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Freshwater catfish (*Tandanus tandanus*) habitat requirements

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Recreational Fishing Trusts

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Cover image: Habitat mapping on the Murray River, 11/09/09 and the Warrego River 12/08/2009 (Jonathon Doyle)

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Non-technical summary

Freshwater catfish (Tandanus tandanus) habitat requirements

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Objectives

- To determine the critical habitat variables required to sustain a reintroduced *T. tandanus* population
- To identify the critical habitat variables that promote breeding

Key words

T. tandanus, Murray-Darling Basin, Habitat Mapping

Summary

Freshwater catfish (*Tandanus tandanus)* were once widespread throughout the Murray-Darling Basin (MDB). While this species is still abundant in some coastal drainages of NSW and QLD, it has suffered a marked decline in the MDB. The factors behind the decline of this species are not well understood given there is little information on its specific habitat requirements. Here we surveyed 36 sites within the MDB that represented areas where catfish were present, present with evidence of breeding or disappeared (population known to be present >10 years ago). At each site, 35 habitat variables were mapped along 1km reaches. Results showed that catfish populations were most likely to be present if there is a high cover of Cobble/Gravel, Submerged Macrophytes and low Daily Flow. Breeding is more likely to occur at sites with a high abundance of Bedrock/Boulders, Riffle/Rapids, Emergent Macrophytes and low Daily Flow. Results of this study will lead to recommendations on locations that may be suitable reintroduction sites for stocking hatchery-bred fish and will also inform future habitat rehabilitation programs targeting freshwater catfish.

Introduction

Successful re-introduction programs for threatened species rely on a detailed understanding of the key habitat variables required to sustain viable populations. Without such information, considerable resources may be expended in introducing a species into an environment where it may not survive, may not remain in the vicinity of the reintroduction locations, or may survive but not reproduce. Thus its persistence is dependent upon repeated releases of captive-bred individuals and this clearly cannot be considered a successful introduction.

The freshwater catfish (*Tandanus tandanus*) was formerly widespread in inland and coastal eastern Australia. It is still reasonably abundant in coastal drainages but has declined markedly across much of the Murray-Darling Basin (MDB). As a result of this decline, the species is listed as an endangered population in the MDB (NSW Government Gazette no. 103), is protected under the *Fisheries Management Act 2007* in South Australia and is listed as threatened in Victoria under the *Flora and Fauna Guarantee Act 1988* in Victoria. The only inland waterways that still support substantial freshwater catfish populations are limited parts of the slopes, upland or highland reaches of the Macquarie, Namoi, Gwydir and Border Rivers in north-eastern region of the Murray-Darling Basin. Importantly, they are believed to be locally extinct over a large proportion of their range.

A range of habitat rehabilitation actions have occurred in many areas of the MDB in recent years, including the construction of numerous fishways, re-snagging of river reaches and provision of environmental flows. Despite these measures, natural recovery of freshwater catfish is unlikely in many areas given that the species is locally extinct over broad areas. Because they are not highly migratory, natural recolonisation is unlikely. In these regions, a conservation stocking program is considered a key approach for recovering populations of freshwater catfish. However, to maximise the success of the stocking program, it is necessary to identify appropriate release locations to ensure that released fish not only survive, but also reproduce and become a self-sustaining population. Catfish are thought to prefer slow-moving or still waters and are found in greater abundance in lakes and backwaters (Lake 1971). In Victoria, several self-sustaining freshwater catfish populations are found in shallow lakes with high coverage of macrophyte beds (Clunie and Koehn 2001). In south-east Queensland, freshwater catfish populations tend to occur in streams with a sand, gravel or cobble substrate, a low to moderate riparian cover and low macrophyte cover (Pusey *et al.* 2004). Catfish have a relatively high minimum spawning temperature threshold relative to other native fishes in the MDB. Thermal pollution may partly explain their disappearance from some rivers in the MDB subject to cold-water releases from large impoundments (Pollard *et al.* 1996; Pusey *et al.* 2004 and references therin). Peak releases from impoundments typically occur during the spring months, coinciding with the peak catfish spawning season where water temperatures of around 24^{o}C are required to trigger nest building.

From these qualitative descriptions, it can be deduced that ideal release sites for freshwater catfish would be a lake or backwater not exposed to cold-water pollution and with moderate to extensive cover of macrophytes. However, quantitative habitat assessment would enable identification of the driving habitat variables that may have been overlooked in previous studies, but are critical to promote a self-sustaining population. Furthermore, quantitative methods may also identify multiple habitat features that act synergistically to have a beneficial effect. Therefore, a quantitative approach is preferred for identifying the best possible sites for reintroduction of freshwater catfish, and specific habitat enhancements can be made where necessary to maximise the successful establishment of the reintroduced population.

Anthropogenic disturbances may force threatened species into suboptimal habitat, which could potentially affect the results of any projects that seek to determine the key habitat requirements (Wang & Li 2008). Fortunately, there are still healthy remnant populations encompassing a portion of the species' former range. Therefore, quantitative methods that examine multiple habitat features to determine the species' habitat preferences are well suited for catfish. Habitat use has previously been quantified for freshwater catfish in the Wet Tropics (north-east Queensland) and south-eastern Queensland (Pusey, Kennard et al. 2004). These tropical and sub-tropical coastal rivers have vastly different geomorphology and flow regimes to rivers within the Murray-Darling Basin. The catfish in north-east Queensland have recently been recognised as a new species, *T. tropicanus (Welsh et al. 2017)* and therefore they may have acquired unique habitat requirements. Previous studies that have quantified *T. tandanus* habitat use in the MDB are confined to one river system (Balcombe *et al.* 2006; Boys *et al.*) or a single lagoon (Koster *et al.* 2015). Therefore, these studies provide limited data to inform potential stocking programs for *T. tandanus*.

