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Gadopsis marmoratus

Ecology, Monitoring, Conservation

The status of the Murray crayfish recreational fishery in Victoria

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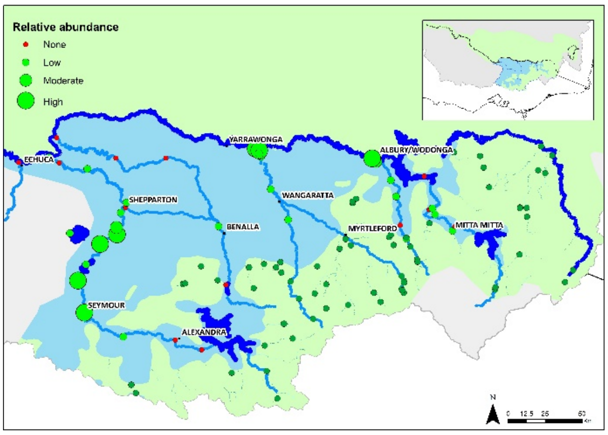
EXECUTIVE SUMMARY

Murray crayfish is an iconic freshwater crayfish that forms an important recreational fishery across Victorian waterways. In addition to providing a valuable food resource, the Murray crayfish recreational fishery contributes socially and economically to local communities during winter months. Yet, this once widespread species has experienced substantial declines across its range, and is now classified as threatened within each state and territory that it occurs. Indeed, some areas of its range continue to experience a declining trend in population status. To ensure the benefits provided by the recreational fishery are maintained in the future, sustainable populations of the species are necessary, especially given the life-history of this slow growing and late sexually maturing species. Whilst a range of conservation actions, such as flow and habitat management, will be necessary, it is acknowledged that sound management of the recreational fishery is critical to ensure long-term population sustainability.

The Victorian recreational fishery has a long history of regulation, with the most recent amendments, informed by research and monitoring of New South Wales populations, occurring in 2013. These amendments implemented a harvestable slot length limit (HSLL = 100–120 mm occipital carapace length, OCL) and increased the duration of the closed season (September to May), whereas daily (two) and possession (four) limits were reduced (noting that protection of berried females was maintained). Whilst it was pragmatic to adopt consistent regulations (for the first time) across both Victorian and NSW recreational fisheries, the effectiveness of their impact on the status and sustainability of Victorian Murray crayfish populations remained unclear. This project helps to answer this key question through population benchmarking and exploration of long-term trends at key sites (Section 3) and population modelling to evaluate a range of fishery management scenarios (Section 4). This multifaceted assessment provides the information necessary to inform sound management of the recreational fishery.

The benchmarking assessed key population parameters (abundance, length structure, sex ratio) across the spatial extent of the Victorian population. This was achieved through standardised sampling of lowland areas, which are target by recreational fishers (that is, accessible by boat), as well as compiling sampling data (courtesy of Arthur Rylah Institute) from upland areas to provide a more complete picture of the status of the species. A total of 469 Murray crayfish were recorded from the 43 lowland sites sampled, with distribution patchy (i.e. not detected at 15 sites) and abundance variable (0–0.38 crayfish net^{-1} hour^{-1}).

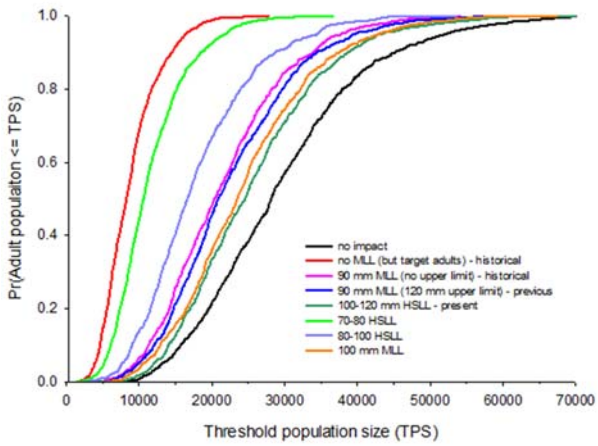


Relative abundance (light green and red dots) across lowland areas (blue shade) along with presence (dark green) across upland areas

The sampled Murray crayfish population, exhibited a broad and normally distributed length structure (19−156 mm occipital carapace length, OCL), with corresponding ages ranging between 0.9 to 19.3 years but most of the population was estimated to be less than eight years old (applying previously developed length-at-age relationships). The overall sex ratio was significantly skewed toward females (0.58 : 1, males to females), with a more pronounced female-bias with the present HSLL range (0.28 : 1) although was almost in unity (0.8 : 1) for individuals below the HSLL. The size at onset of sexual maturity of 50% of females (SOM_{50}) was estimated at 87.28 mm, whereas 95% of females (SOM_{95}) were mature at 104.44 mm.

This benchmarking only identified moderate to high relative abundance of the species in three areas – the mid-Goulburn River (from Seymour to upstream of Shepparton), the lower Ovens River (downstream of Wangaratta to Murray junction) and Wodonga Creek. This reconfirms these areas as supporting stronghold populations, where greatest intensity of recreational fishing effort is anticipated. However, comparison of long-term monitoring at key sites in these stronghold areas indicate that abundance has declined over the past 25 years, emphasising that conservative management is required. Across other sections of the Goulburn (downstream of Shepparton and upstream of Seymour) and Ovens (upstream of Wangaratta) catchments as well as the Broken, Kiewa and Mitta Mitta catchments (but not Campaspe, although small populations may persist in the catchment), the species persists in low abundance (<0.043 crayfish net^{-1} hour^{-1}) or was not detected at over half of sampled sites. The species was broadly distributed across uplands areas, with 792 crayfish detected from 130 sites, yet almost all individuals observed were smaller than 84 mm, reflecting colder water temperatures and smaller waterways, and therefore do not form part of the recreational fishery.

A recently developed stochastic length-based age structure population model was utilised to explore the influence of a range of length limit regulation scenarios on population sustainability (population risk, sex ratio, spawning potential) and harvest potential (mean number of individuals potentially harvested). Specifically, these scenarios related to historical (no length limit; 80 and 90 mm MLL), previous (90 mm MLL, with 120 mm upper limit to reflect the allowance to take one crayfish above this limit) and present fishery regulations (100−120 mm HSLL), as well as a number of alternative regulations (70−90 mm HSLL; 80−100 mm HSLL; 100 mm MLL). The modelling simulations undoubtedly emphasise that the present HSLL are most sympathetic to the species, affording the greatest population sustainability (i.e. lowest population risk, least skewed sex ratio and highest spawning potential) whilst achieving the highest harvest potential (i.e. number of individuals potentially harvested). In contrast, the historical as well as alternative scenarios investigated were deemed to be largely unsustainable with high population risk, skewed sex ratios and a considerable reduction in spawning potential, thus resulting in the lowest harvest potential (due to smaller population sizes). Whilst the previous regulations (e.g. 90 mm MLL; with or without 120 mm upper limit) were an improvement on these historical regulations, they still resulted in inferior population sustainability and harvest potential compared to the present HSLL.



