Astacopsis gouldi Clark: habitat characteristics and relative abundance of juveniles

P.E. Davies[1,3]*, L.S.J. Cook[1,3], S.A. Munks[2,3] and J. Meggs[4]
[1]Freshwater Systems, 82 Waimea Ave, Sandy Bay 7005
[2]Forest Practices Authority, 30 Patrick Street, Hobart 7000
[3]School of Zoology, University of Tasmania, Private Bag 5, Hobart 7001
[4]Forestry Tasmania, GPO Box 207, Hobart 7001
*p.e.davies@utas.edu.au (corresponding author)

Abstract

A survey of juvenile Astacopsis gouldi *was conducted in streams in northern Tasmania. Differences in catch per unit distance (CPUD) and catch per unit area (CPUA) of juvenile* A. gouldi *between stream classes (as defined in the Tasmanian Forest Practices Code) were examined, as well as relationships between CPUD, CPUA and habitat variables. Use of Class 4 streams (catchment area < 50 ha) by* A. gouldi *was consistently low compared to Class 2 streams (catchment area > 100 ha) in the stream systems studied, with* A. gouldi *occurring in only very low densities in Class 4 streams.*

Streams of 50–200 ha catchment area (stream Classes 2 to 3) and potentially those with significant and sustained groundwater input were found to be important for A. gouldi. *Streams with less than 2% area of substrate as silt, high proportions of moss cover, moderate to high proportions (10–30%) of substrate as boulders, and channel slopes of less than 15% were associated with higher densities of juvenile* A. gouldi. *Meso-habitat features favoured by juvenile* A. gouldi *included large rocks or logs that overlie coarser substrates and/or which had a distinct cavity underneath. These characteristics of optimal habitat can be used to identify sections of stream drainage that may require local or upstream protection measures for juvenile* A. gouldi.

Introduction

The giant freshwater crayfish, *Astacopsis gouldi* Clark, is listed as 'Vulnerable' under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* and the Tasmanian *Threatened Species Protection Act 1995.* Much recent debate has centred on the effects of forest harvesting operations on headwater streams, particularly small streams with catchment areas of less than 50 ha, classified as 'Class 4' under the Tasmanian Forest Practices Code (Forest Practices Board 2000; Box 1, p. 2). Observations made by Growns (1995) of the presence of mature females in some tributary streams in a survey of *A. gouldi* populations in the Gog Range have led to a public belief that such streams may be of particular significance to *A. gouldi*, especially as areas for reproduction, juvenile rearing and subsequent recruitment into mainstream populations. As a result, there has been concern that timber harvesting operations adjacent to and around Class 4 streams may be having a significant negative impact on *A. gouldi* populations both in the headwaters and across river catchments as a whole.

Other than the observations made by Growns (1995), there have been no published reports of the presence of *A. gouldi* in Class 4 streams. *Astacopsis gouldi* surveys reported by Horwitz (1991, 1994), Hamr (1990), Webb (2001) and Walsh and Nash (2002) have largely focussed

BOX 1

Definition of stream classes (from the *Forest Practices Code 2000*)

Class 1

Rivers, lakes, artificial storages (other than farm dams) and tidal waters – generally those named on 1:100 000 topographical series maps.

Class 2

Creeks, streams and other watercourses from the point where their catchment exceeds 100 ha (1 km^2).

Class 3

Watercourses carrying running water most of the year between the points where their catchment is from 50 to 100 ha (0.5–1 km^2).

Class 4

All other watercourses carrying water for part or all of the year for most years.

A Class 4 watercourse is differentiated from a drainage depression by having at least one of the following features:

- A gravelly, pebbly, rocky or sandy bed, indicative of flowing water;
- An obvious gully;
- A short steep section of streambank adjacent to the watercourse bed.

A Class 4 watercourse will often have a change in understorey vegetation from the streambank to the surrounding forest; for example, riparian/moist vegetation on streambanks—ferns, mosses, sedges.

on higher order stream populations and relationships with impacts from previously poorly controlled fishing (for crayfish) and land-use change. Horwitz (1991) presented some evidence for the effects of fishing on *A. gouldi* population size and age structure, and this work was a significant contributor to changed fishing regulations pertaining to the species in the 1990s. A recent unpublished survey has implicated sedimentation from agricultural and/or forestry-related land-use as contributing to reduced numbers of *A. gouldi* (Walsh and Nash 2002). Hamr (1990) provides the only formal attempt at an assessment of *A. gouldi* population size and structure, although that study was limited to one river.

No surveys have been conducted to look specifically at the issue of recruitment and habitat use by juveniles, aspects fundamental to population viability. This study was therefore initiated to assess the occurrence of juvenile *A. gouldi* in Class 4 streams relative to larger streams, and to identify the habitat characteristics associated with higher juvenile densities.

Stream classes

The stream 'class' system used in this study is as defined within the Tasmanian Forest Practices Code (Forest Practices Board 2000; Box 1). This classification is used primarily to define prescriptions for forest operations at or adjacent to streams draining different catchment areas.

Class 4 streams correspond to first-order streams *sensu* Strahler (1952), with catchment areas less than 50 ha, and are frequently seasonal or unpredictably ephemeral in flow. They are also highly heterogeneous geomorphologically in