We investigated the critical habitat variables required to a) sustain a reintroduced *T. tandanus* population and b) promote breeding. Thirty-six sites were selected from throughout the MDB that fell into one of three categories; i) *T. tandanus* population currently present but with no evidence of recent recruitment (present - P), ii) *T. tandanus* population currently present with evidence of recent recruitment (breeding – B), and iii) *T. tandanus* known to be formerly present but not reported for over 10 years (disappeared – D). Thirty-five habitat variables were mapped in each site and the data were analysed using logistic regression models. We assessed the results based on; computational efficiency, success of discrimination between categories, and; consistency of predictions by the habitat variables. We present a range of the best models and interpret the habitat variables most likely to be related to catfish presence/absence or breeding/non-breeding. Results of this study will allow the most suitable re-introduction sites to be identified and may also be used to guide rehabilitation of sub-optimal habitat where adult catfish populations persist, but where recruitment no longer occurs.

Methods

Site selection

The majority of the fish assemblage data collected by the NSW state government fisheries agency since 1994 has been collated in the NSW Aquatic Ecosystems Research Database (AERD). The AERD contains data collected from over 4,000 sites across NSW using a wide variety of fish sampling methods, but primarily electrofishing (NSW Department of Primary Industries – Fisheries, unpublished). We queried the AERD for data collected between 1 January 2000 and 30 June 2010 to identify sites where *T. tandanus* had been collected. These sites were categorised as either ‘breeding’ (B) or ‘present but not breeding’ (P). Breeding sites were those that showed evidence of recruitment based on the presence of young-of-year fish (YOY), identified as individuals less than 83 mm in total length (Davis 1977). We used museum records and pre - 2000 data to identified sites that formerly supported *T. tandanus* but where none had been collected since 2000. These sites were categorised as ‘disappeared (D). Twelve sites from each category (B, P and D) were selected for analysis and then mapped for 35 habitat variables (Fig. 1 Table 1, Table 2). However, following completion of the habitat mapping, larval *T. tandanus* were collected in one of the sites that was designated as “disappeared”. Consequently, instead of having 12 reaches in each of the three categories, we had 13 reaches where they were “breeding” 11 reaches where they had “disappeared” and 12 reaches where they are “present” but not breeding (Table 1).

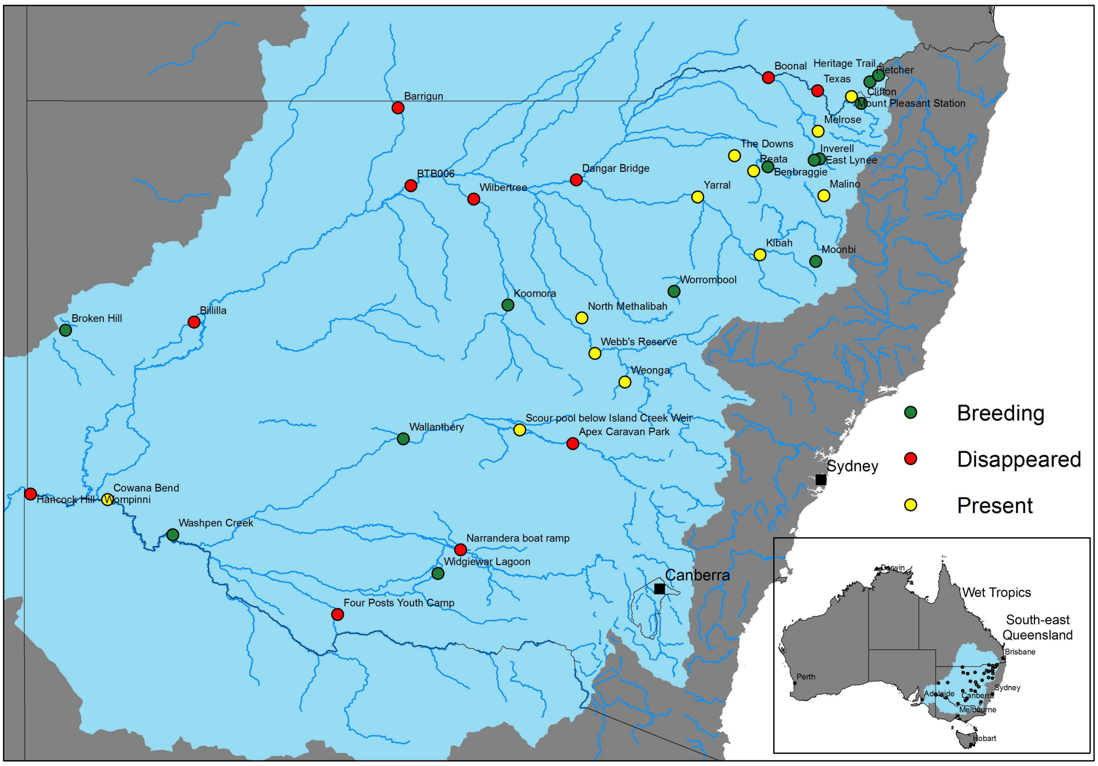


Figure 1. Location of each mapped site within the breeding (green dots), disappeared (red dots) and present categories (yellow dots).

Table 1. Sites where habitat mapping was conducted for three categories of catfish populations; Breeding (if individuals <83mm in total length present (Davis 1977), Present (not breeding) and Disappeared.