Population risk curves for length limit regulation scenarios
← increasing population risk; decreasing population risk→

This investigation is the most comprehensive assessment of the Victorian Murray crayfish recreational fishery ever conducted. The assessment indicates that Murray crayfish occur patchily across Victoria, with the recreational fishery likely to be largely restricted to three stronghold areas, which have undergone declines in abundance over the past 25 years. Given this status assessment and the outcomes of modelling simulations, the main recommendation which can be put forward is retaining the present HSLL. It is acknowledged that whilst these present regulations manage fishing effort, they do not regulate overall harvest imposed by the recreational fishery; it is recommended to assess overall harvest through collaboration with recreational fishers, and it may ultimately be necessary to explore the suitability of a quota system (i.e. regulating overall harvest) for the species. It is also acknowledged that the potential closure of areas (e.g. such as lower Goulburn River) and reintroductions where low abundances and environmental disturbances persist may be warranted. Retaining the present HSLL would continue the consistency of regulation across both Victorian and NSW recreational fisheries, and supports moving toward a coordinated management approach across the whole range of the species. Implementation of a long-term monitoring strategy, working with recreational fishers (to determine overall fishing effort) as well as addressing research priorities (including understanding movement patterns, population sizes and age structures) will be critical to the ongoing sustainability of the Victorian Murray crayfish recreational fishery.

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Section 1 INTRODUCTION

Murray crayfish *Euastacus armatus* (von Martens 1866) is an iconic freshwater crayfish endemic to the waterways of the southern Murray-Darling Basin (MDB). This long-lived and slow-growing species was once widespread, but has experienced substantial declines in range and abundance over the second half of the twentieth century (Gilligan et al. 2007; Furse and Coughran 2011c). Recent population decline across sections of its range (McCarthy et al. 2014; Noble and Fulton 2017) indicate that the species is experiencing a declining trend in population status. It is now classified as threatened in each state and territory it occurs, with concerns over its long-term sustainability. Now more than ever there is a need for robust research and monitoring to inform the conservation and management of the species.

Murray crayfish form the basis of important recreational fisheries in both Victoria and New South Wales (NSW). The recreational harvest is considerable, with 30% of the estimated annual catch of 551,047 crayfish in Victoria and NSW consisting of Murray crayfish (in Victoria, just under 35,000 Murray crayfish were estimated to be harvested annually) according the National Recreational and Indigenous Fishery Survey conducted over 2000–01 (Henry and Lyle 2003). In addition to providing a valuable food source, recreational fishing contributes to well-being and health (McManus et al. 2011) as well as local economies during winter months (Henry and Lyle 2003). To ensure these benefits are maintained in the future, sustainable populations of the species are necessary.

Both Victorian and NSW recreational fisheries have a long history of regulation, but consistency of fishery regulations was not achieved until 2013. At this time, the harvestable slot length limit (HSLL = 100–120 mm occipital carapace length, OCL), the timing of closed season (September to May), and daily (two) and possession (four) limits (along with continued protection of berried females) were made consistent across both fisheries. These amendments were informed by research and monitoring of NSW populations (Zukowski et al. 2012; McCarthy et al. 2014) and adopted across the Victorian recreational fishery. Yet, the effectiveness of these fishery regulations on the present status of Victorian Murray crayfish populations remains unresolved. Given the importance of the Victorian recreational fishery and the need for fishery regulations to ensure the sustainability of the species, it is critical for this assessment to take place.

1.1 Project objectives

This present project aimed to provide the information necessary to assess the Victorian Murray crayfish recreational fishery by describing the (a) present status of Victorian populations, and (b) effectiveness of the fishery regulations to manage the species. Specific aims were to undertake:

- Population benchmarking across the spatial extent of the Victorian population,
- Exploration of long-term trends in population status at key sites, and
- Population modelling of management scenarios to assess effectiveness of fishery regulations.

This information will be combined to provide a multifaceted assessment of the status of the Victorian Murray crayfish recreational fishery. This assessment will afford confidence in present regulations or provide direction to revise them to ensure greater population sustainably and harvest potential. This information will also set the baseline for future surveys that will be a critical requirement for demonstrating the improved status of populations of Murray crayfish into the future.

1.2 Report structure

The report is divided into five sections, including this introduction (Section 1) and Section 2, which contains background information relevant to the management of the recreational fishery in Victoria. The benchmarking of population status is detailed in Section 3 while a Section 4 describes population modelling of scenarios to help inform management of the species. In the general discussion (Section 5), the outcomes of the benchmarking and population modelling are synthesised to facilitate assessment of stock status across the Victorian recreational fishery. In addition, the outcomes are discussed in the context of broader conservation and management and a range of research and management recommendations are provided.

Section 2 RELEVANT BACKGROUND

A major review of the current understanding and knowledge gaps for the species across its range was achieved by Gilligan *et al.* (2007). Since this review, several research and monitoring projects have been instigated to address knowledge gaps and assess environmental disturbances. Specifically, research has focused on the sustainability of recreational fishing (Stewart 2010; Zukowski et al. 2011; Zukowski et al. 2012; Zukowski et al. 2013); the impacts of extreme hypoxic blackwater (King et al. 2012; McCarthy et al. 2014; Whiterod et al. in review) and habitat degradation (Noble and Fulton 2017). Other studies have provided insight into diet and feeding habitats (Starrs et al. 2015), juvenile recruitment (Alves et al. 2010b) and metabolic functioning (Stoffels et al. 2016), as well as novel sampling techniques (Fulton et al. 2012). Comprehensive genetic assessment has been undertaken across the present range of the species (Whiterod et al. 2017) and a stochastic population model has recently been developed to provide a framework to address management and conservation scenarios (Todd et al. in review). Background information, threats and recommendations were compiled during genus-wide conservation assessments (Furse and Coughran 2011a; Furse and Coughran 2011b; c).

The following sections update key sections of the review of Gilligan *et al*. (2007) with new information from recent research and monitoring to provide general background to guide the management of Murray crayfish in Victoria.

2.1 Species description

Murray crayfish is a member of the *Parastacidae* family, and recognised as the second largest freshwater crayfish in the world (Riek 1969). It is characterised by a hard carapace (exoskeleton) and robust sharp spines on its abdomen and chelae (claws) with smaller spines on the pereiopods (walking legs) and the carapace (Morgan 1986; Morgan 1997). It can be variable in colour; typically, the carapace and abdomen is brown-green to brown (and sometimes slightly tinged blue). It spines and chela are white or cream, except for juveniles which have mottled green and yellow chelae (Morgan 1986; Morgan 1997). Murray crayfish are easily distinguished from other spiny crayfish by its large size, white claws and absence of male cuticle partition (Morgan 1986; Gilligan et al. 2007).

