control grasses. Broad-leaved and woody plants, Control of woody weeds in pastures
Risks and Effects	Stable in water, breaks down only slowly in soils (DT50 1-6 months) High risk of groundwater contamination.
Tebuthiuron (e.g. GRASLAN, TEBULAN)	
Description	Substituted urea herbicide
Uses	Used for total control of herbaceous and woody plants in areas not used for cropping (pastures, industrial areas) Broad-spectrum herbicide for control of herbaceous and woody plants, grasses and broad-leaved weeds in pastures and non-crop land (roadsides etc)
Risks and Effects	Very high water solubility and leachate risk.

It is difficult to ascertain where these herbicides are actually used. Products may be registered for certain crops but can also be used on other crops or for non-cropping purposes, e.g. weed control in rights-of-way, railway or other infrastructure corridors.

All of the herbicides that were detected in the Katherine River were highly water soluble. The most likely pathway for herbicides to reach the streams is through groundwater. Many herbicides are water soluble and can leach through the soil into the water table below with rain or irrigation. The contaminated water then moves below the ground and enters the river through springs and seepages.

The Katherine River is entirely groundwater-fed during the dry season, when sampling took place. It is supplied by two different groundwater systems: the upstream reaches (Site 1) are supplied by waters of Cretaceous sandstone origin, and the lower reaches (Sites 2-4) are fed by waters from the Tindall limestone aquifer.

The upstream site, Site 1, was free of all traces of herbicides, indicating that there is no contamination of the Cretaceous sandstone aquifer. Most of the upper catchment is contained within Nitmiluk National Park and there is no agriculture in the region.

However, downstream of the influence of the Tindall aquifer, traces of herbicides were found at all three sites. The Tindall aquifer is the main water supply for irrigated horticulture and cropping in the Katherine area and also supplies drinking water for stock and domestic use. The results of this pilot study indicate that there is some low level contamination of the Tindall aquifer with herbicide residues.

Detailed local data on the amount of herbicide and pesticide use and local application are not available.

5.2 Pesticides and other chemicals (Group 2)

Pesticides are generally less water soluble than herbicides and are therefore more likely to be found in sediments than in the water column. Only two pesticides were detected in the river, chlorpyrifos and methamidophos. A summary of uses and risks of all Group 2 chemicals that were detected is given in Table 6.

Since the banning of organochloride pesticides (e.g. DDT, Dieldrin) in the 1980s chlorpyrifos has been widely used in the Northern Territory for termite control but also for control of other insects in home and garden, and in a variety of crops. It is highly toxic to aquatic life.

Chlorpyrifos was detected at low levels at Sites 2 and 3, but not at Sites 1 and 4. Both sites are within the Katherine township, indicating that it may originate from the urban area. Chlorpyrifos can persist in sediments and it is possible that stores in sediments contribute to the water column concentrations of the chemical.

Table 6. Uses and risks associated with pesticides and other chemicals (Group 2) detected in the Katherine River (information adapted from Waugh and Padovan, APVMA 2011, Barron and Woodburn 1995, PAN 2012)

Chlorpyrifos	
Description	Organo-phosphorus pesticide
Uses	Most important use is against subterranean termites, also used in variety of crops as well as in pasture, machinery, turf and general home and garden uses. Probably no longer used in broad-acre cropping
Risks and Effects	Highly toxic, particularly to crustaceans and insect larvae (Barron and Woodburn 1995) degrades more rapidly in alkaline waters. Sediments contribute to persistence. Very high toxicity to most aquatic organisms except algae and molluscs. Potential for bioaccumulation but also deteriorates rapidly.
Methamidaphos (e.g.NITOPHOL, MONITOR)	
Description	Organophosphate insecticide, non-systemic. Also a breakdown product of acephate
Uses	Used to control a variety of pests in crops, especially brassicas, tomatoes, potatoes. Acephate is used in bananas.
Risks and Effects	Highly toxic to many aquatic organisms and bees, potential groundwater pollutant (PAN 2012)
Tonalide/Galaxolide	
Description	Musk-fragrances
Uses	Commonly used in personal care products, laundry detergents, perfumes, cosmetics
Risks and Effects	Found in almost all aquatic systems, persistent in environment, little toxicology data available.(Randelli et al. 2011, Rimkus 1999)
DEET (N,N-Dimethyl-m-toluamide)	
Uses	Active ingredient of many insect repellents
Risks and Effects	Ubiquitous in aquatic ecosystems.

Methamidophos, an organophosphate insecticide, is not commonly found in Australian surface waters. It is used for a variety of crops and is also a breakdown-product of another pesticide, acephate. Acephate is used on bananas and potatoes, both of which are grown in the Katherine region (M. Bennett, DoR, pers. comm.). It was only found at Site 2.

The insect repellent DEET was the only chemical from Groups 1 and 2 found at all four sites. DEET is found in most in Australian waterways. Unlike the other chemicals, the highest concentration of DEET was found at Site 1, upstream of Katherine township. Tourism is the main land use upstream of Site 1. It is possible that the high numbers of tourists and locals swimming at Katherine Gorge during the dry season contribute to the relatively high DEET concentrations at this site, although no other personal care chemicals were detected. The levels found in the Katherine River are similar to those found in some surface waters of South Australia (Christie Bentley, Entox, pers. comm.).

Galaxolide and Tonalide are musk fragrances that are used in most scented personal care products (e.g. soaps, shampoos, laundry detergents etc). These human-generated chemicals are very commonly found in Australian surface waters, and are often in high concentrations in waste water discharges. Both substances were detected at Sites 2, 3 and 4.

5.3 PAHs

Three PAHs were found at all sites, and five at Site 2. Natural sources of PAHs include forest fires and volcanic eruptions; however, a significant fraction of PAHs originates from anthropogenic combustion processes. PAHs are commonly found in road runoff (ANZECC/ARMCANZ 2000b). Because of their low water solubility, PAH concentrations in aquatic ecosystems are usually highest in sediments, intermediate in aquatic biota and lowest in the water column.

5.4 Usefulness of passive samplers

Passive samplers provided a practical and cost-effective method for the detection of toxicants in the river. Samplers were prepared and provided by the National Research Centre for Environmental Toxicology at the University of Queensland (EnTox). Aquatic Health Unit staff deployed and retrieved the samplers and returned them to EnTox for extraction and analysis. No problems occurred during deployment or retrieval of the samplers, although it is important to remember to mark sites carefully so that the submerged samplers can be located easily upon retrieval.

Flows in the Katherine River are low in the dry season, so that site selection was limited by river depth. Samplers had to be deployed in pools to ensure that falling water levels over the deployment period would not expose the samplers to the air or make them a hazard to other river users, especially boats.

Some bio-fouling occurred over the deployment period, as was to be expected. Algae growth on the samplers was not excessive and was not considered likely to have adverse effects on the results.