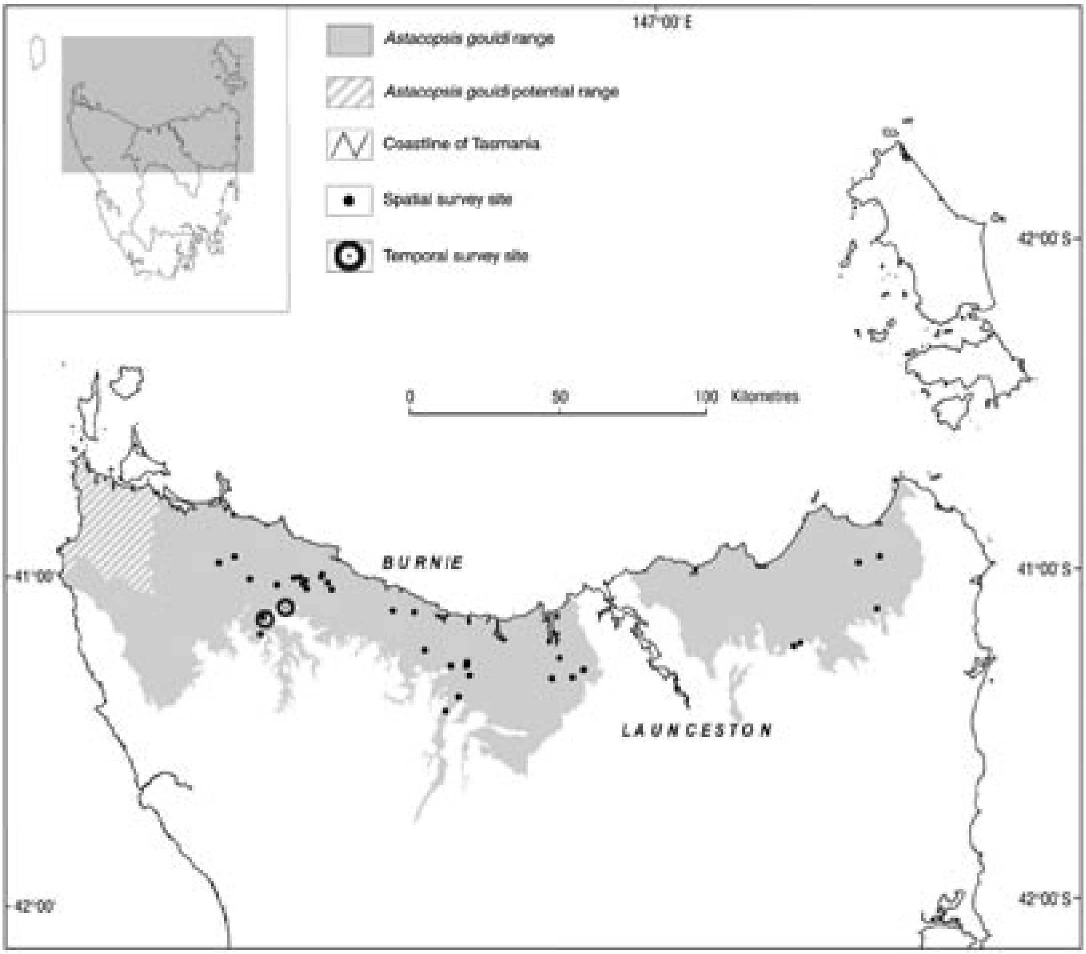

Figure 1. Location of sites surveyed for juvenile Astacopsis gouldi *during temporal and spatial surveys. Note several location points include multiple sites. Current ranges and potential (historical) ranges are derived from Horwitz (1991, 1994), Webb (2001) and Walsh and Nash (2002).*

Tasmania, due to variability in local geomorphological context, stream hydraulic control by local elements (boulders, bedrock, logs), groundwater–surface water interactions, and local variations in riparian and catchment soils and vegetation. Class 3 streams are typically second- to third-order streams (*sensu* Strahler 1952) with a higher frequency of perennial flow, but still fairly heterogeneous. Class 2 (and Class 1) streams comprise all remaining and larger streams, with Strahler stream orders ranging from 3 to 9. The vast majority of Class 2 streams are perennial, named creeks and rivers, and frequently contain habitat elements the spatial arrangement of which is largely dictated by the interaction of stream power with hydraulic controls. These interactions occur over a range of scales substantially larger than those for small headwater (e.g. Class 4) streams.

Methods

A survey for juvenile *A. gouldi* was conducted between 2000 and 2003 in headwater streams across a range of stream sizes ('Classes' as defined in the Tasmanian *Forest Practices Code 2000*) and habitat types. The survey was conducted in two parts—a repeated 'temporal' survey of selected sites

Table 1. *Sites sampled during the temporal survey.*

Catchment	Site	Catchment area (ha)	Stream class
Chellis Creek – Flowerdale River	CF1	451	2
	CF2	23	4
	CF3	41	4
	CF4	70	3
	CF5	15	4
	CF6	32	4
Relapse Creek	R1	993	2
	R2	18	4
	R3	12	4
	R4	7	4
	R5	14	4
	R6	31	4

over a 14-month period, and a 'spatial' survey of a range of sites, each sampled once.

Temporal survey

Twelve sites in two drainages (Chellis Creek – Flowerdale River, and Relapse Creek; Figure 1, Table 1) were surveyed in daytime every two to four months over a 14-month period between March 2002 and April 2003 to assess the abundance of juvenile *A. gouldi* over time. The two drainages were known to have substantial populations of *A. gouldi* in their main channels (Class 2 stream reaches) and were not substantially modified by human disturbance. In each of the drainages, one downstream Class 2 reach was sampled along with four or five Class 4 streams. Sampling was conducted using an active visual search method (see below), with a two-hour search effort on every sampling occasion. All captured adult (> 70 mm overall carapace length, CL) and juvenile (< 70 mm CL) *A. gouldi* were measured, counted and released at the site of capture.

Spatial survey

Seventy-two sites in 35 stream catchments were visited as part of a spatial survey between late 2001 and early 2004. They covered a range of catchment areas (0.12–124 km^2), elevations (18–252 m above sea level) and channel dimensions (1–20 m bankfull width). Sites were selected to minimise any potential disturbance from clearfell harvesting within the past ten years. Six sites were rejected from further study as they had been compromised by nearby harvesting. Sixty-six sites were surveyed in detail once each, between spring and late autumn (October to April) (Figure 1, Table 2). Thirty-nine, eight and 19 of these sites were in Class 2, 3 and 4 streams respectively. For most Class 4 streams surveyed, a survey was also conducted in a Class 3 and/or Class 2 reach within 1 km downstream of the Class 4 site.

Trial sampling (Davies and Cook, unpublished data) indicated that juveniles were consistently absent in Class 4 streams upstream of Class 2 streams where juveniles were also absent. A substantial number (20) of Class 2 stream sites visited in this survey either did not contain adult or juvenile *A. gouldi* (although a number of these contained other crayfish species) or were significantly disturbed by recent riparian and catchment vegetation clearance. From 2001, sampling of Class 4 streams within the upstream catchment was therefore not conducted for such locations.

Difficulty was experienced in finding a set of sites with a range of stream sizes and conditions in north-eastern Tasmania at which juveniles were present. In addition, the manual searching technique (see below) was limited in its applicability when used in sand-bed streams in this region. Attempts to assess juveniles using electrofishing also failed to produce juveniles consistently in these streams.

Sampling methods

An active searching method was used throughout this study. An unpublished pilot study conducted by Davies and Cook (1999) assessed a variety of methods for surveying juvenile *A. gouldi*. Trapping, electrofishing and baiting all had a low and variable success rate. Active searching across all instream

Table 2. Sites sampled during the spatial survey.