Category	Waterbody name	Latitude	Longitude
Breeding	Gwydir River	-29.8434416	150.524238
Breeding	Cockburn River	-31.0606299	151.138695
Breeding	Tenterfield Creek	-29.0311789	151.724585
Breeding	Imperial Lake	-31.9463019	141.495296
Breeding	Severn River	-28.7517881	151.835698
Breeding	Lachlan River	-33.3424	145.83774
Breeding	Castlereagh River	-31.44841	149.31784
Breeding	Quart Pot Creek	-28.66726	151.94753
Breeding	Swan Brook	-29.74331	151.18874
Breeding	Washpen Creek	-34.576	142.874
Breeding	Macintyre River	-29.761	151.12
Breeding	Widgiewar Lagoon	-35.073	146.283
Present	Little River	-32.6118589	148.687274
Present	Horton River	-29.8976395	150.342767
Present	Namoi River	-30.9761866	150.424288
Present	Namoi River	-30.2330136	149.622804
Present	Murray River	-34.1244119	142.03566
Present	Island Creek	-33.22642	147.3326
Present	Macquarie River	-32.24511	148.29984
Present	Ewenmar Creek	-31.78962	148.13155
Present	Georges Creek	-30.21713	151.2429
Present	Tycannah Creek	-29.70192	150.09497
Present	Tenterfield Creek	-28.9417	151.59901
Present	Severn River	-29.38995	151.17115
Breeding*	Bogan River	-31.6243722	147.18046
Disappeared	Darling River	-31.8425357	143.145273
Disappeared	Edward River	-35.6015976	144.993197

Disappeared	Bogan River	-30.2617278	146.7413
Disappeared	Murray River	-34.0516787	141.044424
Disappeared	Darling River	-30.0873	145.93537
Disappeared	Murrumbidgee River	-34.7699558	146.573957
Disappeared	Barwon River	-30.0146298	148.059377
Disappeared	Warrego River	-29.0891099	145.770986
Disappeared	Dumaresq River	-28.867556	151.163149
Disappeared	Macintyre River	-28.7003165	150.530502
Disappeared	Lachlan River	-33.40318	148.0167

*This site was originally classified as "Disappeared" but 3 larval *T. tandanus* were subsequently reported in January 2008 after the habitat mapping was complete (NSW DPI, unpublished data). This site was therefore included in the "Breeding" group for data analysis.

Quantification of habitat variables

Aquatic and riparian habitat features were mapped for 1 km reaches for each of the 36 sites between August and September 2009 (Table 2). Substratum, mesohabitat, physical cover, macrophyte species, macrophyte beds, willows (*Salix* spp.), eroded and undercut banks and depth were mapped in the field using hand-held PDA units (Dell Axim X51U and MIO Digi-walker pocket PC) with ESRI Arcpad 6.0.3 data acquisition software. Each PDA was linked to a Garmin 72 GPS unit via a bluetooth device (i.Trek Bluetooth Battery Adapter) to record positional data. Each PDAs loaded with the 1: 50,000 topographical map (GDA 94_MGA Zone 55) for that region as a background layer at a screen resolution of 1:2,000. Two technicians were each equipped with the mapping unit, and working in pairs, mapped all the habitat features within the bank-full river channel. Shallow and narrow reaches were mapped on foot. Deeper reaches were mapped from a canoe or kayak. Spatial data were recorded in either of two formats, position dependent or position independent, depending on the habitat feature being recorded. All data were uploaded into a GIS for processing (ArcGIS 9.3.1, ESRI Inc.).

Substratum was mapped as the position of a transition from one type to another and defined as a position-dependent feature. Substratum transitions were mapped at the point considered to be the base-flow waterline, regardless of ambient flows on the day of mapping. Substratum categories were based on the classification of Platts *et al.* presented in Hamilton and Bergersen (1984): bedrock, boulders (> 512 mm), cobble (64 – 512 mm), gravel (2 – 64 mm), sand (62 µm – 3 mm), mud (< 62 µm and dispersible), clay (< 62 µm and pliable) or detritus (organic material). In instances where a mid-stream bed of a particular substratum occurred within a matrix of another substratum type, but did not reach the bank (i.e. a cobble bed in the centre of an otherwise sandy stream bed), the substratum that occupied the greatest proportion of that half of the stream bed was mapped. Meso-habitat transitions were also mapped as position-dependent features as for substratum, but at the current waterline. Meso-habitat categories were: pool (still or very slowly flowing water), run (flowing water with little or no surface turbulence), riffle (flowing water with a turbulent surface), rapid (very turbulent with the presence of one or more abrupt drops in surface water level) and dry (no surface water). Each time a pool was recorded, its maximum depth was recorded as a position dependent feature to 0.1 m accuracy. To calculate the area of each substratum or meso-habitat type, the river channel boundary was manually digitised within a desktop GIS using Spot 5 imagery as a template at a resolution of 1:3,000 to create a polygon representing the total area of the river channel. In cases where overhanging riparian vegetation obscured the underlying stream bank, the stream bank was recorded as the centre line of the row of riparian trees and/or the substratum transition points or locations of willows that had been recorded in the field. The resulting polygon was then manually split along its centreline in GIS. These half-channel polygons were then cut (from bank to centre-line) at each substratum or meso-habitat transition point and the resulting polygon fragments coded by substratum and meso-habitat type.

The start and end points of undercut and eroded banks were recorded as position-dependent features. Undercut banks were classed as those that overhang the water by at least 30 cm at a point where the water is at least 30 cm deep. The bottom of the overhang must be no more than 10 cm above the water surface. Actively eroding banks were defined as areas of stream bank where removal of material by surface wash, undercutting or slope failure was evident and unchecked by plant growth or showing signs of stabilising. These features were digitised by drawing a polyline connecting the start and end point of each feature along the outline of the channel polygon.

The position of individual woody habitats (snags), rocky habitats, macrophyte beds and willows were mapped as position-independent features. Woody and rocky habitats were further characterised as large or small, and simple or complex. The size of woody habitats was distinguished by having a maximum length of 2 m for small, or > 2 m for large. Simple structures were those with a single branch or trunk, whereas those with multiple branches, trunks with branches, trunks with hollows or root masses were classified as complex. An additional category of woody habitats; snag piles, was identified as dense accumulations of snags where the number of individual items contained within the pile could not be determined. The location of each woody habitat item was recorded as the position of the middle of the snag. Any individual item of simple woody habitat with a maximum dimension of < 1 m in length was not recorded.