Figure 2-1. The Murray crayfish.

2.2 Population status

2.2.1 Historical

Murray crayfish is endemic to the southern Murray-Darling Basin (MDB) with its range naturally extending from Australian Capital Territory (ACT), through Victoria, New South Wales (NSW) downstream to South Australia (SA) (Morgan 1986; Morgan 1997). It is the most widely distributed *Euastacus* species natural encompassing 12,500 km of waterways, or an extent of occurrence (EOO) in excess of 150,000 km^2 (Gilligan et al. 2007; Furse and Coughran 2011a). The natural Victorian range included the Ovens, Goulburn, Kiewa and Mitta Mitta rivers and tributaries, but not more westerly catchments such as the Campaspe, Loddon, Avoca or Wimmera (Morgan 1986). In NSW, the species naturally occurred in the Murray and Murrumbidgee rivers and tributaries including the Edward, Wakool, Niemur and Tumut rivers (Morgan 1997; Gilligan et al. 2007). Although once thought to be part of the natural range (cf. Riek 1969; Morgan 1997) recent genetic analyses has concluded that outlying NSW populations in the Macquarie (and also Lachlan) Catchment are the artefact of translocation (Whiterod et al. 2017). In SA, the species was once abundant in the Murray River downstream as far as Murray Bridge (Geddes 1990) and has even been recorded in the Lower Lakes

(Warneke 2000). In the ACT, the species is known from the Murrumbidgee and Cottor rivers and tributaries (Lintermans and Rutzou 1991). Across its natural range, it was considered locally abundant.

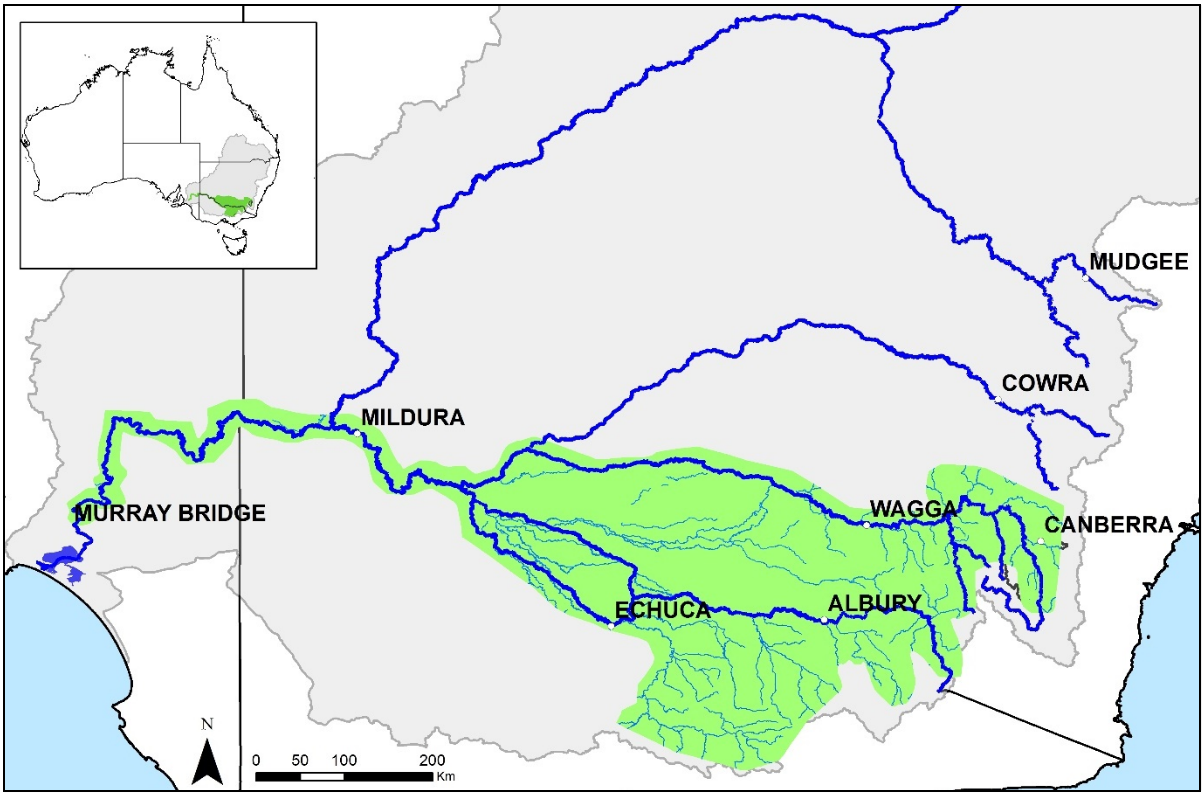

Figure 2-2. Historical distribution of Murray crayfish (green shade) across waterways (blue lines) of the southern Murray-Darling Basin (grey shade).

2.2.2 Present

The species has undergone substantial declines in its range and abundance since the 1940s and 1950s (Figure 2-3) (Gilligan et al. 2007). Nowadays, the species maintains a broad, but patchy, distribution across Victoria (Raadik et al. 2001; O'Brien 2007), with declines documented in several areas, including the lower Ovens River (Stewart 2010). In the NSW section of the Murray River, it is now absent between SA-NSW border to just upstream of the Mildura Weir Pool (McCarthy 2005; NSW Fisheries, unpublished data, 2013-2014), rare from downstream of Robinvale to Echuca (McCarthy et al. 2014; Whiterod et al. in review) and absent from weir pools and impoundments (McCarthy 2005; Zukowski 2012). It is also rare in tributaries including the Edward, Wakool and Niemur rivers (NSW DPI 2014).