Catchment	Number of sites	Number of sites in different stream classes		
		Class 1 and 2	Class 3	Class 4
Big Creek	3	3	-	-
Dowlings Creek	1	1	-	-
Chellis Creek	6	3	1	2
Relapse Creek	4	2	-	2
Ten Foot Creek	2	-	-	2
Zig Zag Creek	4	2	1	1
Groove Creek	1	-	1	-
Hebe River	3	2	-	1
Ingram Creek	1	1	-	-
Barrington Creek	1	1	-	-
Puzzle Creek	1	-	1	-
Champion Road Creek	1	1	-	-
Dip River	1	1	-	-
Brands Creek	2	1	-	1
Rubicon River	1	1	-	-
Parrot Creek	1	1	-	-
Franklin Rivulet	3	2	1	-
Radford Creek	3	1	1	1
McBride Creek	2	1	-	1
Natone Creek	2	1	-	1
Weld River	1	1	-	-
Sandy Creek	1	1	-	-
Bonser Creek	1	1	-	-
Mackenzie Rivulet	1	1	-	-
Little Mackenzie Rivulet	1	1	-	-
Unnamed creek (Devils Gate Dam)	2	1	-	1
Blackfish Creek	2	1	-	1
'Todds' Creek	1	-	-	1
Unnamed creek (eastern shore, Lake Barrington)	1	1	-	-
Unnamed creek (western shore, Lake Barrington)	3	2	-	1
Blackfish Creek #2	1	-	1	-
Coopers Creek	2	1	-	1
Gibson Creek	2	1	-	1
Melin Rivulet	2	1	-	1
Maynes Creek	2	1	1	-
Total	66	39	8	19

habitats, standardised by time and/or distance, was the most effective method, with the highest and most consistent capture rate. A capture-mark-recapture study of marked juveniles indicated that this method had a low success rate (of the order of 10% of the juvenile population being caught in a single search event). However, with consistent search effort and method, and experienced field personnel, the method was deemed suitable for comparative assessments of juvenile population status across stream types and a range of habitat conditions (e.g. land-use).

At each location, a study site of 100–250 m length was identified. A two-person team, working closely together, searched the site actively for juvenile *A. gouldi* by a combination of visual streambed scanning and lifting of all major substrate and wood debris elements across the entire stream

Table 3. Environmental variables measured for each survey site. In addition, channel slope (%) was measured for all sites surveyed after January 2003.

Variable	Description	Unit
Carea	Catchment area	km^2
Stream class	Class as per Forest Practices Code (2000)	rank
Altitude	Site altitude	m
Algae	Per cent cover of riffle substrate by filamentous algae	%
Silt	Per cent cover of riffle substrate by superficial silt	%
Detritus	Per cent cover of riffle substrate by organic detritus (leaves etc)	%
Moss	Per cent cover of riffle substrate by moss	%
Bedrock	Per cent of site substrate as bedrock	%
Boulder	Per cent of site substrate as boulder	%
Cobble	Per cent of site substrate as cobble	%
Pebble	Per cent of site substrate as pebble	%
Gravel	Per cent of site substrate as gravel	%
Sand	Per cent of site substrate as sand	%
Silt	Per cent of site substrate as silt	%
Depth	Mean depth over site	cm
Overhanging vegetation	Cover by overhanging/shading vegetation	rank
Trailing vegetation	Cover by vegetation trailing in channel	rank
LH Rip vegetation	Width of riparian vegetation, left bank (facing upstream)	rank
RH Rip vegetation	Width of riparian vegetation, right bank (facing upstream)	rank
Temperature	Water temperature at time of sampling	°C
Conductivity	Measured on date of sampling	µS/cm
WWidth	Mean width of wetted channel	m
BNWidth	Mean width of channel, bank to bank	m
Flow	Flow	rank
Clarity	Water clarity	rank
Riffle	Per cent of site as riffle habitat	%
Run	Per cent of site as run habitat	%
Pool	Per cent of site as pool habitat	%
Snag	Per cent of site as snag (wood debris) habitat	%

channel within the search area. Searching was conducted for 1.5–2 h during daylight hours, and the search time, length of stream and channel area searched were recorded. A suite of 29 environmental variables was measured for each site (Table 3), either on-site or derived from maps. Channel slope was also measured in the field at all sites sampled from January 2003 onward.

All crayfish captured during surveys were identified, measured (CL to nearest mm), counted and released. Juvenile *A. gouldi* leave the mother as stage 3 post-larvae at about 7 mm CL. *Astacopsis gouldi* reaches maturity at greater than 76 mm CL for males and greater than 119 mm for females (Hamr 1990). For the purposes of this study, juveniles were defined as those of less than 70 mm CL.

Data on total cumulative length of Class 4, 3 and 2 streams for all river catchments within the existing distribution of *A. gouldi* were prepared by the Planning Branch of Forestry Tasmania (FT) based on streamlines defined by a statewide digital elevation model (DEM) developed by FT.

Spatial data analysis

All juvenile capture data (*n*, number of individuals) were converted to catch per unit distance (CPUD, as *n* per 100 m of stream length surveyed), and catch per unit area (CPUA, as *n* per 100 m^2 of stream channel area). CPUA data were also converted into rank categories, as 'CPUAR', using the rank categories of juvenile *A. gouldi* CPUA shown in Table 4.

All CPUD, CPUA and environmental data were entered into SYSTAT (version 10.1, Wilkinson 2000) and analysed as follows. CPUD and CPUA were correlated (Pearson and Spearman rank) with environmental variables. Principal components analysis (using the data reduction routine in SYSTAT) was conducted with environmental variable data to evaluate redundancy in the data and generate principal component factors. Multiple linear regression analysis (interactive, forward stepwise in the SYSTAT GLM routine) was conducted with CPUD and CPUA as dependent variables and the reduced set of environmental variables as independent variables. Model performance was assessed using the adjusted R^2 statistic and the ANOVA F statistic. Only variables with high tolerance values were included in models, and residual plots were examined in each case for homogeneity of variance and outliers.

Logistic regression analysis (interactive, forward stepwise, and complete, in the SYSTAT regression routine) was conducted with presence/absence of juveniles as the dependent variable and the reduced set of environmental variables as independent variables. Model suitability was assessed by examining the 95% bounds of parameter odds ratios, a Chi-squared test based on log likelihood, and McFadden's rho-squared (Wilkinson 2000; Quinn and Keough 2002). Complete stepwise model development was conducted initially. Models were then developed sequentially, with decreasing numbers of variables. Relative model performance was assessed using the G statistic based on differences between model log likelihood ratios, assessed as a chi-squared statistic. In addition, models were evaluated by classifying all sites in the data set as having either presence or absence of juveniles. Discriminant analysis (interactive forward stepwise and complete in SYSTAT) was conducted with CPUAR as the grouping variable and the reduced set of environmental variables as independent variables. Model suitability was assessed by examining the jacknifed classification success and ensuring that Wilks' lambda, Pillai's trace and the Lawley-Hotelling trace were all significant at $P < 0.05$ (Wilkinson 2000).

Table 4. Population density classes for juvenile Astacopsis gouldi *derived from CPUA data. (CPUA = catch per unit area,* n *per 100 m*^{2} *of stream channel area; CPUAR = CPUA rank)*

Density	CPUA	CPUAR
Absent	0	0
Very low	0–1	1
Low	1–2	2
Moderate	2–5	3
High	> 5	4

Mean CPUD and CPUA for Class 4, 3 and 2 streams were also compared by one-way analyses of variance for those streams containing juvenile *A. gouldi* (i.e. stream systems where no *A. gouldi* were found were excluded). Both variables were log-transformed using a $\ln(x+1)$ transformation prior to analysis to ensure homogeneity of variance. Post-hoc comparisons between stream classes were conducted using Tukey's Honest Significant Difference test (HSD).