6. CONCLUSION

Despite the detection of low levels of a number of pesticides and PAHs, the Katherine River is still one of the cleanest in Australia. Although the current concentrations of these toxicants are very low they are an indication that chemicals do leach into the groundwater and eventually reach the river, and that atmospheric toxicants can pollute rivers.

The passive samplers provided a cost-effective and practical methodof field sampling and detected toxicants at levels that cannot be detected with conventional grab sampling.

7. RECOMMENDATION

Pesticide monitoring is included in a catchment-wide monitoring of the Daly River system's water quality and aquatic health. Monitoring for PAHs from river water however is not warranted, and would be better monitored in river sediments or biota than river water.

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APPENDIX 1. COMPLETE LIST OF ANALYTES FOR PDMS

Acephate	DEET	Haloxyfop methyl	Phosmet
Aldrin	Deltamethrin	HCB	Phosphamidon
Ametryn	Demeton-s-methyl	HCH-A	Phosphate tri-n-butyl
Amitraz	Desethylatrazine	HCH-B	Piperonyl butoxide
Atrazine	Desisopropylatrazine	HCH-D	Pirimicarb
Azinphos ethyl	Diazinon	Heptachlor	Pirimiphos methyl
Azinphos methyl	Dichloroaniline	Heptachlor epoxide	Procymidone
Benalaxyl	Dichlorvos	Hexazinone	Profenophos
Bendiocarb	Diclofop methyl	Iprodione	Prometryn
Bifenthrin	Dicofol p,p	Isophenophos	Propagite
Bioresmethrin	Dieldrin	Lindane	Propanil
Bitertanol	Dimethoate	Malathion	Propazine
Bromacil	Dimethomorph	Metalaxyl	Propiconazole
Bromophos ethyl	Diuron breakdown product	Methamidophos	Propoxur
Cadusaphos	Endosulfan alpha	Methidathion	Prothiophos
Captan	Endosulfan beta	Methoprene	Pyrazaphos
Carbaryl	Endosulfan ether	Methoxychlor	Rotenone
Carbophenothion	Endosulfan lactone	Metolachlor	Simazine
Chlordane cis	Endosulfan sulphate	Metribuzin	Sulprofos
Chlordane trans	Endrin	Mevinphos z+e	TCEP
Chlordene	Endrin aldehyde	Molinate	TCPP
Chlordene epoxide	Ethion	Monocrotophos	Tebuconazole
Chlorfenvinphos e+z	Ethoprop	Musk ketone	Tebuthiuron
Chlorothalonil	Etrimiphos	Musk xylene	Temephos
Chlorpyrifos	Famphur	Nicotine	Terbuphos
Chlorpyrifos me	Fenamiphos	Nonachlor cis	Terbuthylazine
Chlorpyrifos oxon	Fenchlorphos	Nonachlor trans	Terbutryn
Coumaphos	Fenitrothion	Omethoate	Tetrachlorvinphos
Cyfluthrin	Fenthion ethyl	Oxadiazon	Tetradifon
Cyhalothrin	Fenthion methyl	Oxychlor	Tetramethrin
Cypermethrin	Fenvalerate	Oxydemeton methyl	Thiabendazole
DCPP	Fipronil	Oxyfluorfen	Tonalid
DDD O,P	Fluazifop butyl	Parathion ethyl	Transfluthrin
DDD P,P	Fluometuron	Parathion methyl	Triadimefon
DDE O,P	Fluvalinate	Pendimethalin	Triadimenol
DDE PP	Furalaxyl	Permethrin	Triallate
DDT O,P	Galaxolide	Phenothrin	Trifluralin
DDT P,P	Haloxyfop 2-etoet	Phorate	Vinclozalin

List of PAHs

Naphthalene	Benz[a]anthracene
Acenaphthylene	Chrysene
Acenaphthene	Benzo[b+k]fluoranthene
Fluorene	Benz[e]pyrene
Phenanthrene	Benz[a]pyrene
Anthracene	Perylene
Fluoranthene	Indeno[123cd]pyrene
Pyrene	Benzo[ghi]perylene
Dibenz[ah]anthracene	

Daly River fish and flows project: an environmental flows study

This is the first in a series of newsletters to provide information about a new research project on fish and environmental flows in the Daly River in the Northern Territory

May 2007

Australian Government Land & Water Australia
Charles Darwin University
Griffith University
CSIRO
Northern Territory Government
Wagiman – Guwardagun Rangers
TRaCK Tropical Rivers and Coastal Knowledge
Natural Heritage Trust Helping Communities Helping Australia

Why do we need to learn more about fish and their water needs in the Daly?

Australia's tropical rivers account for about 70% of the country's total runoff. With water becoming an increasingly valuable resource in southern Australia, there is growing interest in the water resources of the north, particularly for irrigated agriculture. There is also recognition that tropical river systems sustain important fisheries, and underpin a wealth of other natural and cultural assets valued by society.

The need to understand how our river systems work is particularly pressing in the Daly River catchment in the Northern Territory. Most of the Northern Territory's current irrigation activity is found in the Daly, and it is a region likely to experience further agricultural development, due to its reliable groundwater reserves and relatively good soils. The Daly River is also recognised for its high conservation values, especially the large and permanent river flows.

The ecological impacts of changes in river flows are poorly understood, especially in the wet-dry tropics. Previous environmental flow studies in the Daly River have examined the water requirements of plants growing in and alongside the river, algae and the pig-nosed turtle. However, the river also supports nearly 50 species of freshwater and estuarine fish, including some endangered and vulnerable species, but little is known about their environmental water requirements.

The Daly River Fish and Flows project aims to address this knowledge gap.

This project is a collaboration between Charles Darwin University, Griffith University, CSIRO Sustainable Ecosystems, the Northern Territory Government, the University of Washington, Wagiman people and the Guwardugan Rangers and the Wardaman Aboriginal Corporation. The project is funded by Land and Water Australia, the Natural Heritage Trust and TRaCK (Tropical Rivers and Coastal Knowledge research hub).

The broad aims of the project are to investigate variation in fish distribution and ecological requirements in the Daly River, as well as to document Indigenous knowledge and learn about the cultural significance of fish. This information will be combined to produce models relating fish ecology and flow, which can be used in water planning. The knowledge gained will also be applicable to other river systems in northern Australia and for future planning processes.

This project commenced in the dry season of 2006 and with additional funding from TRaCK it will continue until 2009.

Clayton Muggleton and Liz Sullivan fishing at Claravale.

What is an environmental flow study?

It is generally accepted by scientists and river managers, and increasingly by the general public, that the amount of water within a river and the timing of river flows (i.e. when floods occur, how long they last, whether floods are followed by drought periods etc) are both important for maintaining river health and for meeting the needs of the plants and animals that occur in rivers. Water is also important for meeting the needs of the people that live within a river's catchment (e.g. supply of water for the irrigation of crops or provision of drinking water for stock, domestic and industrial supply, tourism, and maintenance of Indigenous customary values). Unfortunately, environmental and human needs can sometimes be in conflict as the use of water for one purpose may reduce the amount of water available for others.