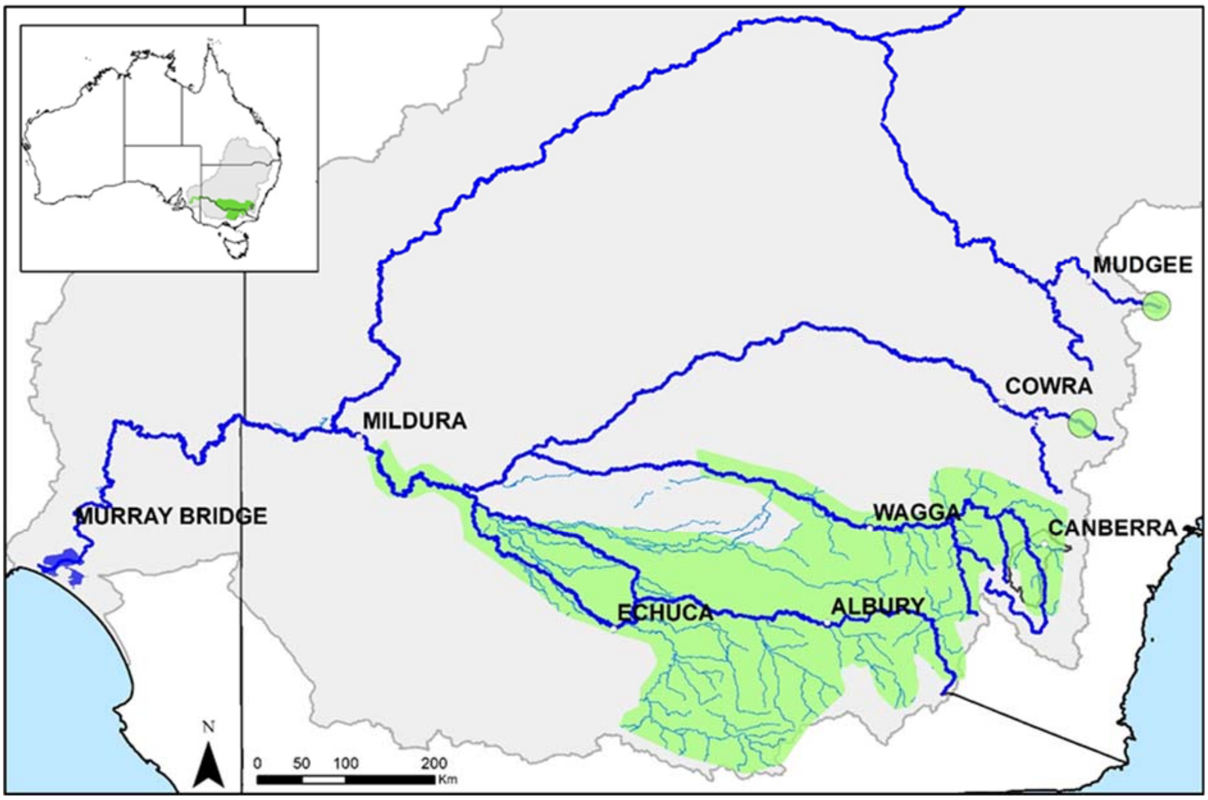

Figure 2-3. Predicted present distribution of Murray crayfish (green shade) across waterways (blue lines) of the southern Murray-Darling Basin (grey shade).

In the Murrumbidgee River, it is locally absent downstream of Hay and has undergone recent rapid declines across the mid-reaches between Narrandera and Wagga Wagga (NSW DPI 2014). Significant population declines, between 2008 and 2015, have also been noted in an upper Murrumbidgee Catchment tributary (Goobarragandra River) (Noble and Fulton 2017). The two translocated outlying NSW populations in the Lachlan and Macquarie catchments are known to persist (NSW Fisheries, *unpublished data*, 2013−2014).

The species is considered locally extinct from the SA section of the Murray River (Walker 1982; Geddes et al. 1993), which is supported by recent targeted sampling (Whiterod and Zukowski, *unpublished data*, 2013−2016). In the ACT, the species persists in extremely low numbers largely restricted to deeper river sections of the Murrumbidgee River and its tributaries (Lintermans and Rutzou 1991; Lintermans 2000; Ryan 2005; Fulton et al. 2010).

2.3 Biology and ecology

2.3.1 Life history

Murray crayfish is a long-lived (potentially up to 28 years) and slow-growing species with a maximum length 174mm occipital carapace length (OCL, in mm) observed (Morison 1988; Gilligan et al. 2007). The species is a late maturing (i.e. 8−9 years) annual spawner with a winter-spring brooder strategy (Gilligan et al. 2007). Typically, females are first observed with eggs as water temperatures decline in late autumn, and fertilised eggs and then larvae (through a succession of moults) remain attached to the pleopods under the abdomen until independent juveniles are released during late spring to early summer (O'Connor 1986; Geddes et al. 1993; Gilligan et al. 2007; Zukowski et al. 2012).

2.3.2 Habitat requirements

The species occurs across a wide range of mesohabitats – cool, clear upland streams, impoundments, and turbid lowland river sections – with a strong preference for cool, oxygenated and flowing water (Riek 1969; Gilligan et al. 2007). Flow velocity (and its link to higher dissolved oxygen concentrations) is considered an important overriding habitat feature guiding both the species' mesohabitat (i.e. the species is largely absent from slow-flowing impoundments and weir pools) and microhabitat preferences (i.e. where the species occurs it prefers medium to high flows) (McCarthy 2005; Gilligan et al. 2007; Zukowski 2012; Noble and Fulton 2017). Other microhabitat features include physical structure such as rocks and woody structure that provide shelter and refuge, as well as clay banks believed to be necessary for burrowing (Gilligan et al. 2007; Zukowski 2012; Noble and Fulton 2017). Overhanging riparian vegetation and deeper pools appear to be important microhabitat features for upland populations of the species (Noble and Fulton 2017).

2.3.3 Diet and feeding

Freshwater crayfish form important links in the transformation of energy through aquatic food webs (Reynolds and Souty-Grosset 2011). Murray crayfish are opportunistic omnivores, consuming decomposing vegetation, algae, aquatic macrophytes, invertebrates and fish and other animal meat (Gilligan et al. 2007). Starrs *et al.* (2015) recently demonstrated Murray crayfish feeding on terrestrial materials (i.e. fine woody debris and leaf litter), emphasising the importance of these food resources. More comprehensive dietary studies are necessary.

2.3.4 Movement and home ranges

Murray crayfish is considered to have lower dispersal abilities and occupy small home ranges (O'Connor 1986). Consistently, a radio-telemetry study of upland populations did not detect large-scale movements, but rather activity was restricted to small home ranges (i.e. single pools: Ryan et al. 2008). For lowland populations, movement may occur across a broader home range as revealed through a mark-recapture study (O'Connor 1986) and intimated by genetic analyses (Whiterod et al. 2017). Whilst the genetic analyses suggest home ranges may be up to 50 km, exploration of movement and home ranges across lowland populations, guided by recent advances in telemetry, is required. This work would be particularly useful to assess how the fragmented nature of existing populations and potential barriers to dispersal (e.g. weir pools) may influence the ability of the species to recolonise areas impacted by disturbance events.

2.3.5 Environmental tolerances

The species is broadly tolerant; however, mortality is experienced during adverse environmental conditions that occasionally prevail across its range. For water temperature, short-term exposure to 30°C resulted in 50% mortality of the test individuals (i.e. 12 hour LC_{50}) with peak movement performance occurring 18°C (Geddes et al. 1993; Stoffels et al. 2016). The species can tolerate salinities greater than 16 mgL^{-1}, but not low dissolved oxygen (DO) concentrations (i.e. hypoxia) with the 12-hour LC_{50} estimated at 2.2 mgL^{-1} (Geddes et al. 1993). An understanding of the sensitivity of the species to agricultural chemicals and pesticides remains lacking (Gilligan et al. 2007).