Results

Temporal survey

Thirty-seven adults and 93 juveniles were captured from the Class 2 stream sites ($n = 2$, six sampling occasions each). Three adults and one juvenile were captured from the Class 3–4 streams ($n = 10$: nine Class 4 plus one Class 3 stream; six sampling occasions each). Altogether, 134 *A. gouldi* individuals were captured in the temporal survey.

Numbers of juveniles captured were reasonably consistent through the year in the Class 2 sites, with the exception of the final sampling visit in April 2003 (Figure 2a).

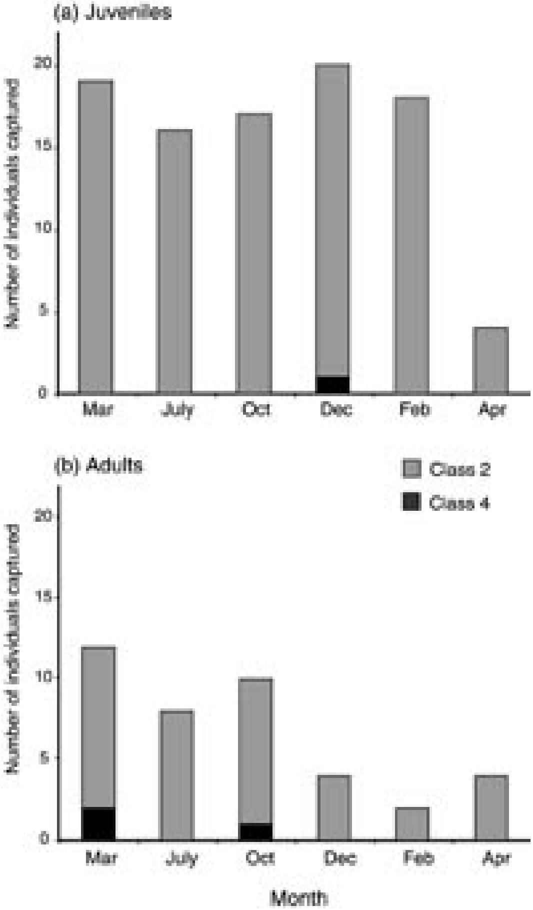

Figure 2. Total abundance of all Astacopsis gouldi *juveniles and adults captured at sample sites in the Chellis Creek – Flowerdale River and Relapse Creek drainages between March 2002 and April 2003.*

Numbers of adults captured in the Class 2 sites (Figure 2b) were higher in March to October (autumn–winter) than in December and February (spring–summer). Very few individuals were captured in the Class 3–4 streams, with all three adult captures being in the lower reaches of two streams. Only one juvenile was caught in the Class 4 streams, in December, over 72 sampling occasions. The repeated sampling did not identify a marked temporal peak in the abundance of juvenile *A. gouldi*.

Spatial survey

A total of 259 juvenile and nine adult *A. gouldi* were caught during the single-visit spatial survey. Of the juveniles, 242, seven and ten were caught in Class 2, 3 and 4 streams respectively. Nine juveniles were caught in one Class 4 stream alone (a tributary of Coopers Creek in the Flowerdale – Hebe River catchment). In stream sites found to contain juvenile *A. gouldi*, the CPUD ranged between 0.28 and 27.5 individuals per 100 m stream length, and the CPUA between 0.18 and 18.3 individuals per 100 m^2 of stream bed area. The mean size of *A. gouldi* captured was 35.5 mm CL, with individuals ranging from 9 mm to 153 mm. The size frequency distribution is shown in Figure 3. The majority (97%) of *A. gouldi* captured were juveniles.

Total and mean *A. gouldi* catches per site are shown (as CPUD and CPUA) by stream class in Table 5 for all sites that contained *A. gouldi* in their Class 2 reaches. Data is also shown excluding the Coopers Creek tributary site. This was considered an outlier, due to higher than normal juvenile abundance, possibly related to spring-fed baseflows (see Discussion). Mean total catch, and mean CPUD and CPUA were higher in Class 2 streams than in Class 3 and Class 4 streams.

Analysis of variance indicated that both CPUD and CPUA were significantly different between stream classes whether the Coopers Creek tributary site was included ($P < 0.005$) or excluded ($P < 0.0001$). Both CPUD and CPUA were significantly and substantially higher in Class 2 than in Class 3 streams ($P = 0.024$ and 0.006, respectively, by Tukey's HSD test) and in Class 4 streams ($P = 0.0001$ and 0.00002, respectively, excluding Coopers Creek). No significant differences were observed between Class 3 and Class 4 streams ($P > 0.2$).

A number of sites surveyed did not contain *A. gouldi*, but contained *A. tricornis* Clark, *A. franklinii* Gray or a species of burrowing crayfish from the genera *Engaeus* or *Parastacoides*. *Astacopsis*

Table 5. Summary statistics for Astacopsis gouldi *catches (all sizes and juveniles only) during the spatial survey. Sum = total number of crayfish captured per stream class; N = number of crayfish captured per site; CPUD = catch per unit distance (n per 100 m); CPUA = catch per unit area (n per 100 m²); juvs = juveniles. * indicates values for Class 4 streams excluding the Coopers Creek tributary 'outlier'.*

Class	Number of sites	Sum all	Sum juvs	Mean N all	Mean N juvs	Median N all	Median N juvs	CPUD mean	CPUD median	CPUA mean	CPUA median
1+2	40	246	242	6.15	6.05	4.00	3.50	3.82	2.47	1.79	0.80
3	8	8	7	1.00	0.88	0	0	0.64	0	0.39	0
4	18	14	10	0.78	0.56	0	0	0.26	0	0.52	0
4*	17	4	1	0.06	0.06	0	0	0.04	0	0.07	0

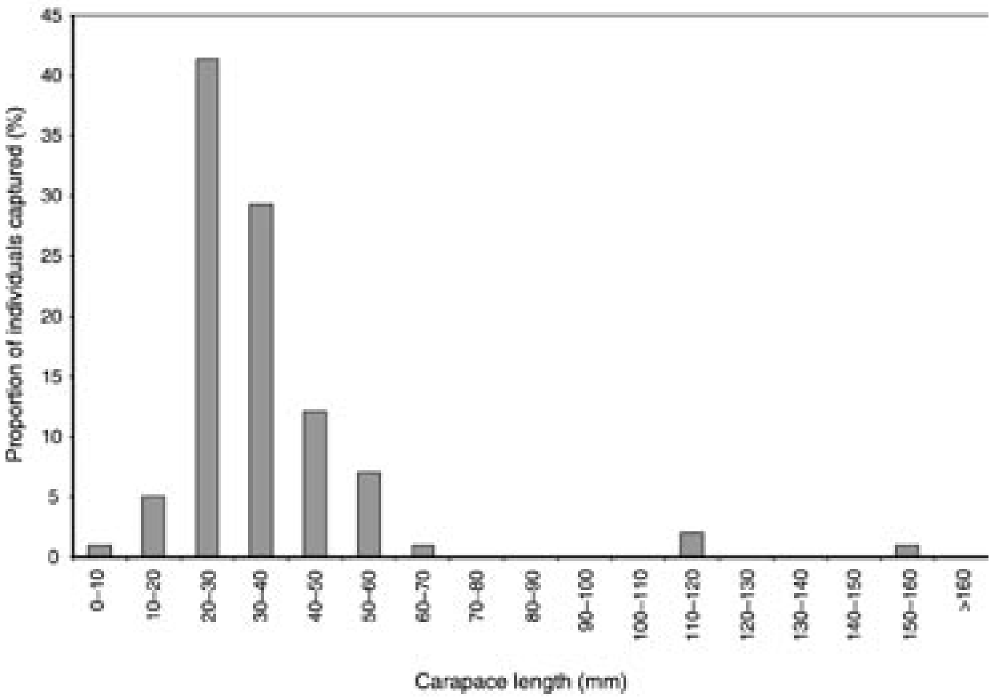

Figure 3. Size frequency distribution of Astacopsis gouldi *captured during the spatial survey.*