Rocky habitat was considered to be any rocks classified as a boulder (or number of boulders > 512 mm diameter) that existed within an area of another substratum type (i.e. a single boulder surrounded by sandy or muddy substratum). Small rocks were those < 1,000 mm diameter and large were > 1,000 mm diameter. Simple rocky habitat consisted of isolated single rocks or rocks spaced widely amongst the dominant substratum. Complex rocky habitat consisted of closely spaced aggregations or piles of rocks.

The size, shape and area of macrophyte beds were mapped by drawing the outline of the macrophyte bed as a polygon onto the screen of the PDA in the field. The identity of macrophytes was recorded to genus level using Sainty and Jacobs (2003).

The position of each willow trunk (> 10 cm diameter at breast height) was marked as a position-independent feature.

Four additional aquatic habitat metrics were derived from existing spatial data layers; area of riparian canopy within a 100 m and a 10 m riparian buffer, altitude and mean daily flow. Ten metre and 100 m buffers was generated for the stream from the digitised stream area polygon in ArcGIS. All riparian canopy cover within the buffers was manually digitised as polygons from a Spot 5 satellite image (dated late 2004 – early 2005) at 1:3,000 scale resolution. Altitude data for each 1 km reach were extrapolated from a 100 m grid-cell DEM of NSW as the altitude ASL at the downstream limit of each segment. Average daily flow for each 1 km reach was derived from a stream network model developed by Stein *et al*. (2009).

Table 2. Aquatic habitat variables mapped or otherwise derived at the 1km reach scale.

Habitat variable	Unit of measure	Mean and range of habitat variables (all reaches) (per km)
Altitude	Metres ASL	293 (110-910)
Large complex snags	Count	19 (2-98)
Large simple snags	Count	63 (0-381)
Small complex snags	Count	27 (1-103)
Small simple snags	Count	39 (2-93)
Snag Pile	Count	4 (0-15)
Large complex rocks	Count	1 (0-11)
Large simple rocks	Count	1 (0-8)
Small complex rocks	Count	2 (0-14)
Small simple rocks	Count	2 (0-33)
Willow (*Salix* spp.)	Count	22 (0-19)
Erosion (length m)	Total length in m	222 (0-887)
Undercut (length)	Total length in m	17 (0-272)
Free floating macrophytes	Area (m^2)	829 (0-13,177)
Narrow-leaved emergent macrophytes	Area (m^2)	2,060 (0-14,608)
Non-feathery submerged macrophytes	Area (m^2)	1,462 (0-7,625)
Broad-leaved emergent macrophytes	Area (m^2)	32 (0-582)
Floating attached macrophytes	Area (m^2)	275 (0-9,648)
Submerged & emergent feathery macrophytes	Area (m^2)	193 (0-1,620)
Riparian canopy within 100m of the stream bank	Area (ha)	8 (1-15)
Riparian canopy within 10m of the stream bank	Area (ha)	1 (0-2)
Maximum depth	Metres	2 (0-6)
Average Daily flow	ML per day	2,611 (1-24,451)

Pool (still or very slowly flowing water)	Area (ha)	1 (0-5)
Rapid (very turbulent with the presence of one or more abrupt drops in water level)	Area (ha)	0 (0-0)
Riffle (flowing water with a turbulent surface)	Area (ha)	0 (0-1)
Run (flowing water with little or no turbulence)	Area (ha)	2 (0-15)
Bedrock	Area (ha)	0 (0-2)
Boulder (> 512 mm)	Area (ha)	0 (0-0)
Clay (< 62 µm and pliable)	Area (ha)	0 (0-1)
Cobble (64 – 512mm)	Area (ha)	0 (0-1)
Detritus (organic material)	Area (ha)	0 (0-1)
Gravel (2 – 64mm)	Area (ha)	1 (0-4)
Mud (< 62 µm and dispersable)	Area (ha)	2 (0-10)
Sand (62 µm – 3mm)	Area (ha)	0 (0-7)

Data analysis

Reducing the number of variables and variable transformation

Given that 35 variables were recorded, it was important to identify redundancy and reduce the number of variables used in the analysis. This included (1) combining or omission of correlated variables which reduced collinearity, reduced the number of zeroes or increased the range or sensitivity of the response; (2) pre-processing elimination of invariant or over-dispersed data (filtering), and; (3) identification of ineffective variables during processing (wrapping). Area of non-feathery submerged and submerged & emergent feathery macrophytes were merged as a ‘Submerged Macrophytes’ variable. Area of broad-leaved emergent and narrow-leaved emergent were merged as an ‘Emergent Macrophytes’ variable. Area of rapid and riffle mesohabitats were merged as a ‘riffle-rapid’ variable. Area of bedrock and boulder substratum were merged as a ‘bedrock-boulder’variable and cobble and gravel were merged as a ‘cobble-gravel’ variable. Small simple and small complex snags were combined as “Small snags”. Large simple snags, large complex snags and snag piles were combined as “Large snags”. Complex and simple rocks were combined as “Rocks”.

The distribution of each variable was initially investigated by looking at the normalised scores within each catfish category. Variables with more than 50% zero values in all three categories (*T. tandanus* absent/present/or breeding) were removed from the data set because they lacked discriminatory ability. Variables that were apparently normally distributed within each category were entered to the models in their raw format. Variables that occurred enough times to be included but still had 50% or more zeroes in one or more categories converted to presence/absence. The remaining variables were square root or $\log_e$ transformed where appropriate to normalise their distribution and this resulted in 19 potential variables for discriminating between the three catfish categories (Table 3).

Table 3. Habitat variables included in analyses to discriminate between catfish absence/presence/breeding, (1,0) indicates conversion to presence/absence.