2.4 Conservation status

Murray crayfish is considered *threatened* in Victoria under the *Flora and Fauna Guarantee Act 1988* and *vulnerable* in NSW (*Fisheries Management Act 1994*) and the ACT (*Nature Conservation Act 1980*). In South Australia, it is classed as *protected* under the *Fisheries Management Act 2007*. The species is listed nationally as *indeterminate* (under the

Environment Protection and Biodiversity Conservation Act 1999) and internationally as *data deficient* (under *International Union for Conservation of Nature Red List of Threatened Species 2010*) (Alves et al. 2010a).

2.5 Recreational fishery

Recreational fisheries occur in Victoria and NSW, but recreational harvesting has been prohibited in South Australia and the ACT since 1989 (Gilligan et al. 2007). The Victorian and NSW recreational fisheries are regulated by length limits (both minimum (MLL) and harvestable slot (HSLL) length limits), daily (bag) and possession limits, as well as season and Table 2-1).

Initially (since 1883), the NSW fishery was regulated only by a minimum legal limit (MLL = 4 ounces, ~61 mm), but a range of amendments, such as area closures and the protection of berried females, were enacted up until major regulation change in 1989. In 1989, a MLL of 80 mm was established and bag (10) and possession (20) limits were first installed in 1995. In 2003, substantial changes occurred with an increase in the MLL (to 90 mm), limitations placed on the take of larger crayfish (i.e. only one individual above 120 mm) and reductions in bag (5) and possession (10) limits as well as establishment of a closed season (September to April).

In Victoria, there were no size restrictions but fishing effort were regulated (e.g. only two baited lines and three hoop nets permitted) until the recreational fishery was closed in 1983. This statewide closure was enacted due to concerns over declining abundances and smaller sizes (Barker 1992). The recreational fishery was re-opened in 1991 with a MLL = 90 mm, an increase in the allowable fishing effort (i.e. increased from three to five hoop nets) whereas the possession limit (10) and the protection of berried females were retained (Barker 1992). In 1993, an open season (September to April) was introduced in Victoria and the possession limit was reduced from 10 to five crayfish, with only one above 120 mm was enacted in 2001.

In 2013, amendments to the fishing regulations were made across both Victorian and New South Wales recreational fisheries guided by the outcomes of recent research (Zukowski et al. 2012; McCarthy et al. 2014). Specifically, the HSLL (100–120 mm) was established, the daily (2) and possession (5) limits were reduced and the closed season (now September to May) was increased. Additionally, large sections of the NSW range were closed due to observed population declines. The amended MLL was adopted the Victorian fishery, but its suitability has not been assessed until the present project.

Table 2-1. Timeline of fishery regulation amendments for Murray crayfish. MLL = minimum length limit; HSLL = harvestable slot length limit.

<table>
<tr><th rowspan="2">State or territory</th><th rowspan="2">Fishery regulation</th><th colspan="9">Year</th></tr>
<tr><th>1983</th><th>1989</th><th>1991</th><th>1993</th><th>1995</th><th>2001</th><th>2003</th><th>2007</th><th>2013</th></tr>
<tr><td rowspan="5">Victoria</td><td>Length limit</td><td colspan="2" rowspan="4">Fishery closed</td><td colspan="3">90 mm MLL</td><td colspan="3">90 mm MLL; with only one above 120 mm</td><td>100–120 mm HSLL</td></tr>
<tr><td>Daily bag limit</td><td colspan="6">-</td><td>2</td></tr>
<tr><td>Possession limit</td><td>10</td><td colspan="5">5</td><td>4</td></tr>
<tr><td>Closed season</td><td>-</td><td colspan="5">September to April</td><td>September to May</td></tr>
<tr><td>Berried females</td><td colspan="9">Totally protected; no take or harming (including removal of eggs)</td></tr>
<tr><td rowspan="6">NSW</td><td>Length limit</td><td>~61 mm MLL</td><td colspan="5">80 mm MLL</td><td colspan="2">90 mm MLL; with only one above 120 mm</td><td>100–120 mm HSLL</td></tr>
<tr><td>Daily bag limit</td><td colspan="4">-</td><td colspan="2">10</td><td colspan="2">5</td><td>2</td></tr>
<tr><td>Possession limit</td><td colspan="4">-</td><td colspan="2">20</td><td colspan="2">10</td><td>4</td></tr>
<tr><td>Closed season</td><td colspan="6">-</td><td colspan="2">September to April</td><td>September to May</td></tr>
<tr><td>Area closure</td><td colspan="6">-</td><td colspan="2"></td><td>Fishing only allowed between Albury and Tocumwal on the Murray River and between Gundagai and Berembed Weir on the Murrumbidgee River</td></tr>
<tr><td>Berried females</td><td colspan="9">Totally protected; no take or harming (including removal of eggs)</td></tr>
<tr><td>ACT</td><td>Total closure</td><td colspan="9">Fishery closed</td></tr>
<tr><td>SA</td><td>Total closure</td><td colspan="9">Fishery closed</td></tr>
</table>

Section 3 BENCHMARKING

3.1 Introduction

Understanding the present status across its range has been identified as the most significant knowledge gap for the Murray crayfish (Gilligan et al. 2007; Furse and Coughran 2011c). Work toward this knowledge gap has been achieved in NSW (NSW Fisheries, *unpublished data*, 2011−2015), the ACT (Fulton et al. 2010) and South Australian sections of the Murray River (Whiterod and Zukowski, *unpublished data*, 2013−2016), but remains lacking in Victoria. The present project redressed this deficiency by providing comprehensive benchmarking across the spatial extent of the Victorian range of the species – with a focus on areas targeted by recreational fishers (e.g. that is accessible by boat) as to assess the fishery. This benchmarking was guided by sampling methodology proposed by Gilligan *et al.* (2007) to allow consistent information on relative abundance and key population parameters, with temporal trends explored at sites previously monitored. Specific aims of the benchmarking were to:

- Document range and abundance,
- Define population parameters (length structure, sex ratio and sexual maturity), and
- Explore temporal patterns in abundance and population parameters by comparing present benchmarking with previous monitoring at key sites.

This benchmarking will not only assess the sustainability of the recreational fishery but also provide insight in the conservation status of the species.