tricornis was occasionally observed in the upper reaches of drainages of the coastal river catchments at higher altitudes, while *A. franklinii* was also observed at two sites at higher altitudes (200–250 m) in the north-east. *Engaeus* and *Parastacoides* species were observed in more ephemeral, smaller streams with small baseflows.

Environmental relationships: all streams

The following results are for analyses conducted on data collected for all stream sites surveyed in detail (n = 66), including those with no *A. gouldi* recorded in this survey (but which are located within river catchments known to contain *A. gouldi*).

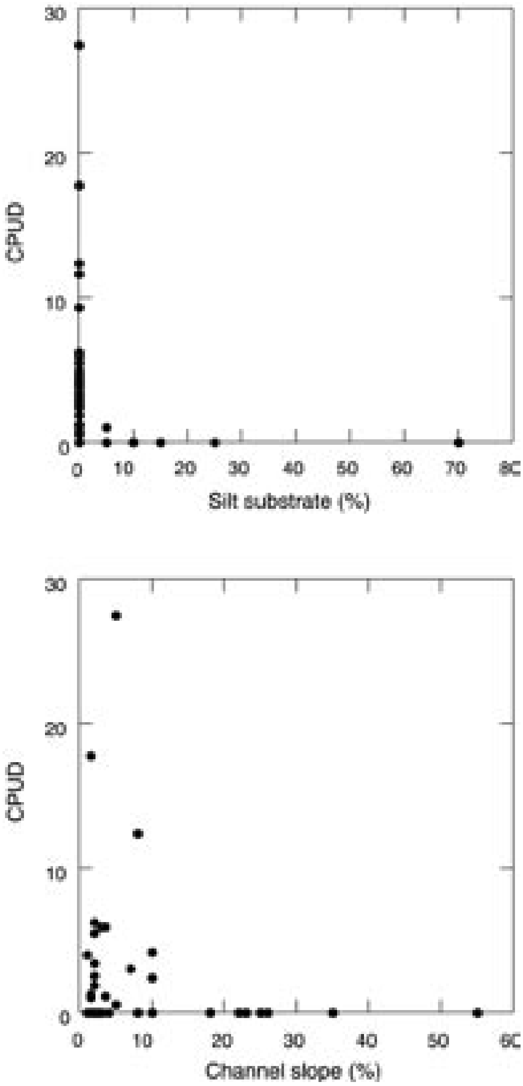

Figure 4. Relationships between Astacopsis gouldi *catch per unit distance (CPUD) and silt substrate and channel slope.*

Juvenile *A. gouldi* density, as CPUD, was positively correlated (by Spearman rank correlation) with catchment area ($P < 0.0001$), channel width (wetted and bankfull) ($P < 0.0001$), algal cover ($P < 0.01$) and boulder substrate ($P < 0.01$). Juvenile *A. gouldi* density, as CPUA, was also positively correlated with channel width (wetted and bankfull, both $P < 0.001$). CPUD was very low or zero when silt substrate was 5% or greater (Figure 4).

In addition, no juvenile *A. gouldi* were recorded at sites with channel slopes greater than 10% (Figure 4).

Principal components analysis (PCA) conducted on the environmental variables resulted in two factors which accounted for 35.8% of the variance in these variables (22.5% and 13.3% for Factors 1 and 2, respectively). PCA Factor 1 was positively correlated with catchment area, algal cover, boulder substrate, cobble substrate, wetted width, bankfull width, flow rating, water clarity rating, proportion of stream reach as run, and proportion as pool. PCA Factor 1 was negatively correlated with organic detritus, moss cover, pebble substrate, gravel substrate, silt substrate, overhanging vegetation, trailing vegetation, and riffle habitat. CPUD and CPUA were both significantly correlated with PCA Factor 1, with $R = 0.291$ and 0.245, respectively ($P = 0.019$ and 0.049), but not with PCA Factor 2 or any of the remaining PCA factors.

Multiple linear regression of CPUD against the environmental variables resulted in a regression model with only three variables (catchment area, moss cover, wetted width) and with an adjusted R^2 of only 0.35. Inspection of residuals suggested log transformation of CPUD was necessary, but overall model performance was not significantly improved (adjusted $R^2 = 0.37$). A consistent outlier was identified in both model runs—the tributary of Coopers Creek. The analyses were repeated with this outlier site removed but resulted in models with only marginally improved adjusted R^2 values (0.39 and 0.45).

Discriminant analysis of CPUAR successfully discriminated sites with no to low density *A. gouldi* (CPUA < 1) from those with moderate to high density (CPUA > 2) using three variables: catchment area, bankfull width and boulder substrate. Moderate to high density sites had higher mean values for all variables than the low density sites. Of these sites, 75% were successfully reclassified by the resulting discriminant

Table 6. Summary of the logistic regression results for the relationship between juvenile Astacopsis gouldi *presence/absence and environmental variables across all streams.*

Parameter	Estimate	S.E.	*t*-ratio	*P*-value
Constant	-0.788	2.133	-0.369	0.712
Catchment area*	-1.555	0.687	-2.263	0.024
Wetted width*	5.314	1.657	3.206	0.001
Moss cover**	3.929	2.017	1.948	0.051
Stream class	-1.067	0.556	-1.921	0.055

* = ln(*x*+1) transformed; ** = arcsin(sqrt) transformed

functions, and all three diagnostic tests were significant (all $P < 0.004$).

A logistic regression model for the presence/absence of juvenile *A. gouldi* was successfully developed with a significant log-likelihood ratio using four variables—stream class, catchment area, moss cover and wetted width (Table 6). There was thus an increased probability of presence of juvenile *A. gouldi* with decreased catchment area, increased wetted width and increased moss cover. The increased probability of presence at smaller catchment areas and in larger, wider streams appears contradictory, but is a product of decreasing density at very large catchment areas. This model successfully classified 74% of sites by presence or absence of juvenile *A. gouldi*.