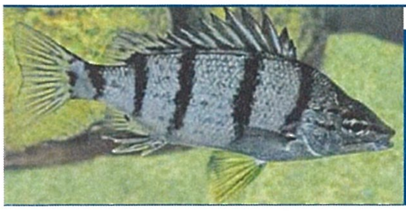
Environmental flow studies are needed when such conflicts occur or when there is a potential for conflict to arise. Their main aim is to ensure that different users of river water, including the environment, are treated fairly and that damage to the environment is kept to a minimum or to a level that is acceptable to all members of the public with an interest or stake in the catchment. As an example, if too much water was removed from a river to meet the needs of some users, then there might be too little available for irrigation or there might be too little to support healthy and abundant fish communities. In northern Australia, changes in the amount of water in a river might also adversely affect Indigenous land-owning communities.

There are many different ways to do an environmental flow study depending on the financial capacity of the funding bodies (which may determine the level of detail used or the duration of scientific investigation), the types of planned or existing water use (e.g. dry season abstraction or wet season flood harvesting), planned or existing infrastructure (e.g. dams or weirs) and the environmental asset of particular concern (e.g. fish, water birds, estuarine fisheries production etc.). However, the need for information or data to guide the process is common to all approaches.

How do we do an environmental flow study in the Daly River?

We have designed the study to make use of information that may already exist in the Daly and other nearby catchments, as well as collecting new information during field studies in the Daly River catchment. A conceptual diagram of the project design is presented in Figure 1. Existing scientific knowledge concerning fish/flow relationships is scant but studies done in nearby catchments such as the Alligator River may be used to provide some indication of how fish respond to or rely on different parts of the flow regime. Knowledge gained from traditional owner groups and other long-term residents on ecological aspects such as fish distributions and reproduction will also be gathered.

Jessie Brown holding a garfish.



Environmental flow study – Daly River

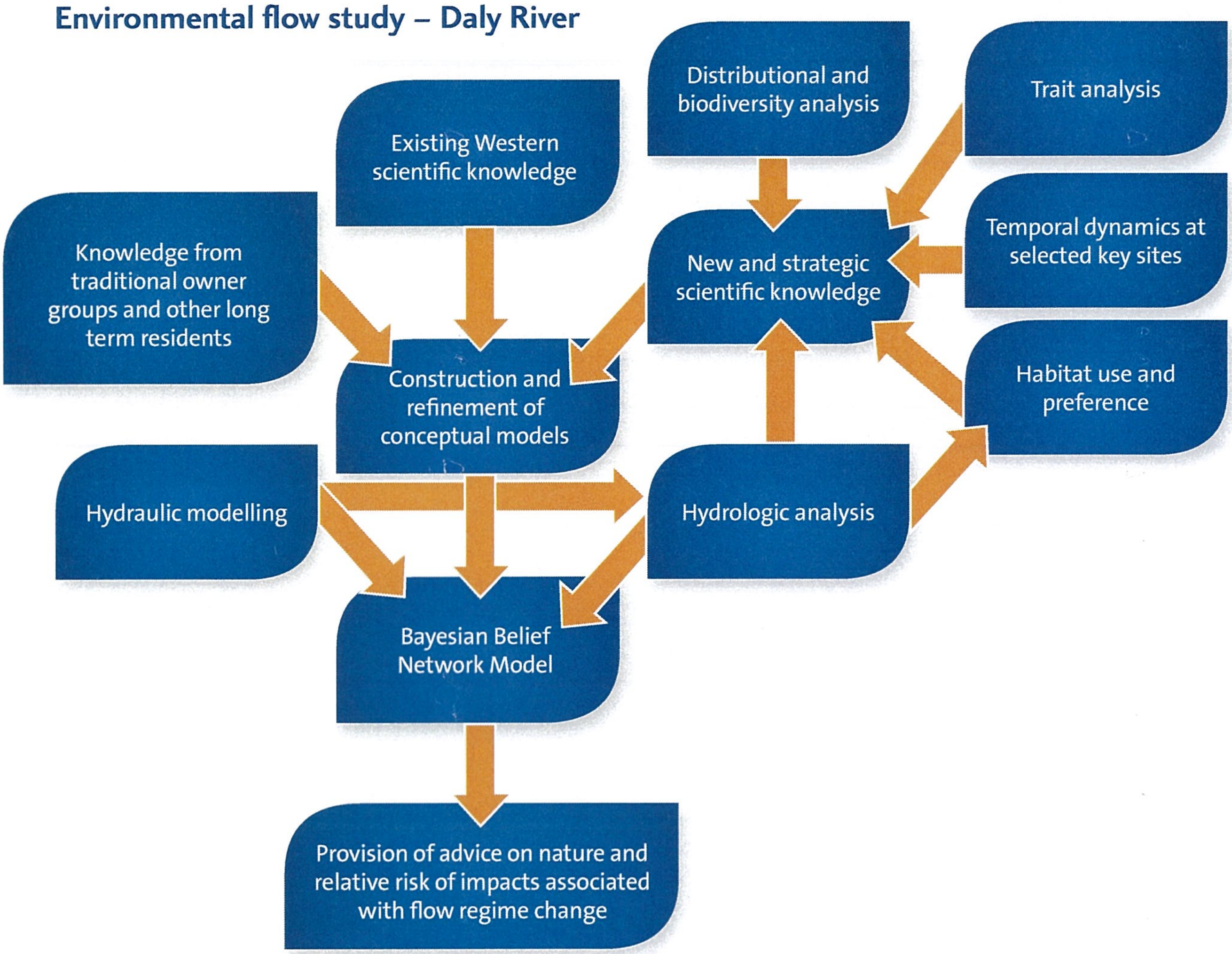


Figure 1. *Flow diagram illustrating the design of the Daly River Fish and Flows project showing how use will be made of different sets of information to predict the types and risks of impacts associated with changing the flow regime of the Daly River.*

Museum records can also be used to provide background information on the distribution of different species and this can be combined with data gathered during targeted field surveys (see Figure 2). We are monitoring seasonal (early dry season and late dry season changes) changes in fish communities and habitat at a number of locations in the catchment (see Figure 2). Data collected during these field surveys include information on fish species composition and abundance, fish lengths, fish microhabitat use, and also hydraulic habitat availability (i.e. fine scale mapping of water depth and velocity). These datasets will be used to develop predictive models of fish species distributions and relationships with habitat and flow conditions. We will also collect information on the ecological traits of different species (e.g. age structure, age and size at first breeding, fecundity, spawning habits, feeding habits, migration patterns). This information will be brought together to provide a better understanding of the mechanisms that influence seasonal changes in fish distributions and abundance.

We will hold a scientific workshop in late 2007 to capture the existing knowledge of fish in the Daly River. During the workshop, we will construct a conceptual model of how we think the fish communities and habitats respond to seasonal changes in the flow regime. This information will form the basis of a decision support system and predictive computer model (known as Bayesian Belief Network) that will allow us to evaluate the possible future impacts on fish communities if we change the natural dry season flows the Daly River.