Variable	Transformation used
Altitude	$\sqrt{Y}$
Willow	$Log_e(Y+1)$
Erosion (length m)	$Log_e(Y+1)$
Undercut (length)	$Log_e(Y+1)$
Floating macrophytes	$Log_e(Y+1)$
Emergent macrophytes	$\sqrt{(Y+0.5)}$
Submerged macrophytes	$Log_e(Y+1)$
100m Riparian Veg cover (ha)	Y
Maximum depth (m)	Y
Average Daily flow	$\sqrt[4]{Y}$
Pool (ha)	$Log_e(Y+1)$
Riffle-Rapid (ha)	$Log_e(Y+1)$
Run (ha)	$Log_e(Y+1)$
Bedrock-Boulder (ha)	(1,0)
Cobble-Gravel (ha)	(1,0)
Mud (ha)	$Log_e(Y+1)$
Rocks	$Log_e(Y+1)$
Small snags	$\sqrt{(Y+0.5)}$
Large snags	$\sqrt{(Y+0.5)}$

Selection of variables for discriminating between the three catfish categories

Comparison of sites where catfish have disappeared with those where they were breeding is not a desired objective for this study, and could cause statistical inefficiency by including variables that mask differences of interest. Therefore, separate models for comparing between presence and absence of catfish (P+B combined vs D), and between presence (breeding) and presence (non-breeding) (B vs P) offered the best flexibility and rigor in the statistical models.

We wanted to identify all the variables potentially related to catfish presence or breeding, so rather than search for a single, statistically most efficient model we used a multiple model, information theoretic approach. Using a single best model will often ignore the potential relationships with other important variables (Pacheco *et al.* 2006; Van Sickle *et al.* 2006). The best 5 subsets of each combination of 1 to 5 variables in a logistic regression were determined using the best subsets option in SAS® logistic procedure (SAS Institute Inc. 2014). That is, the best 5 single-variable models, the best 5 two-variable models, etc. For the breeding versus presence model (B vs P), the event was breeding and for the presence versus absence model (B+P vs D) the event was presence. We did not go beyond 5 predictor variables because it is a small data set, and there is an inherent risk of overfitting the data. That is, adding more variables may improve the classification rate, but would also create models that were so specific to the current data set that they would have no utility for generalisations of catfish and habitat relationships in other parts of the basin. Every model was run using a jack-knifing algorithm, where each site is dropped and the model applied to the other 35 sites to predict the event for the dropped site. The underlying philosophy was not to find a single best model, but to look for consistency between the models chosen. Consistency means that the predictor variables most likely to be related to the responses were regularly included in models and that their parameter estimates indicated the relationship was in the same direction and were also consistent in magnitude.

We thus provide three summary tables for each analyses (B Vs P and P+B Vs D);

- The 5 best subsets models that were chosen the most often
  - That is, if the best subset algorithm consistently selected the same subset of predictor variables even when different sites were dropped.
- How often each predictor variable was chosen across all best subsets models
- The Odds Ratios of the predictor variables that selected in any best subsets model that was used at least 10 times.

The odds ratio (OR) allows simple interpretation of the results in logistic regressions because it describes the direction and influence of a predictor variable on the response variable. In this case, the effect on the presence / absence or breeding / non breeding status of *T. tandanus*. a predictor variable that has no relationship would have an OR of close to 1. However an OR < 1 indicates that the variable has a negative relationship with the response whilst an OR > 1 indicates a positive relationship. Consistency in the OR for predictor variables even when fitted in different models is therefore an indicator of strong relationships with catfish presence and/or breeding. To determine this consistency we only include models that had been selected at least 10 times during the best subsets selection process as we deemed that these could not have been spurious models. Further, we felt that models needed to be used at least 10 times to estimate reasonable model accuracy (rate of predicting presence / absence or breeding / non breeding status of *T. tandanus*). We interpreted the relationship between the best predictor variables by calculating the weighted average odds ratio for each predictor variable from every model that was selected at least 10 times. We also present the ORs for the variables in the best single prediction model. We then generated prediction curves displaying the predicted presence / absence or breeding / non breeding status of *T. tandanus* in relation to the predictor variables.

Results

Results Present vs Disappeared

There were 540 potential predictive models evaluated, including 102 unique models. The top five models contained 3 to 5 predictor variables and an overall accuracy between 77 and 87 % (Table 4). Submerged Macrophytes and the presence of Cobble or Gravel were included in all five of the top predictor models (Table 4). In addition, these three predictor variables occurred in more than half the best subsets models (Table 5). Maximum Depth, Pool Area, Run Area and Willows were seldom chosen (Table 5).

The best single model (Table 4) also contains the three best predictor variables; Submerged Macrophytes, Daily Flow, Cobble and Gravel (Table 5). Catfish were more likely to be present in sites with Cobble/Gravel present and larger areas of Submerged Macrophytes and less likely to occur in areas with higher Average Daily Flow (Figure 2a). Importantly, the best model predicts that when Cobble or Gravel is present, the catfish are more likely to occur regardless of flow or macrophytes (Figure 2a and b). However, when Cobble or Gravel are absent, then low flows and larger macrophyte areas become very important for catfish (Figure 2a and b). For example, if there is no macrophyte cover at all, six in ten sites that have cobble or gravel present will have catfish (Figure 2b), but as macrophyte cover increases, so the probability of catfish being present also increases.