3.2 Sampling methodology

3.2.1 Site selection

Spatial analyses were used to identify potential sampling sites that targeted areas where recreational fishers used standard methods (i.e. hoop netting from a boat). To achieve this the spatial scope was constrained to large waterways (defined as discharges >100 $MLday^{-1}$ based on National Environmental Stream Attributes spatial layer: Stein et al. 2014) at elevations below 400 m Australian Height Datum (AHD) across the historical Victorian distribution (from Gilligan et al. 2007). This spatial scope of sampling was stratified by the seven catchments (Goulburn, Ovens, Broken, Mitta Mitta, Kiewa, Campaspe and Murray) where the species is expected to occur, to ensure broad coverage across the Victorian range. The number of sites selected within each catchment was guided by the length of each major river in that catchment (i.e. the longer the river, the more sampling sites). Finally, a randomised process was used to identify potential sampling sites across the spatial scope of sampling, except for long-term monitoring sites, which were preferentially selected to allow assessment of temporal patterns.

The final list of sites sampled during the Victorian benchmarking was governed by the ability to access the river and sample efficiently (Table 3-1). All spatial analyses were conducted in ArcMap v10.4 (ERSI, Redlands, CA).

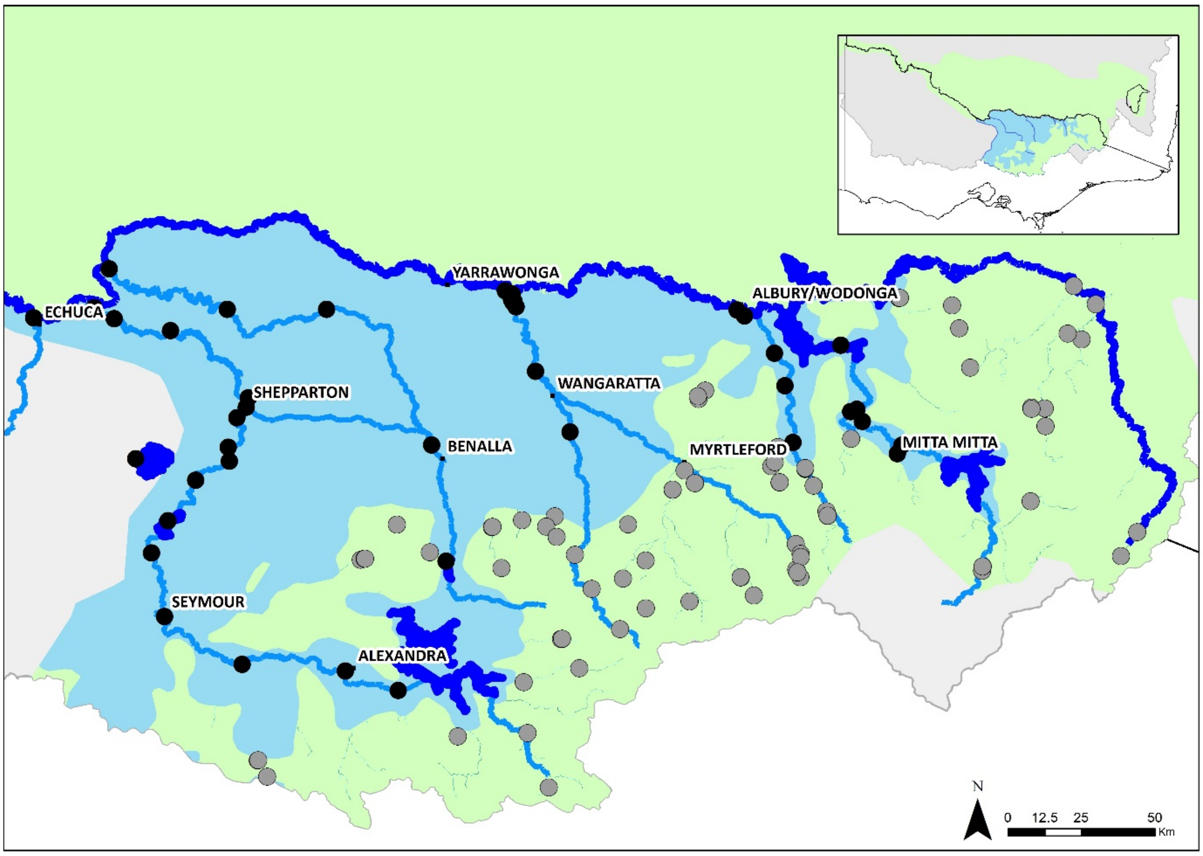

Figure 3-1. Spatial extent of present benchmarking (black dots) and addition upland sampling sites (grey dots).

All sites were sampled between 2014 to 2016, over winter and early spring months when Murray crayfish catches are highest (Zukowski et al. 2012). All monitoring was conducted in accordance with Victorian permits (Fisheries Victoria research permit no. RP1092; National Parks Act 1975 and Flora and Fauna Guarantee Act 1988 research permit no. 10006992) and ethics approvals (Wildlife and Small Institutions Animal Ethics Committee approval numbers 21.12 and 12.15).

Table 3-1. Summary of sites sampled during Victorian benchmarking.

Catchment	Waterway	Location	Easting	Northing	Date sampled
Broken	Broken Creek	Dip Bridge	376622	6004700	07-Jul-16
	Broken River	Goulburn junction	355055	5971129	10-Aug-15
	Broken Creek	Murray junction (us regulator)	316487	6017354	05-Aug-15
	Lake Nillahcootie	Sandy Creek arm	410376	5919624	09-Jul-16
	Broken River	Scholes Road	406012	5959004	10-Aug-15
	Broken Creek	Walshs Road Bridge	349262	6004238	05-Aug-15
Campaspe	Campaspe River	Murray Junction	296016	6000310	06-Aug-15
Goulburn	Goulburn River	Alexandra Bridge	383446	5881985	01-Jul-16
	Goulburn River	Arcadia	350756	5952710	07-Aug-15
	Goulburn River	Cemetery Bend	350339	5957438	05-Jul-16
	Goulburn River	Frasers Bend	333788	5996751	06-Jul-16
	Goulburn River	Ghin (Yea junction)	355390	5883836	02-Jul-16
	Lake Nagambie	Kirwans Bridge (us)	334356	5932185	24-Jul-14
	Goulburn River	Mitchelltown	330049	5921197	30-Jun-16
	Goulburn River	Murchison (Campbell Bend)	341638	5946076	04-Jul-16
	Goulburn River	Point Hill	397905	5875559	01-Jul-16
	Goulburn River	Pykes Road	352563	5967455	10-Aug-15
	Goulburn River	River Bend Caravan Park	312640	6004079	07-Jul-16
	Goulburn River	Seymour (Goulburn Caravan Park)	334014	5899626	02-Jul-16
	Goulburn River	Shepparton (Youngs Bend)	355565	5974282	05-Jul-16
	Waranga Basin	Western Section (Caravan Park)	325115	5953098	04-Jul-16
	Goulburn River	Yambuna	318206	6000446	06-Aug-15
Kiewa	Kiewa River	Barton's Lane (Yika's Point)	499946	5990670	01-Aug-15
	Mt Beauty tailrace	Behind AGL office	514825	5933961	24-Jul-14
	Kiewa River	Keenans Bridge	505023	5960336	30-Jul-15
	Kiewa River	Kergunyah Bridge	502795	5979625	31-Jul-15
	Kiewa River	Mongan's Bridge	508320	5951301	21-Jul-14
Mitta Mitta	Mitta Mitta River	Giltrap Road	534848	5959364	13-Jul-16
	Mitta Mitta River	Haggerty Lane	520788	5970816	31-Jul-15
	Mitta Mitta River	Mitta Mitta (Snowy Creek junction)	533541	5956477	13-Jul-16
	Mitta Mitta River	Mitta North Road	523990	5967450	21-Jul-14
	Mitta Mitta River	Peters Bridge	522509	5971618	14-Jul-16
	Lake Hume	Upper Mitta Mitta arm	518176	5993348	15-Jul-16
Murray	Wodonga Creek	Lower section	489618	6005266	18-Jul-16
	Wodonga Creek	Morison Site	491694	6003302	08-Aug-15
Ovens	Ovens River	Boorhaman Reserve	428783	6006108	04-Aug-15
	Ovens River	Bundalong junction	425751	6011481	04-Aug-15
	Ovens River	Cameron Bend	427953	6007506	12-Jul-16
	King River	Oxley Recreation Reserve	443917	5963777	11-Jul-16
	Ovens River	Parolas Bend (Punt Creek)	427512	6008530	12-Jul-16
	Ovens River	Parolas Bend, downstream	427762	6010403	08-Jul-16
	Ovens River	Parolas Bend, upstream	428228	6007945	08-Jul-16
	Ovens River	Warby Range Road (Boorhaman)	434306	5984231	23-Jul-14