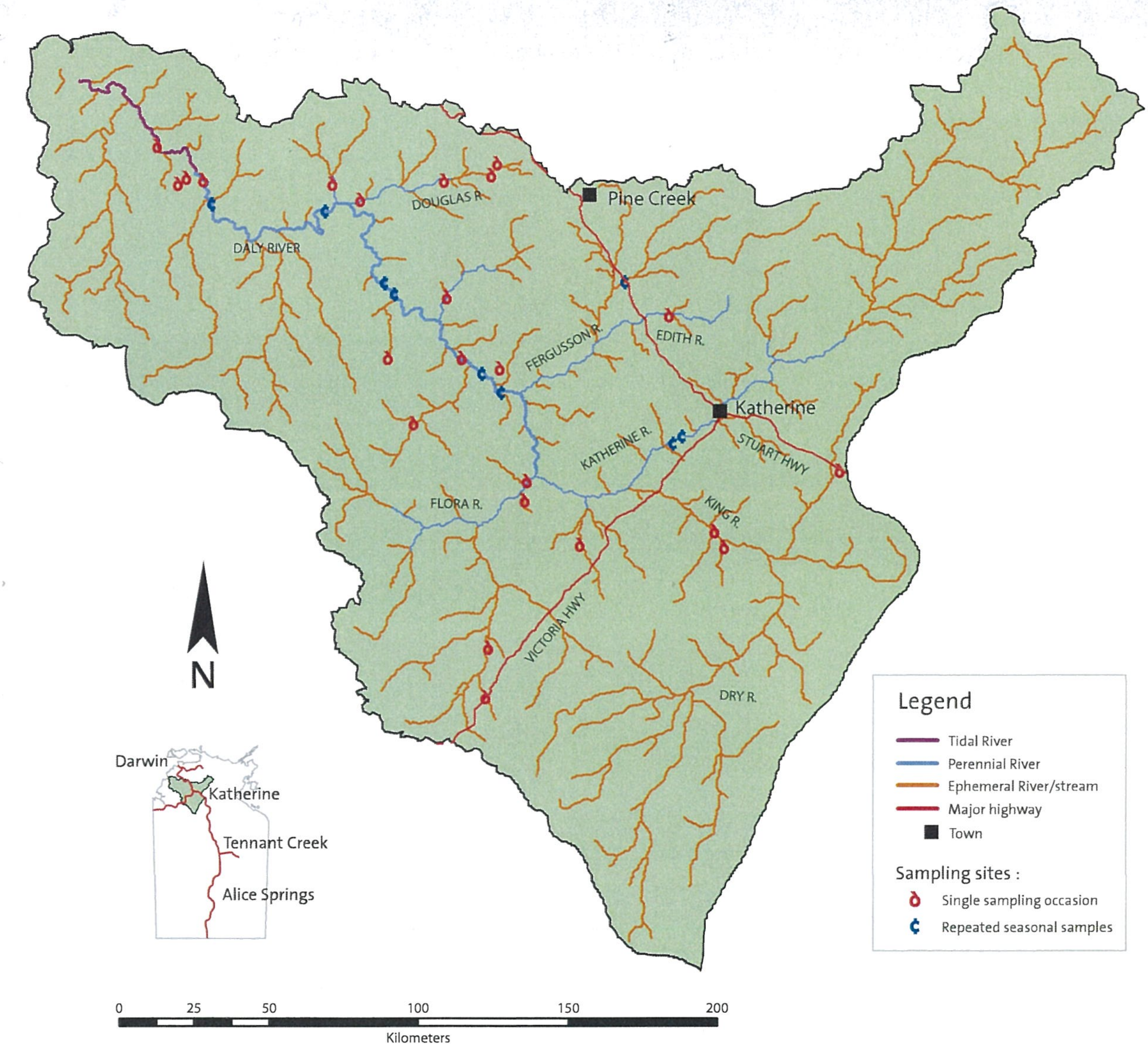
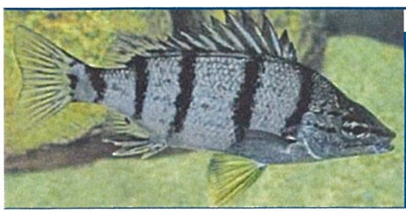


***Figure 2**. Map of the Daly River catchment showing the study sites sampled during 2006.*

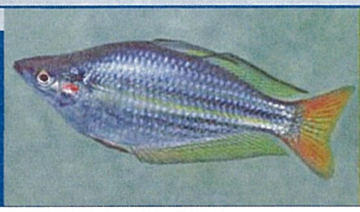


How do we sample fish communities in the river?

A large part of this project will involve sampling fish communities at different locations throughout the catchment (A list of fish species recorded from the Daly River catchment can be found in the flyer accompanying this newsletter). The main technique we use is called electrofishing. This involves passing a pulsed DC electrical current through the water. Fish within the electrical field are momentarily stunned and able to be collected in a landing net. They can then be identified, measured and returned alive to the point of capture. Electrofishing is a very useful technique as it is non-destructive, can be used to sample different types of habitats effectively, and allows application of a standardised sampling protocol.

In deeper sections of the river or in areas where we might encounter estuarine crocodiles, we use a boat mounted electrofisher (belonging to NT Fisheries) powered by a generator.

In shallow streams, we use a backpack electrofisher powered by batteries. The operators are protected by rubber gloves and waders.



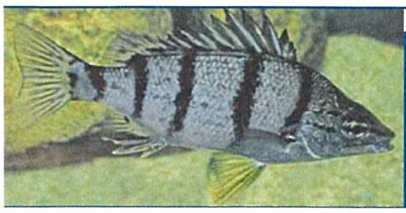
How will we engage with traditional owners in the region?

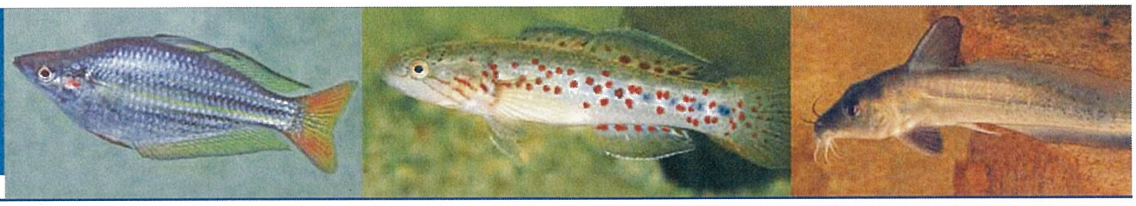
The project obtained the consent and involvement of the appropriate Aboriginal traditional owners from the relevant sections of the Daly River during preliminary meetings in 2005. A plain English story book describing the project was produced to ensure a good understanding of the research project in the Aboriginal community, and importantly, its management context.