Environmental relationships: streams containing juvenile Astacopsis gouldi

The following results are for analyses conducted on data collected from the 54 streams in which juvenile *A. gouldi* were recorded in at least the Class 2 (downstream) reach. Thus, these data are for stream systems in which juvenile *A. gouldi* are known to occur.

Juvenile *A. gouldi* density, as CPUD and CPUA, was positively correlated (by Spearman rank correlation) with catchment area ($P < 0.0001$), channel width (wetted and bankfull) ($P < 0.0001$), algal cover ($P < 0.01$), boulder substrate ($P < 0.01$), and proportion of reach as run habitat ($P < 0.01$). CPUD was also negatively correlated with riffle habitat and cover of overhanging and trailing vegetation (both $P < 0.01$). A significant negative correlation was observed for both CPUD and CPUA with silt substrate (both $P < 0.01$).

Principal components analysis (PCA) conducted on the environmental variables resulted in two factors (1a and 2a) which accounted for 39% of the variance in the environmental data (24.5% and 14.5% for Factors 1a and 2a respectively). PCA Factor 1a was positively correlated with the same variables as PCA Factor 1: catchment area, algal cover, boulder substrate, cobble substrate, wetted width, bankfull width, flow rating, water clarity rating, proportion of stream reach as run and proportion as pool. PCA Factor 1a was also negatively correlated with catchment area, organic detritus, moss cover, pebble substrate, gravel substrate, silt substrate, overhanging vegetation, trailing vegetation, and riffle habitat. CPUD and CPUA were both significantly positively correlated with PCA Factor 1a (both $P \leq 0.001$ by Spearman rank correlation), but not with PCA Factor 2a or any of the remaining factors from this PCA.

Multiple linear regression of CPUD, after ln(*x*+1) transformation, against the environmental variables resulted in a regression model with only two independent variables and with an adjusted R^2 of 0.55 (Table 7a). The two variables were bankfull width and boulder substrate, for which the partial correlations with CPUD were both positive. Multiple linear regression of CPUA, after ln(*x*+1) transformation, against the

Table 7. Summary of multiple linear regression results for catch per unit distance (CPUD) and catch per unit area (CPUA) for stream systems containing juvenile Astacopsis gouldi*.*

Effect	Coefficient	Standard Error	Standard Coefficient	Tolerance	*t*	*P* (2-tail)
(a) CPUD						
Constant	-1.053	0.259	0.000		-4.075	0.00016
Boulder substrate*	1.153	0.452	0.252	0.886	2.552	0.014
Bankfull width**	1.040	0.164	0.626	0.886	6.348	< 0.0000005
(b) CPUA						
Constant	-1.039	0.256	0.000		-4.054	0.00017
Moss cover*	1.396	0.520	0.194	0.875	2.686	0.0097
Wetted width**	2.258	0.177	0.926	0.875	12.855	< 0.0000005

* = arcsin(sqrt) transformed; ** = ln (x+1) transformed

environmental variables resulted in a regression model with only two independent variables, and with an adjusted R^2 of 0.76 (Table 7b). The two variables were moss cover and wetted width, for which the partial correlations with CPUA were both positive.

Overall, juvenile *A. gouldi* had higher densities in wider streams with higher algal and/or moss cover and high proportions of boulder substrate. Juvenile densities were negatively correlated with the presence of silt, and were very low when silt levels and slopes were high.

Discussion

Significance of Class 4 streams for juvenile Astacopsis gouldi

This study has found that occasional headwater streams may contain suitable habitat for juvenile *A. gouldi*. In general, however, Class 4 headwater streams (< 50 ha in catchment area) support densities of juvenile *A. gouldi* that are consistently and substantially lower than those in Class 2 streams within the same drainage, and do not support a substantial component of the overall population of juveniles in a catchment. The temporal survey, though limited in extent, suggested that this pattern is sustained throughout the year.

The limited capture success and relatively low density of juvenile *A. gouldi* found in Class 4 streams in this study does not mean that they are absent from Class 4 streams. Although capture rates in Class 4 streams were low, capture success rates for all methods previously trialled were low, and for the visual search method were 10% or less. More intensive searching, or the use of a more effective capture method, would undoubtedly result in higher capture rates. However, we are confident that search effectiveness and intensity is reasonably similar across a range of stream channel sizes and types, with the exception of sand bed or highly complex channels (e.g. with significant underground or cryptic channel sections). It is also important that searches are not conducted during periods of high or turbid flow (when juveniles are harder to see and may be more cryptic) or of very low water temperature (when juveniles are less active and may be more cryptic). Searches were not conducted under such conditions during the spatial survey reported here.

We believe that the magnitude of the differences in observed densities between stream classes are broadly representative. We combined mean density (per stream length) data for each stream class with the cumulative length of all sections of stream drainage in catchments within

Table 8. Estimated total stream length of various stream classes within the range of Astacopsis gouldi *for north-western Tasmania and north-eastern Tasmania, and mean proportions (as %) of juvenile* Astacopsis gouldi *population by stream class. (CPUD = catch per unit distance,* n *per 100 m of stream length).*

	Class 1+2[1] (km)	Class 3 (km)	Class 4 (km)	Total	Class 4 (%)
NORTH-WESTERN CATCHMENTS					
Black-Detention River	627	159	898	1,685	53.3
Montagu River	160	43	221	424	52.2
Duck River	473	105	598	1,176	50.9
Inglis River	612	118	783	1,513	51.7
Arthur River	1 851	480	2 763	5 095	54.2
Cam River	236	50	243	529	45.9
Emu River	140	33	132	306	43.2
Blythe River	268	64	328	660	49.7
Leven River	662	134	710	1 507	47.1
Forth–Wilmot River	384	109	489	982	49.8
Mersey River	986	241	852	2 079	41.0
Rubicon	546	131	624	1 301	47.9
Total	6 947	1 668	8 641	17 257	Mean = 50.1
Mean juvenile *A. gouldi* CPUD[2]	3.82	0.640	0.26 (0.04)[3]		
Proportion of population (%)	**88.90 (95.04)[3]**	**3.58 (3.83)[3]**	**7.53 (1.13)[3]**		
NORTH-EASTERN CATCHMENTS					
Ringarooma River	825	196	687	1 708	40.2
Boobyalla–Tomahawk River	625	135	508	1 268	40.1
Pipers River	641	160	715	1 516	47.1
Little Forester River	371	97	586	1 053	55.6
Great Forester River	831	199	991	2 022	49.0
North Esk River	435	117	474	1 026	46.2
Total	3 728	904	3 961	8 593	Mean = 46.1
Mean juvenile *A. gouldi* CPUD[2]	3.82	0.640	0.26 (0.04)[3]		
Proportion of population (%)	**89.85 (94.07)[3]**	**3.65 (3.82)[3]**	**6.50 (2.11)[3]**		

[1] No Class 1 streams were sampled in the north-east.
[2] Values from Table 5; includes all populations.
[3] Index when single 'outlier' case (tributary of Cooper Creek) is removed prior to estimating CPUD.

the range of *A. gouldi* in the north-west and north-east of the State (Table 8). This gives a relative index (albeit crude) of the population of juveniles in each stream class, and indicates that, overall, Class 4 streams would contain only a small proportion (< 8%) of the total abundance of juveniles in these drainages. The density estimates for juvenile *A. gouldi* could be made more precise by sampling a greater number and range of sites. Densities in the more developed (cleared and intensively managed) lower end of stream catchments are also likely to be lower than in less developed catchments (e.g. see Horwitz 1991, 1994; Walsh and Nash 2002). This is partly reflected in our data by a decline in median CPUA at higher catchment areas, where survey sites were unavoidably downstream of a degree of historical rural land clearing. The latter may cause the representation of juveniles in larger Class 2 streams to be partly overestimated in these calculations.