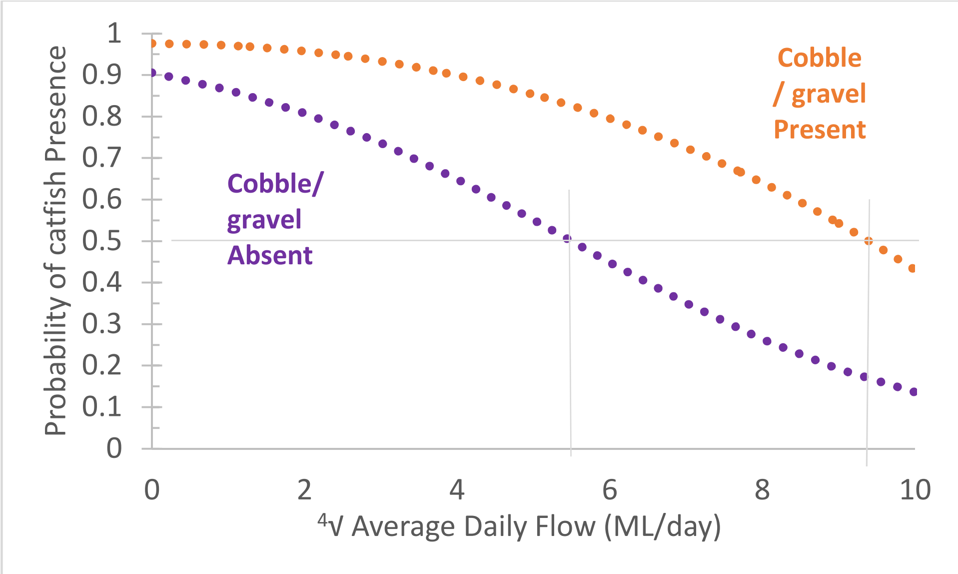
Table 4. The five most chosen Best subsets logistic models for predicting presence or disappearance of catfish in MDB, etc.

Variables in model	Number of times the model was selected (possible max = 36)	Correct prediction of Presence	Presences missed	Correct prediction of Absence	Absences missed	Overall Accuracy (%)
Submerged macrophytes Daily Flow Cobble/Gravel present	35	22	3	7	3	0.83
Submerged macrophytes Daily Flow Bedrock/Boulder present Cobble/Gravel present	32	19	3	7	3	0.81
Erosion length Submerged macrophytes Riparian cover Cobble/Gravel present Bedrock/Boulder present	31	18	4	6	3	0.77
Submerged macrophytes Daily Flow Cobble/Gravel present Complex and Simple Rock	31	19	4	5	3	0.77
Erosion length Submerged macrophytes Cobble/Gravel present	30	20	2	6	2	0.87

Table 5. Number of unique models determining catfish presence or disappearance each predictor variable was chosen in (N = 102). Bolded predictor variables are used in subsequent best single model calculations.

Predictor Variable	Number of unique models	% of unique models
Cobble/gravel presence	**68**	**67**
Submerged Macrophytes	**63**	**62**
Daily Flow	**54**	**53**
Erosion Length	45	44
Undercut Length	29	28
Floating Macrophytes	20	20
Emergent Macrophytes	20	20
Complex + Simple rock	18	18
Riparian Veg cover	17	17
Large Complex + Simple snags +snag pile	16	16
Altitude	14	14
Small Complex + Simple snags	12	12
Bedrock/boulder presence	11	11
Riffle/Rapid	10	10
Mud area	10	10
Maximum Depth	9	9
Pool area	9	9
Run area	6	6
Willows	2	2

a)



b)

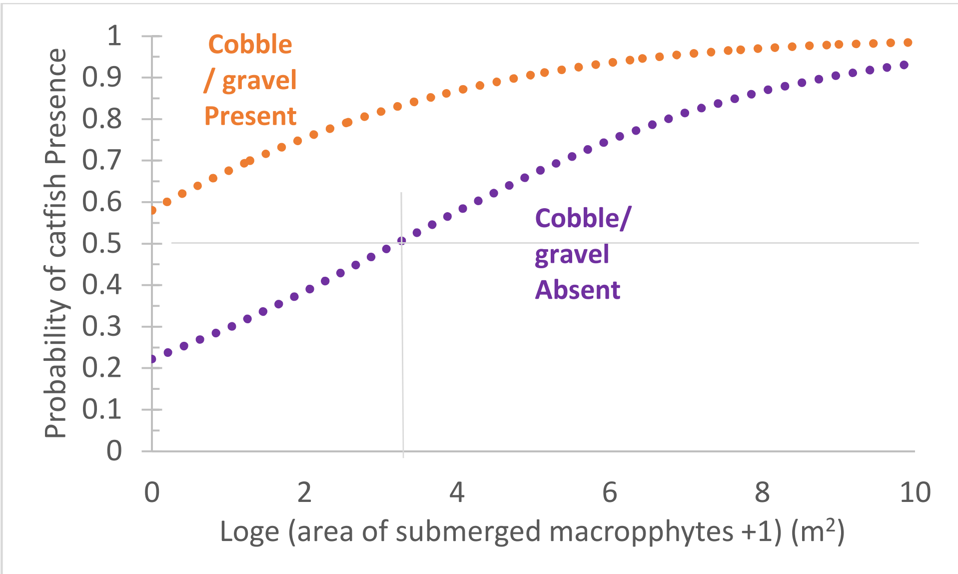


Figure 2. Relationship between the best environmental predictors (a) daily flow and (b) area of submerged macrophytes and the presence (n=25) and absence (n = 11) of catfish in 36 MDB sites. Dotted lines indicate the predicted relationship with the prediction variable and the vertical cross hair line indicates the value on the x axes where catfish are predicted as more likely to occurr than not (Prob occur > 0.50), i.e. values above 0.5 means catfish are more likely to be present than not. In Figure 2a), the prediction curves are made at the mean value formacrophyte area, and for mean Daily Flow in figure 2b.

The odds ratios of the three best predictor variables, whether looking at the single best model, or the weighted average across all good models (Table 6) confirm direction and strength of the curves in Figure 4. That is, the presence of Cobble/Gravel, has a large positive relationship with catfish presence, Flow has a negative relationship and area of Submerged Macrophytes a positive relationship.

Table 6. Odds ratios of commonly chosen predictor variables for modelling probability of occurrence or disappearance of catfish in MDB, etc.