A research agreement was negotiated with the Wagiman (Guwardugan) Rangers in early 2006. A similar agreement will be finalised with the Wardaman Association in 2007. These agreements guide the conduct of research activities, the communication of results and protection of intellectual property. The project has also received approval from Charles Darwin University's human ethics committee.

Aboriginal participation will be facilitated through regular communication and periodic face-to-face consultation with traditional owners, as well as through fish sampling activities. Time has been factored into the fish surveys for in-field explanations, demonstrations and training of Aboriginal assistants in fish sampling and recording methodologies. Two elders from Wagiman (Mona Liddy) and Wardaman (Bill Harney) language groups are members of the Project Steering Committee and contribute to oversight of the entire project.

Members of the research team with Wagiman Rangers at Chilling Hole, Daly River.





Wardaman traditional owners and members of the research team at the Flora River.

Collection of traditional ecological knowledge started with the first round of fish surveys held in 2006. The accounts given of fish, their ecological requirements and cultural significance are being recorded. Video documentation may be of use to the communities concerned and training will be provided to those interested. Other communication products may also be generated.

In the next newsletter we will report on the findings from the first round of sampling conducted during 2006.

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FACTORS CONTRIBUTING TO A FISH KILL IN THE AUSTRALIAN WET/DRY TROPICS

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(First received October 1991; accepted in revised form February 1992)

Abstract—Factors which contributed to the death of 5000 fish, comprising 18 species, and accompanying water quality changes in Donkey Camp Pool, a part of the Katherine River system in the Australian wet/dry tropics, are discussed. The water quality of the pool was modified by the first run-off of the 1987–1988 wet season. A similar run-off event 9 days later caused significant water quality changes. Colour, turbidity, iron and manganese were at least an order of magnitude greater and coliform concentrations several orders of magnitude higher than typical dry season values. Furthermore, the pool was stratified with low surface dissolved oxygen concentrations and anoxic conditions at depth. These conditions remained until the pool was completely flushed by a large run-off event 11 days later. The fish kill was primarily related to natural causes associated with low dissolved oxygen concentrations. The pool water was displaced with cool run-off from a tributary of the Katherine River which carried a substantial organic load and had a high oxygen demand. It is concluded that the low dissolved oxygen concentrations were the major cause of the fish kill with possible additional harmful effects from toxic humic compounds. The event highlights the significant impact storm run-off can have on the quality of receiving waters in the Australian wet/dry tropics.

Key words—fish kill, deoxygenation, oxygen depletion, oxygen demand, organic toxins, water pollution, tropical waters, run-off

INTRODUCTION

Fish kills in tropical regions are frequently attributed to low dissolved oxygen concentrations, however the circumstances causing these events vary considerably. Beadle (1981) and Payne (1986) attributed fish mortalities in African lakes to the upwelling of anoxic water and associated lethal concentrations of hydrogen sulphide. The deoxygenation of shallow Lake Chilwa, Malawi, and consequent death of large numbers of *Tilapia*, was caused by the resuspension of lake sediments (Morgan, 1972). In floodplain waterbodies, oxygen depletion and subsequent fish deaths have been caused by the rapid breakdown of stratified conditions by wind and inflow (Welcomme, 1979).

Fish kills in the Australian wet/dry tropics occur in billabongs (waterholes) and rivers throughout the year but are most frequent during the transition period from the dry to wet seasons (October–January). On the Magela floodplain (12° S, 133° E) fish deaths have been ascribed to biotoxic concentrations of aluminium in naturally acidic (pH 2–3) run-off into billabongs (Brown *et al.*, 1980; Morley *et al.*, 1983), and to low dissolved oxygen concentrations and a physiological inhibition to oxygen uptake (Bishop, 1980). Organic ichthyocides may also cause fish deaths in the region (Noller, 1983).

The spatial and temporal unpredictability, and remoteness, of fish kills in northern Australia, and other tropical regions, have limited their detailed investigation. In this paper a substantial fish kill in Donkey Camp Pool, Katherine River, is described and the hydrological and limnological factors associated with the event discussed.

STUDY AREA

Donkey Camp Pool (14° S, 132° E) is part of the Katherine River system (Fig. 1) and has an essentially undisturbed catchment. Maude Creek enters the Katherine River 1 km upstream of Donkey Camp Pool, and drains a catchment of 205 km^2 comprising of *Eucalyptus* woodland, with low intensity grazing by cattle and feral animals. Two seasons dominate the region, the wet (November–April) and the dry (May–October), with two transitional periods during which convective thunderstorms frequently occur. The average annual rainfall at the township of Katherine, 5 km south-west of the pool, is 972 mm, of which 83% falls in the months December–March inclusive. Temperatures are uniformly high, the mean daily maximum temperature at Katherine ranges from 30.0 °C in June to 38.0 °C in November.

Donkey Camp Pool is 6 km long, 30–40 m wide and bounded by rock bars upstream and downstream. Water is drawn 25 m upstream from the pool's outflow (near site 1, Fig. 1) to supply Katherine township with treated potable water. The river bank is 20–30 m high and features mixed vegetation dominated by *Pandanus aquaticus*,

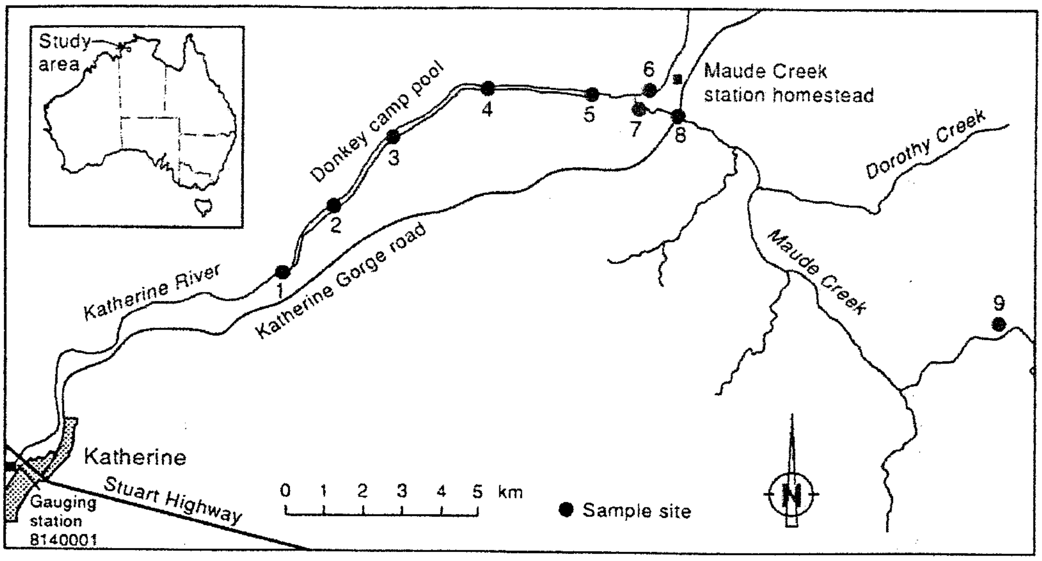

Fig. 1. Donkey Camp Pool and sample sites.