3.2.2 Sampling protocol

Field sampling followed protocols similar to those used by recreational fishers and employed during recent research on lowland populations of the species (Zukowski 2012; McCarthy et al. 2014). At each site, twenty hoop nets (single 800 mm diameter, 13 mm stretch mesh size, 0.3 m drop baited with ox liver) were deployed across a 2-km stretch of the river and retrieved hourly over three deployments (maximum of 60 net lifts). Nets that lost their bait or were snagged upon retrieval were excluded from the abundance.

Sampled Murray crayfish were sexed, weighed (W, in g) using waterproof scales (A&D Weighting, Tokyo, Japan) and length (OCL, in mm) measured with Vernier callipers (Kinchrome, Scoresby, Victoria, Australia) (Figure 3-2). The stage of maturity (stages 1–3) was recorded for females as was the presence of eggs (Turvey and Merrick 1997). Additionally, each crayfish was marked using a Uni PAINT PX-20 marker (Mitsubishi Pencil Co. Ltd, Milton Keynes, UK: see Ramalho et al. 2010) to identify potential recaptures (during sampling event) before being returned to the water at the point of capture.

Figure 3-2. Processing sampled Murray crayfish: measuring length (top left); weight (top right); temporarily marking (to detect recaptures) (bottom left); and sexing (female gonopores highlighted with green circles) (bottom right).

At each site, environmental descriptors, covering differing aspects of underwater cover, edge vegetation, pool condition, flow and water quality (using YSI 556 multi-probe) were recorded to aid the interpretation of results and assist with broader condition assessment.

3.3 Collation of other data

Previous monitoring data was collated as part of the project to provide insight into long-term trends in population status. Data included the sampling of the three important locations (Nagambie Lakes, Wodonga Creek and the Ovens River) between 1984 and 1988 (Morison 1988) and again in 1990 along with an additional site on Waranga Basin (Barker 1992). From 1993 to 1999, two locations on the Ovens River were sampled infrequently (i.e. 1993, 1994, 1996, 1998, 1999, 2003) by Victoria Victorian fisheries agencies and departments, which were resampled in 2010 by Stewart (2010).

3.4 Data treatment and analysis

At each benchmarking site, the total number of Murray crayfish caught and the sampling effort (number of net replicates) was used to compute the catch-per-unit-effort abundance (hence CPUE abundance represented as crayfish net^{-1} h^{-1}). For direct comparison with historical monitoring, CPUE abundance was defined as crayfish net lift^{-1} as soak time was often not recorded. Length structures were developed using 10-mm size classes with differences between sexes and years assessed using two sample Kolmogorov-Smirnoff tests (KS-test). Exact binomial testing was used to assess whether sex ratios over treatments and years deviated significantly from unity (1 : 1, males : females). Further, the length-at-age relationship ($OCL_t = 192.8*(1 - e^{(-0.0843(t + 0.3752)})$), where OCL_t is the occipital carapace length at time t) for the Murray population (O'Connor 1986) was used to provide insight into age structure across sampled sites. The percentage of sexually mature females in a given size class (OCL) was determined, and then fitted by means of the logistic equation (Zukowski et al. 2012; Zukowski et al. 2013):

$$M = \frac{100}{1 + \left(\frac{L}{SOM_{50}}\right)^b}$$

Where M is the percentage of females in a size class, L is the OCL (mm), SOM_{50} is the length at which 50% of females are mature (SOM), and b is a constant. These analyses were performed using Systat, v12 (Systat Software Inc. Richmond, CA, USA).

3.5 Results and discussion

The following section provides summary of the outcomes of benchmarking of Victorian populations and interpretation in context with previous studies and the present recreational fishing regulations.

3.5.1 Overall summary

Numbers and CPUE abundance

Over the present benchmarking study, 469 Murray crayfish were recorded from 43 sampling sites across seven catchments (Figure 3-3). Relative abundance ranged between 0 and 0.38 crayfish net^{-1} hour^{-1}, with three areas of high relative abundance identified, which is consistent with previous monitoring of the species (Morison 1988; Barker 1992):

- **mid-Goulburn River** – between Seymour and upstream of Shepparton,
- **lower Ovens River** – downstream of Wangaratta to Murray junction, and
- **Wodonga Creek** – along the entire length of this short creek.