It should also be noted that no mapping or modelling resources currently available (e.g. through Land Information System Tasmania [Government of Tasmania 2005], or modelled via DEM [digital elevation model]) provide a complete inventory of Class 4 streams for Tasmania. Traditional cartography substantially underestimates the presence of Class 4 streams due to difficulties in observing drainage through forest cover, and when drainage is not associated with gully features, or is partially underground. DEM-based drainage identification assumes that topography dictates stream location which, while generally true for larger streams of sufficient gradient, is not realistic for many Class 4 streams. Class 4 streams are often influenced by local, small-scale variations in geology, vegetation, groundwater accession and topography, which are beyond the resolution or scope of digital elevation models, and not necessarily dictated by topographic control. Thus, the values in Table 8 are likely to underestimate the contribution of Class 4 streams to overall drainage lengths at sub-catchment or catchment scales. However, we believe that the overall conclusion of a small relative contribution of Class 4 stream populations to the overall juvenile population in a catchment is unlikely to change substantially if this length estimate were corrected.

Removal of the one 'outlier' Class 4 stream case prior to estimating mean CPUD results in a significantly lower (1–2%) proportion of the total catchment-wide abundance of juveniles being resident in Class 4 streams (Table 8). This stream, a tributary of Coopers Creek, represents a particular case of very high juvenile densities for a stream with a small catchment area (40 ha). It is not clear how common streams like this are throughout the range of *A. gouldi* (based on our field observations, they probably represent less than 5% of Class 4 streams). This stream is significantly spring-fed and has its headwaters at a contact between quartzites (in the mid and lower catchment) and erosional relict upland surfaces of basaltic origin. These are two fluvial geomorphological types described as 'northern quartzite ridges hills and valleys' and 'northern relict surfaces' in the fluvial geomorphological analysis conducted for Tasmania by Jerie *et al.* (2003). These two types are restricted to the area south-west to south-east of Rocky Cape, and include parts of the catchments of the Flowerdale, lower Inglis and upper Detention Rivers. The contact between them is, however, restricted to the lower Flowerdale River catchment. Observations in a Class 4 stream of high densities of juveniles (T. Walsh, pers. comm.) suggest that more streams of this type are to be expected within the Flowerdale – Hebe River catchment. Suitable spring-fed streams may occur at other contacts between geologies or lithologies which produce substantial groundwater contributions to Class 4 stream baseflows, and this possibility is currently being assessed in a follow-up study. Streams with sources rising adjacent to basalt-sedimentary geological contacts have recently been confirmed as having consistently higher *A. gouldi* densities than other Class 4 streams in the same catchments (Davies and Cook, unpublished data).

One key factor that determines juvenile *A. gouldi* densities was not studied in this survey—the density of adults, and particularly reproductive females. Resource and time constraints prevented us from conducting surveys of adults. Estimation of densities of adults is difficult, and must be based on catch per unit trapping effort or capture-mark-recapture sampling. Trapping efficiency of adult crayfish is difficult to quantify and highly variable (Hamr 1990; P. Hamr, pers. comm.).

The absence in the survey sample of stage 3 post-larvae (the stage at which larvae permanently leave the mother, at a maximum recorded size of 7.3 mm, Hamr 1990) could be due to a limitation of the sampling technique and/or the clustered nature of post-larval distributions. In any event, these post-larvae must grow through the size-classes recorded in this study, in order to be effectively recruited into the adult population.

Habitat preferences of juvenile Astacopsis gouldi

Juvenile *A. gouldi* were found in streams at all elevations surveyed (18–250 m above sea level), and in channels of all widths encountered (1–20 m bankfull width). Juveniles were observed in catchment areas ranging between 0.4 and 124 km^2. Juveniles were not found at any site with catchment areas ranging between 0.12 and 0.4 km^2 (12–40 ha).

Analysis of relationships between measures of juvenile *A. gouldi* density and environmental variables indicated that densities are higher in streams with intermediate catchment sizes (typically 2–30 km^2), channels of 1–3 m wetted width at baseflow, with low levels of silt substrate (< 2%), higher proportions of moss cover (> 10% stream bed area) and higher proportions (10–30%) of area as boulder substrate. No juvenile *A. gouldi* were observed in streams with channel slopes greater than 10%, with silt substrate greater than 5%, or with baseflow conductivities greater than 160 µS/cm. These conditions are therefore associated with very low absolute densities of juveniles.

The Class 2 stream reach immediately downstream of the high density Coopers Creek tributary site also contained a high density of juveniles. There was, however, no significant correlation between Class 4 densities and densities in downstream stream reaches, when assessed over all sites (Pearson correlation, $P > 0.4$). The Coopers Creek tributary stream was unusual in having a high baseflow, the magnitude of which was distinctly higher than that expected from the catchment area and behaviour of other streams in the area. The high baseflow was due to groundwater input from springs. The density of juveniles in this stream was likely to be related to the large baseflow and perennial nature of the stream, resulting in similar habitat characteristics to larger, Class 2 streams in the area.

Logistic regression indicated that presence/absence of juveniles could be reasonably well predicted using four variables: stream class, wetted width, moss cover and catchment area. Seventy-four per cent of stream sites were successfully classified with presence/absence of juveniles using this model. Juvenile *A. gouldi* density was lower both in higher stream classes (3 and 4) and at very large catchment areas, which accounts for the presence of both these variables in the logistic regression. The contribution of the variables to the prediction of the presence of juvenile *A. gouldi* decreased in the order: stream width, moss cover, stream class, catchment area. Overall, presence of juveniles is dictated primarily by stream dimensions and catchment area, and then by the presence of moss. The latter factor probably relates to the presence of larger, stable instream rocks (and occasionally logs) which form small refuge cavities. These microhabitats are key features favoured by juveniles. The difficulty of capturing juveniles in sandy granitic streams in north-eastern Tasmania may be related to the absence of such features.