Barringtonia acutangula, *Eucalyptus camaldulensis* and *Acacia* spp. The river bed consists of gravel and pebbles with little particulate material because of the high wet season flows. The minimum and maximum mean monthly discharge at Katherine township are, respectively, 2.08 m^3/s (September) and 293 m^3/s (March). Wet season flows are characterized by high sediment loads (3–400 NTU) compared to the dry season (0.7–20 NTU). Physical and chemical features of Donkey Camp Pool, before the first run-off of the wet season, are summarized in Table 1.

MATERIALS AND METHODS

Water samples and *in situ* data were collected from Donkey Camp Pool at site 1 on 9, 17 and 18 November, and sites 1–5 on 12 November 1987 (Fig. 1). Data for Katherine River (site 6) and Maude Creek (sites 7 and 8) were collected on 12 November. An upper Maude Creek catchment site (site 9; Fig. 1) was sampled on 13 November.

Temperature, conductivity, pH and dissolved oxygen at sites 1–8 were measured with a Martek MK XV multi-parameter probe. Conductivity and pH for site 9 were measured from water samples. Secchi disc depth was determined with a standard 20 cm diameter black and white disc.

Table 1. Donkey Camp Pool water quality before the onset of the wet season

Parameter	Minimum	Maximum
Temperature (°C)	25.1	34.3
Dissolved oxygen	4.0	7.0
Conductivity (μS/cm)	23	33
pH	6.7	7.3
Turbidity (NTU)	1.4	1.7
Total suspended solids	3	7
Volatile suspended solids	2	2
Secchi disc (cm)	220	340
Total iron	0.17	0.20
Total manganese	0.02	0.02
True colour (Hazen units)	<5	10
Ammonia (as N)	<0.01	<0.01
Soluble reactive phosphorus (as P)	<0.001	0.003
Total phosphorus (as P)	0.004	0.010

All units are in mg/l unless otherwise stated (excluding pH). Based on data collected on 18/8/86, 31/8/88, 19/10/88 and 3/11/88.

Samples for chemical analyses were collected in polyethylene bottles 15 cm below the surface and analysed according to APHA (1985) for parameters listed in Table 2. Samples for total and faecal coliform counts were collected in sterile glass bottles and processed within 24 h of collection. Total (unfiltered) concentrations were determined for all metals. Samples for chlorinated hydrocarbons determination were collected in 2 l. glass bottles and analysed by gas chromatography.

Hydrographic data for station 8140001 (Fig. 1), 9 km downstream of Donkey Camp Pool outflow and turbidity at the inlet of Katherine water treatment plant were supplied by the Northern Territory Power and Water Authority. Daily rainfall was measured at Maude Creek Station homestead and Tindal Airport (Bureau of Meteorology Station 14932), 5 km south-east of Katherine (Fig. 1).

RESULTS

Observations

An estimated 5000 dead fish, ranging in length between 25 and 700 mm, were found near Donkey Camp Pool outflow on the morning of 9 November 1987. The fish were floating in the watercourse, in pools along overflow channels and lying along the northern bank of the pool. Large fish (length >100 mm) were numerically dominant. Approximately 200 dead *Macrobrachium rosenbergii* were also found. Schools of small fish (<50 mm length) swam near the surface "gulping" air. The water was coloured black and had a strong, unpleasant odour. A survey of the entire pool revealed only about 80 dead fish upstream of the pool's outflow. Water markings on the steep southern bank and on a gauge board near the pool's outflow indicated the water level had recently risen about 45 cm. The following day the vast majority (90%) of fish were removed, before a full assessment of fish species and size distribution could be undertaken. The evaluation presented here is based on the remaining fish in the overflow pools.

Table 2. Donkey Camp Pool, Katherine River and Maude Creek water quality data, November 1987

Parameter	Donkey Camp Pool, site 1	Maude Creek, site 7	Katherine River, site 6
Temperature (°C)	34.6	32.2	33.1
Dissolved oxygen	1.2	3.2	6.4
Conductivity (μS/cm)	72	86	29
pH	6.2	6.5	6.7
Turbidity (NTU)	25	18	1.6
Total suspended solids	38	7	2
Volatile suspended solids	21	6	2
Biochemical oxygen demand	5	2	1
Chemical oxygen demand	37	14	4
True colour (Hazen units)	175	100	5
Iron	4.6	2.9	0.02
Manganese	0.65	0.08	0.01
Ammonia (as N)	0.02	0.03	<0.01
Soluble reactive phosphorus (as P)	<0.001	0.006	0.003
Total phosphorus (as P)	0.013	0.025	0.009
Total coliform (cfu/100 ml)	50,000	300	15
Faecal coliform (cfu/100 ml)	18,000	50	10

All units are in mg/l unless otherwise stated (excluding pH). Sample collection dates: site 1, 18:05 h, 9/11/87; site 6, 15:20 h, 12/11/87; site 7, 15:10 h, 12/11/87.

On 10 November 1987, "black water" was observed in Maude Creek where it is crossed by the Katherine Gorge road (Fig. 1). A helicopter survey 3 days later showed Maude Creek to be the only tributary flowing into the Katherine River within 10 km of Donkey Camp Pool inflow. The Creek produced a distinct black plume at its confluence with the Katherine River.

Katherine River flow

Rainfall in the Katherine region on 31 October was recorded at Tindal Airport (65.2 mm) and at Maude Creek Station (23 mm). This storm produced the first 1987–1988 wet season run-off event recorded at gauging station 8140001 (Fig. 2). A similar run-off event recorded on 8 November originated from rainfall in the vicinity of Maude Creek Station (12 mm was recorded at the station and 1.8 mm at Tindal Airport). On both occasions flow was observed in Maude Creek at the Katherine Gorge road crossing. Nine days after the 8 November event heavy widespread rain (100.2 mm recorded at Tindal Airport on 17 November) produced significant flow in the Katherine River.

Fish mortality

A list of species and an estimate of their numbers remaining in pools on 10 November is presented in Table 3. Eighteen dead fish species were recorded at Donkey Camp Pool. The kill was dominated both numerically and in terms of biomass by several large species (*Arius graeffei*, *Lates calcarifer* and *Nematalosa erebi*). Five living species were netted from Donkey Camp Pool on 12 November. These were *Ambassis macleayi*, *Amniataba percoides*, *Megalops cyrinoides*, *Melanotaenia splendida australis* and *Nematalosa erebi*.

Water quality

The first flush (31 October) increased turbidity at the inlet to the Katherine water treatment plant from 1.2 to 41 NTU with the result that Katherine residents reported increased colour, and unpleasant tastes and odours in their reticulated water (Mr R. Polley, Power and Water Authority, Katherine, personal communication). On 3 November, four dead fish were observed at the inflow of the pool, furthermore the water was coloured "black" and obscured a current meter at 20 cm depth (Mr R. Grenfell, Power and Water Authority, Katherine, personal communication).