Effect	Odds Ratio in single Best Model	% of models used in (N=383)	Mean lower confidence limit in 16 best models	Mean Odds Ratio in 16 best models	Mean upper confidence limit in 16 best models	Interpretation
Cobble/gravel presence	4.89	89	1.21	232.1	>999.9	Catfish considerably more likely to occur when Cobbles/Gravel is present
Submerged Macrophytes	1.48	86	0.97	1.86	4.275	Catfish more likely to occur when submerged macrophyte beds are larger
Daily Flow	0.66	44	0.421	0.66	1.034	Catfish more likely to occur when Daily Flow is low

Results Breeding Vs Non-breeding

As there are fewer sites in the models (the 11 sites where catfish had disappeared are not in this analysis), and catfish breeding, even when it occurs, may not be perfectly detected, the results were not expected to be as definitive as the presence analyses. There were 375 models trialled as having potential to differentiate between catfish breeding and non-breeding sites. Prediction of whether or not catfish were breeding when they were present was not as accurate as the occurrence models, with overall accuracy of the best four models between 67% and 82%. The presence of Bedrock or Boulders was chosen in the four best models, with the other variables being mixed combinations of Run Area, Riffle and Rapid Area, area of Mud, and Macrophyte variables (Table 7).

There were 277 unique models required to fit the breeding prediction models, compared to only 102 for the presence analyses. Furthermore, no single variables were selected in more than 30% of models. Interestingly, Mud Area was only selected in 9% of models (Table 8), even though it was chosen in one model 19 times (Table 7). Bedrock/Boulder presence, Daily Flow, Riffle/Rapid, Cobble/Gravel presence and Emergent Macrophytes were selected in 20% or more of models (Table 8) and all of these except Cobble/Gravel presence were in the model with the best classification rate (Table 7) and are subsequently used in the best single model graphs (Figure 3).

Table 7. The four most chosen Best subsets logistic models for prediction of evidence of breeding of catfish when present in MDB, etc.

Variables in model	Number of times the model was selected (possible max = 25)	Correct prediction of Presence	Presences missed	Correct prediction of Absence	Absences missed	Overall Accuracy (%)
Daily Flow **Bedrock/Boulder present** **Mud area**	19	9	2	5	3	0.74
Floating macrophytes **Pool size** **Run area** **Bedrock/Boulder present** **Cobble/Gravel present**	18	8	4	4	2	0.67
Erosion length **Riffle/Rapid** **Bedrock/Boulder present**	18	7	4	6	1	0.72
Emergent macrophytes **Daily Flow** **Riffle/Rapid** **Bedrock/Boulder present**	17	8	2	6	1	0.82

Table 8. Number of unique models for differentiating between catfish breeding and non-breeding sites each predictor variable was chosen in (N = 278). Italicised predictor variables are used in subsequent best single model calculations.

Predictor Variable	Number of unique models	% of unique models
Bedrock/boulder presence	***81***	***29***
Daily Flow	***73***	***26***
Riffle/Rapid	***72***	***26***
Cobble/gravel presence	61	22
Emergent Macrophytes	***56***	***20***
Altitude	40	14
Maximum Depth	40	14
Floating Macrophytes	38	14
Erosion Length	36	13
Run area	35	13
Pool area	27	10
Mud area	26	9
Submerged Macrophytes	24	9
Large Complex + Simple snags +snag pile	24	9
Undercut Length	17	6
Riparian Veg cover	17	6
Complex + Simple rock	16	6
Willows	11	4
Small Complex + Simple snags	4	1

Catfish sites with boulders or bedrock present were more likely to have breeding detected particularly when combined with more than 20 m^2 of emergent vegetation (Figure 3a), flows of <5ML/d (Figure 3 b) or <0.2 m^2 of riffles or rapids. However, the importance of boulders or bedrock was severely diminished if there were no emergent macrophytes, if average daily flow was high or there was a large area of riffle or rapids present (Figure 3a, b and c). If there was no boulder or bedrock present, then catfish were still predicted to breed if there were very large areas of emergent macrophytes in the site (Figure 3a).