The results of this study indicate that optimal macro-habitats for juvenile *A. gouldi* are wide streams with catchment size typically 2–30 km^2, less than 2% area of substrate as silt, high proportions of moss cover, moderate to high proportions (10–30%) of substrate as boulders and channel slopes less than 15%. Streams with a catchment area of 0.4–2 km^2 and substantial and sustained groundwater (spring) input leading to elevated perennial baseflows may also represent optimal habitat. Field observations also indicate that optimal instream meso-habitat features for juvenile *A. gouldi* include:

- Large rocks, big enough not to be easily dislodged by high flows or by platypus, that overlie coarser substrates (boulder, cobble or pebble), that are 40 cm in diameter or greater and flat in profile, with a distinct cavity underneath, and in riffles, runs and pools in mid channel and channel edges and not embedded in finer substrates (gravel, sand or clay);
- Cavities, associated with overlying or underlying rocks but not excavated;
- Logs, well lodged in the stream bed, with a suitable underlying cavity.

It is known that meso-habitats selected by juveniles and adults differ, with adults favouring deeper pools often associated with snags (Webb 2001) and juveniles favouring shallower areas (Hamr 1990; Davies and Cook 1999). This separation of occupied habitat may also be partly due to a competitive or predatory influence of adults on juveniles.

Management considerations

The results of this study indicate that although small headwater streams (Class 4 and 3) can occasionally provide habitat for juvenile *A. gouldi,* they do not represent a substantial component of juvenile *A. gouldi* habitat within a river catchment. Occasional occurrences of juvenile *A. gouldi* in these streams may be related to the occasionally large distances travelled within a drainage network by adult *A. gouldi*, as reported by Webb and Richardson (2004). Our observations suggest that catchment-wide *A. gouldi* population recruitment is unlikely to be strongly dependent on juvenile populations in Class 4 streams.

To assist the recovery of the species, management for the protection of recruitment to *A. gouldi* populations must focus on the catchment as a whole. The emphasis should be on protection of populations in higher order streams from the cumulative pressures associated with land-use activities (e.g. forestry and agriculture), point source pollution and illegal fishing. In particular, measures should be taken to minimise downstream impact on areas of habitat optimal for both adult and juvenile *A. gouldi*. For the latter, this would include Class 4 streams where baseflows are strongly supplemented by groundwater inputs, such as in Coopers Creek.

Current management prescriptions for *A. gouldi* in areas subject to forestry activities (developed in 1999 and revised in 2000/01) take into account the characteristics of habitat utilised by *A. gouldi* suggested in previous studies (Lynch 1967; Growns 1995; Lynch and Bluhdorn 1997; Webb 2001). These prescriptions are currently delivered to forest managers via a decision support system (Threatened Fauna Advisor, Forest Practices Board 2001). The details of the prescriptions vary depending on the class of stream, type of operation, and known occurrence of the species or suitable habitat, within the operation area. These prescriptions should be revised to incorporate the results of this study by using the identified characteristics of optimal macro- and meso-habitat to identify key areas (whole catchments or stream reaches) that may require local or upstream protection measures for juvenile *A. gouldi*. Evaluation of the extent to which forestry operations in Class 4 stream catchments affect *A. gouldi* populations was precluded in this study due to the low abundance of juveniles observed in Class 4 streams. Therefore, the extent to which forestry operations in the headwaters impact on juvenile *A. gouldi* habitat, and the effectiveness of the current management prescriptions, remains unclear. This question is currently being assessed in a new study focussing on the effects of forest harvesting operations on juvenile populations in downstream Class 3 and Class 2 stream reaches.

Acknowledgements

The Forest Practices Board/DPAC, Forestry Tasmania, and North Forest Products/Gunns provided funding for this study. The Mersey and Murchison District offices of Forestry Tasmania provided a range of assistance. The Threatened Species Unit, Department of Primary Industries, Water and Environment provided permits. Peter Von Minden (Forestry Tasmania) conducted the GIS analysis of stream class lengths. Gary King (Forestry Tasmania) and Graham Wilkinson (Forest Practices Authority) commented on a draft of this paper. Alastair Richardson (University of Tasmania) also provided valuable comments on the manuscript.

References

Davies, P. and Cook, L. (1999). The status of juvenile *Astacopsis gouldi* populations in Class 4 streams. Report to Forestry Tasmania, Hobart.

Forest Practices Board (2000). *Forest Practices Code.* Forest Practices Board, Hobart, Tasmania.

Forest Practices Board (2001). *Threatened Fauna Advisor (revised version). Expert System Program*. Forest Practices Board, Department of Industry Energy and Resources, Hobart, Tasmania.

Government of Tasmania (2005). Land Information System Tasmania. Accessed 3 April 2005, <http://www.thelist.tas.gov.au>.

Growns, I. (1995). *Astacopsis gouldi* in streams of the Gog Range, northern Tasmania: the effects of catchment disturbance. *Papers and Proceedings of the Royal Society of Tasmania* 129: 1–6.

Hamr, P. (1990). Comparative reproductive biology of the Tasmanian freshwater crayfishes *Astacopsis gouldi* Clark, *Astacopsis franklinii* Gray and *Parastacoides tasmanicus* Clark (Decapoda: Parastacidae). Ph.D. thesis, University of Tasmania, Hobart.

Horwitz, P. (1991). On the distribution and exploitation of Tasmanian giant freshwater lobster *Astacopsis gouldi* Clark. Centre for Environmental Studies, University of Tasmania, Hobart.

Horwitz, P. (1994). The distribution and conservation status of the Tasmanian giant freshwater lobster *Astacopsis gouldi* Clark (Decapoda: Parastacidae). *Biological Conservation* 69: 199–206.

Jerie, K., Houshold, I. and Peters, D. (2003). *Tasmania's River Geomorphology: Stream Character and Regional Analysis.* Nature Conservation Report 3/05. Nature Conservation Branch, Department of Primary Industries, Water and Environment, Hobart, Tasmania.

Lynch, D.D. (1967). A synopsis of biological data of the giant freshwater crayfish, *Astacopsis gouldi* Clark 1936. Inland Fisheries Commission, Hobart.

Lynch, T.P. and Bluhdorn, D.R. (1997). Reservation assessment and habitat requirements of the giant freshwater lobster, *Astacopsis gouldi*. Report to the Tasmanian RFA Environment and Heritage Technical Committee.

Quinn, G. and Keough, M. (2002). *Experimental Design and Data Analysis for Biologists.* Cambridge University Press, Cambridge, UK.

Strahler, A.N. (1952). Hypsometric (area-altitude) analysis of erosional topography. *Geological Society of America Bulletin* 63: 1117–1142.

Walsh, T. and Nash, W. (2002). Factors influencing the health of the giant freshwater lobster in Tasmanian rivers. Unpublished report, Inland Fisheries Service Hobart, Tasmania.

Wilkinson, L. (2000). *SYSTAT 10: Statistics I.* SPSS Inc., Chicago, Illinois.

Webb, M. (2001). Movement patterns and habitat use of adult *Astacopsis gouldi* in the Dip River, north-west Tasmania. Hons thesis, University of Tasmania, Hobart.

Webb, M. and Richardson, A.M.M.R. (2004). A radio telemetry study of movement in the giant Tasmanian freshwater crayfish, *Astacopsis gouldi*. *Freshwater Crayfish* 14: 197–204.