Donkey Camp Pool water quality and profile data collected on 9 November, 1 day after the second run-off event, are presented in Tables 2 and 4. The pool was stratified with low surface dissolved oxygen concentrations (< 1.2 mg/l) and anoxic conditions below 1.0 m. Surface conductivity was 72 μS/cm and increased to 96 μS/cm at 2.5 m depth. This contrasts with the uniform physical and chemical profiles typical of the dry season. Light penetration, as measured by Secchi disc depth (25 cm), was low due to high colour (175 Hazen units) and turbidity (25 NTU). The pool had faecal coliform concentrations similar to those typical of primary treated sewage. The biochemical oxygen demand (BOD) was 5 mg/l and the chemical oxygen demand (COD) 37 mg/l. Aluminium, arsenic, copper, lead and zinc concentrations were 0.035, 0.001, 0.05, <0.001 and <0.02 mg/l, respectively. Chlorinated hydrocarbons were below the detection limit of 0.01 μg/l.

Data collected at sites 1–5 on 12 November were similar to the 9 November data, excluding bacteriological parameters. Total and faecal coliform concentrations had decreased by more than 99% to 100–300 and 50–100 cfu/100 ml, respectively.

Data for site 6, which is upstream of the confluence of the Katherine River and Maude Creek, and site 7, Maude Creek, are presented in Table 2. The water quality of Donkey Camp Pool was similar to that of Maude Creek but distinctly different to that of the Katherine River sample site. For example, the surface

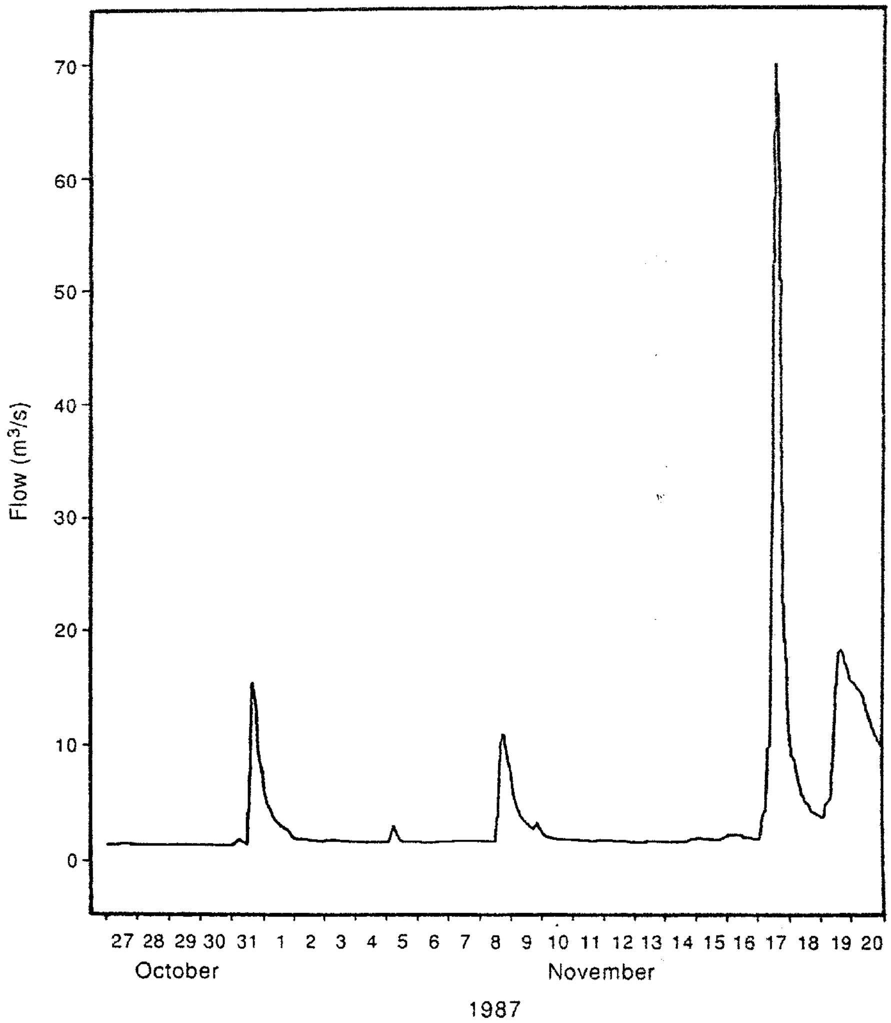

Fig. 2. Katherine River flow at gauging station 8140001.

conductivity of Donkey Camp Pool was 72 μS/cm, similar to that of Maude Creek (86 μS/cm), whilst conductivity of the Katherine River was 29 μS/cm. Iron, manganese, colour and turbidity were at least an order of magnitude higher in Maude Creek and Donkey Camp Pool when compared to Katherine River water quality, which is typical of dry season water quality data.

Table 3. Fish mortalities in isolated pools

Fish species	Number
Ambassis agrammus	10–50
Ambassis macleayi	< 10
Amniataba percoides	< 10
Arius graeffei	> 100
Arius leptaspis	10–50
Glossamia aprion	< 10
Hephaestus fuliginosus	10–50
Lates calcarifer	10–50
Leiopotherapon unicolour	< 10
Megalops cyprinoides	< 10
Melanotaenia splendida australis	10–50
Nematalosa erebi	> 100
Neosilurus hyrtlii	< 10
Oxyeleotris herwerdenii	< 10
Quirichthys stramineus	< 10
Strongylura krefftii	< 10
Syncomistes butleri	< 10
Toxotes chatareus	< 10

Water quality data for Maude Creek sites 7 and 8 were similar. The upper reaches of Maude Creek catchment featured a number of pools formed by the first run-off of the wet season. Site 9 represents one of these. It had high turbidity (62 NTU), colour (175 Hazen units) and iron (2.5 mg/l) and a COD of 36 mg/l.

17 and 18 November data for Donkey Camp Pool were collected during high flow conditions (Fig. 2). A profile at site 1 at 14:30 h on 17 November had uniform conductivity (55 μS/cm) and pH (6.1), low

Table 4. Donkey Camp Pool profile data, site 1, 9 November 1987

Depth (m)	Temperature (°C)	Dissolved oxygen (mg/l)	pH	Conductivity (μS/cm)
0.1	34.6	1.2	6.2	72
0.2	34.4	1.0	6.2	72
0.5	33.6	0.6	6.1	73
1.0	30.1	0.0	6.0	89
2.0	30.0	0.0	5.9	94
2.5	29.8	0.0	5.9	96

dissolved oxygen concentrations (<0.7 mg/l) and temperatures between 27.6 and 27.9 °C. Profile results for 08:40 h on 18 November featured cooler waters (25.6–26.2 °C), lower conductivity (40 μS/cm) and marginally higher dissolved oxygen concentrations (1.1–1.9 mg/l). The pH was unchanged. The mean total and volatile suspended solids for samples collected on 17 November were 57 and 24 mg/l. respectively, and average turbidity was 42 NTU. The following day the mean total suspended solids concentration was 340 mg/l, of which 66 mg/l was volatile, and the mean turbidity was 102 NTU.