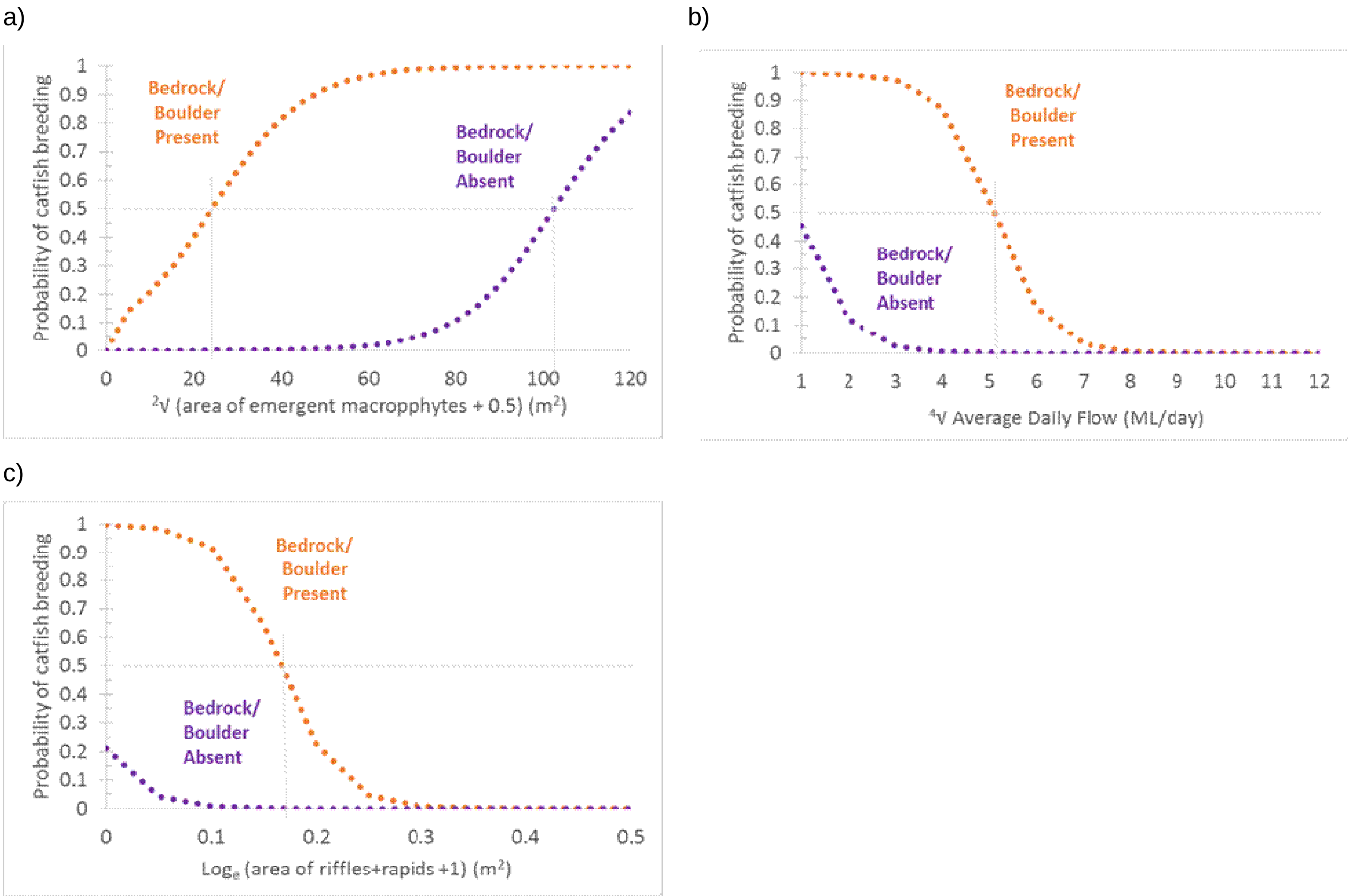


Figure 3. Relationship between the best environmental predictors (a) area of Emergent Macrophytes, (b) Average Daily Flow and (c) Area of Riffles and Rapids and the presence (n=14) and absence (n = 11) of breeding of catfish in 25 MDB sites. Dotted lines indicate the predicted relationship with the prediction variable and the vertical cross hair line indicates the value on the x axes where catfish are predicted as more likely to breed than not (Prob occur > 0.50), i.e. values above 0.5 means catfish are more likely to be present than not. In Fig. 3a, the prediction curves are made at the mean values for Daily Flow and Area of Riffles or Run, and vice versa.

There were only eight models that were selected to run 10 or more times, and these models ran 114 times in total. There were several extremely high or low Odds Ratio estimates from some models that indicate that the models did not always fit well (Table 9), this is a consequence of using such a small data set. Nevertheless, the results are in agreement with Figure 3, as the Odds Ratio for the presence/absence of Boulder or Bedrock is very high and the effect of macrophytes is only weak in comparison.

Table 9. Odds ratios of commonly chosen predictor variables for modelling probability of detection of breeding of catfish when present in MDB, etc.

Effect	Odds Ratio in single Best Model	% of models used in (N=114)	Mean lower confidence limit in 8 best models	Mean Odds Ratio in 8 best models	Mean upper confidence limit in 8 best models	Interpretation
Boulder/ Bedrock presence	1615	91%	0.466	>999	>999	Catfish breeding considerably more likely to occur when Boulder/ Bedrock is present
Emergent Macrophytes	1.10	15%	0.980	1.10	1.232	Catfish breeding slightly more likely to occur when Emergent Macrophyte beds are larger
Daily Flow	0.17	68%	0.06	0.25	1.23	Catfish breeding much more likely to occur when Daily Flow is low
Riffle/ Rapid	<0.001	58%	<0.001	<0.001	3.38	Catfish breeding substantially more likely to occur when the area of Riffles and Rapids is low

Discussion

Here we have shown that catfish are most likely to be present where there is high cover of Cobble/Gravel, extensive Submerged Macrophytes and low Daily Flow. Breeding is most likely to occur at sites with high abundance of Bedrock/Boulders, Riffle/Rapids, area of Emergent Macrophytes, and low Daily Flow. These results appear to be in quite close agreement with historical observations that the species preferred sluggish waters and was most abundant in lakes and backwaters (Lake 1971). In addition, catfish are often found in small dams and lakes with substantial submergent and emergent macrophytes (Clunie & Koehn 2001; Koster *et al.* 2015; Lake 1971; Pollard *et al.* 1996).

The variables that are important for catfish to maintain self-sustaining populations give some insight as to why the species is threatened given all these variables have undergone substantial changes since European settlement. For example, low Daily Flow is crucially important, especially when combined with the presence of Cobble/Gravel. While flow is still relatively low across most of the lowland areas of the MDB where catfish populations have disappeared, river regulation has resulted in a much higher sediment load, particularly in wetlands (Gell & Reid 2016). In rivers, weir pools trap sediments and can result in submersion of the gravel substrate and the loss of critical Submerged Macrophyte cover. In addition, river regulation has drastically reduced the area of Riffles/Rapids, particularly in the lower MDB.

Recommendations

While the variables identified here are not the only ones that are important to catfish, these data suggest that targeting sites that meet these key requirements have the best chance at sustaining a population of catfish. It is clear that the locations that currently support viable populations of catfish tend to be those where there is reliable supply of water and abundant macrophyte cover (Widgiewar Lagoon, Washpen Creek, Tahbilk Lagoon, Boral Dam). Sites where flow is greater than 6 ML day^{-1} (approx. 1,300 ML/day) are unlikely to support catfish populations, especially if there is a lack of Cobble/Gravel. While Cobble/Gravel was identified as an important variable for predicting catfish presence, if there was low Daily Flow and high Submerged Macrophyte cover, Cobble/Gravel was no longer critical. Therefore, the most suitable sites for reintroductions of catfish are large dams with Bedrock/Boulders, a reliable water supply and abundant Submerged Macrophytes. These are the sorts of habitats that were once common throughout the lower MDB, but have been severely affected by river regulation and change of flow regime.

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