DISCUSSION

Sequence of events

Storm run-off on 31 October 1987, from Maude Creek catchment and other tributaries entered the Katherine River upstream of Donkey Camp Pool. Assuming run-off temperatures were similar to those measured in Donkey Camp Pool during the 17–18 November hydrographic event, that is 25–27 °C, this inflow would have been significantly cooler than Katherine River basal flow temperatures at this time of year which are approx. 33 °C. The cool, more dense inflow displaced a portion of Donkey Camp Pool with turbid water of high oxygen demand.

Run-off from Maude Creek catchment on 8 November was also at a lower temperature than the Katherine River receiving waters, and displaced water in Donkey Camp Pool. At this stage therefore, water in the pool originated mainly from Maude Creek rather than the Katherine River. This is feasible since the total combined discharge for the 31 October and 8 November events was approx. 1.5 times the volume of Donkey Camp Pool. The conditions on 8 November, with which the large fish kill was associated, remained until 17 November when the pool was flushed by a large run-off event.

Water quality

The pronounced stratification in the pool after the two run-off events was due to the limited light penetration caused by turbidity and dissolved organic material, high atmospheric temperatures, protection of the pool from wind induced mixing by the high river banks and the inflow of warm water. This stratification prevented oxygenation of the bottom waters of the pool. The conductivity gradient was caused by surface water dilution by the lower conductivity Katherine River water.

The high colour content of the pool may be attributed to Maude Creek catchment vegetation. Towns (1985) observed black coloured water in summer pools in a South Australian stream, and attributed their colour to an interaction of *Eucalyptus* litter and low oxygen concentrations. The highly coloured water in Donkey Camp Pool may have impacted on biological and chemical, as well as the physical, processes in the pool as this material can be toxic, absorb organic toxins and form metal complexes (Peterson *et al.*, 1987).

The second run-off event from Maude Creek catchment carried a substantial organic load resulting from the accumulation of organic matter during the dry season. The death of many thousands of fish further increased oxygen demand in the pool. Microbiological deoxygenation, whilst favoured by the high temperatures, may be inhibited by humic substances (Wetzel 1975), polyphenols in particular (Tremolieres, 1988). The high COD, relative to the BOD, indicates a substantial proportion of organic material could not be readily oxidized by biological processes. The high temperature of the water immediately prior to the event would have contained less dissolved oxygen to satisfy the oxygen demand than would have been available at lower temperatures. This, and the possibility of already low oxygen concentrations resulting from the 31 October event, contributed to the extremely low dissolved oxygen concentrations measured in Donkey Camp Pool after 8 November 1987.

Cattle, horse and donkey faeces in the catchment are the most likely source of faecal coliforms, as human habitation is limited to a station homestead. Faecal coliform organisms are not normally present amongst fish intestinal flora (Waite, 1984). Other coliform organisms were probably of soil origin. The die-off rate of the indicator organisms was rapid, and may have been facilitated by the elevated water temperatures which mitigate against indicator organism survival (McNeill, 1985).

Cause of fish mortalities

The death of approx. 5000 fish at the outflow to Donkey Camp Pool can be estimated to have occurred sometime during a 14 h period between the hydrograph peak at station 8140001 and the first sighting of dead fish. The number of fish and species killed is the largest recorded for a fish kill in the Katherine and Magela Creek floodplain areas. The predominance of large fish species was also observed in Magela Creek by Bishop (1980). Not all fish in Donkey Camp Pool died. It is evident some *Ambassis macleayi*, *Amniataba percoides*, *Megalops cyrinoides*, *Melanotaenia splendida australis* and *Nematalosa erebi* can survive for several days in waters with dissolved oxygen concentrations between 0.5 and 1.0 mg/l.

Oxygen concentrations were very low and are clearly the most significant contributor to fish mortality. The sensitivity of fish to low oxygen concentrations is a function of exposure time, species and life stage (Alabaster and Lloyd, 1980). Oxygen diffusion into the blood depends on the partial pressure difference between the blood and the surrounding water. In warm waters, although oxygen solubility is reduced, its partial pressure decreases only slightly due to increased molecular activity. A fish in warm waters however, compared to cold water fish, must pass more water (and expend more energy) over the gills per unit time to deliver the same volume of oxygen. Consequently, warm water fish would suffer greater exposure to any dissolved toxins because of the greater volume passing over their gills per unit time.

The possibility that organic toxins may have contributed to the fish deaths cannot be discounted. Bark and leaf compounds have been shown to be toxic to fish (Bishop *et al.*, 1982; Tremolieres 1988; Temmink *et al.*, 1989) and other aquatic organisms (Buchanan *et al.*, 1976; Peters *et al.* 1976). Bishop *et al.* (1982) reported the susceptibility of fish to *Owenia vernica* bark compounds, a plant known to occur in the Katherine region. The effect of Douglas fir needles and twigs, western hemlock needles and red alder leaves on fish and oxygen concentrations was investigated by Ponce (1974). He found the toxicity of leaf leachate was very low, and concluded that oxygen depletion would lead to fish deaths long before the leachate effect.

The high turbidity, and moderate pH, would have resulted in a large proportion or metals being adsorbed onto particulates (Hart and McKelvie, 1986), thus reducing their toxicity (Alabaster and Lloyd, 1980). Acute metal toxicity is therefore not considered a contributing factor to the fish kill. This conclusion is further supported by the observation that large fish predominated the kill, as small juvenile fish are more susceptible to metal toxicity. The low pH and high aluminium concentrations reported by Brown *et al.* (1983) and Morley *et al.* (1983) to cause several Magela floodplain fish kills did not occur in Donkey Camp Pool. Chlorinated hydrocarbons were below the level of detection and are also not considered a contributing factor to the fish kill. Nor is ammonia toxicity, because of the moderately acidic conditions and the low ammonia concentrations measured.

The most likely explanations for the concentration of dead fish near the outflow of Donkey Camp Pool are that the fish were carried by the flood wave or that they moved ahead of the anoxic water and were trapped at the outflow where the watercourse constricts to a small set of rapids. We favour the former explanation. Bishop (1980) observed a similar concentration of dead fish at the outflow of Leichhardt Billabong, but attributed this to migratory behaviour.

On the evidence presented here the fish kill at Donkey Camp Pool is primarily related to natural causes associated with low oxygen concentrations in the pool which resulted from the displacement of pool water with cooler run-off from Maude Creek catchment which carried a substantial organic load and had a high oxygen demand. Humic compound toxicity may have had additional harmful effects. The event highlights the impact storm run-off can have on the quality of receiving waters in the Australian wet/dry tropics.

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