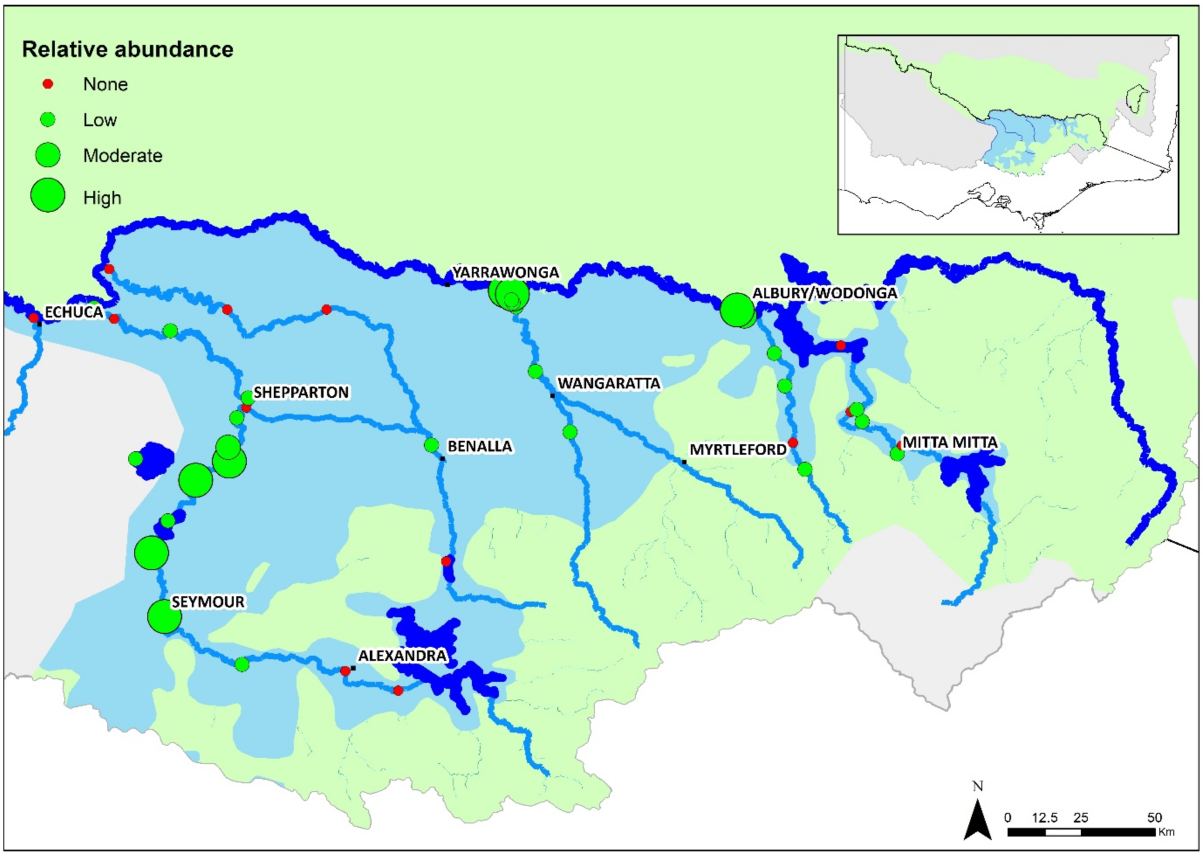

Figure 3-3. Relative abundance (CPUE abundance, crayfish net^{-1} hour^{-1}) of Murray crayfish across the Victorian recreational fishery.

Implication for recreational fishery:

- Species is patchily distributed, with variable relative abundance
- Three areas (mid-Goulburn River; lower Ovens River; Wodonga Creek) with high relative abundance reconfirmed

Length and estimated age structure

Exploration of length and age structure across recreational fisheries provides a snapshot of population dynamics such as recruitment and longevity as well as signs of overfishing (Froese 2004). For Murray crayfish, unfished populations maintain robust normally-distributed length structures (Zukowski et al. 2013), whereas those influenced by fishing pressure typically exhibit length structures that are contracted and unbalanced with lower mean length of individuals (Stewart 2010; Zukowski et al. 2012).

In the present benchmarking study, a broad length structure was observed across the Victorian population, with length ranging between 19 and 156 mm and weight between 14 and 1667 g with a mean length of 87.95 mm and weight 375.57 g (Figure 3-4). Much of the population (69.94%) was under the HSLL range with 23.24% of sampled individuals within the HSLL, but the percentage of harvestable individuals (e.g. those in the HSLL and not in berry) was much lower (5.54%). Only a small percentage (6.82%) of population was above the HSLL, of which only two of these individuals were male. The length structures of all individuals (KS-test, D = 0.167, $p > 0.200$) and females only (KS-test, D = 0.201, $p = 0.101$) were normally distributed, but the male length structure varied significantly from normality (KS-test, D = 0.226, $p = 0.038$). The significantly skewed length structure of males is not surprising given the preferential harvesting of these individuals (see also sex ratio section).

The length structure corresponded with ages between 0.9 to 19.3 years (Figure 3-5), using the known growth (length-at-age) relationship for the species (O'Connor 1986). Despite the fact that the species is estimated to live for over 25 years (Gilligan et al. 2007; Todd et al. in review) the majority of the sampled population were under eight years old and were thus juveniles.

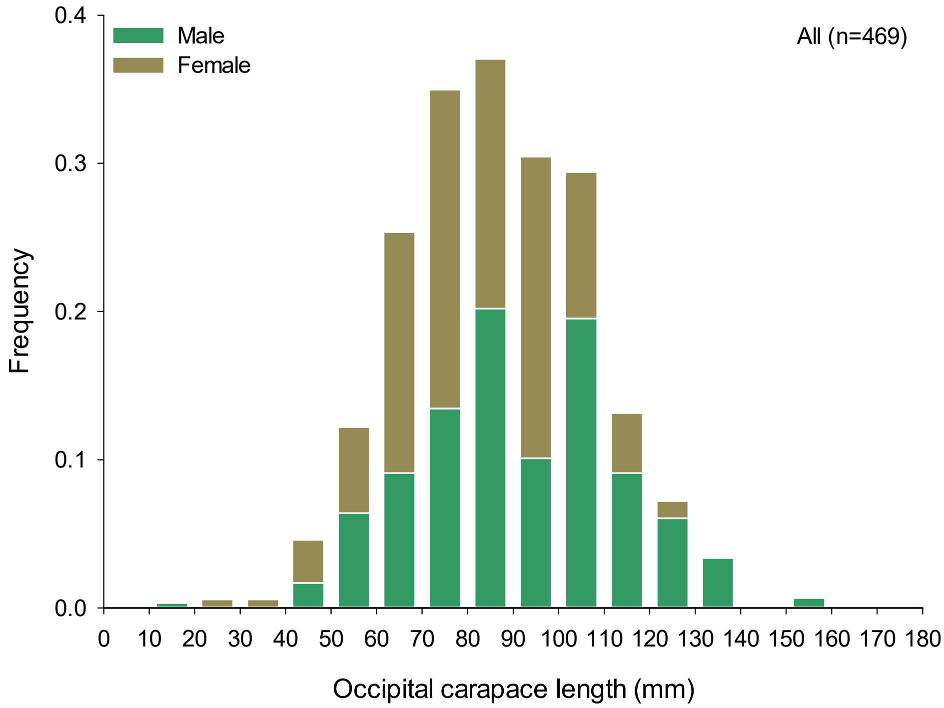

Figure 3

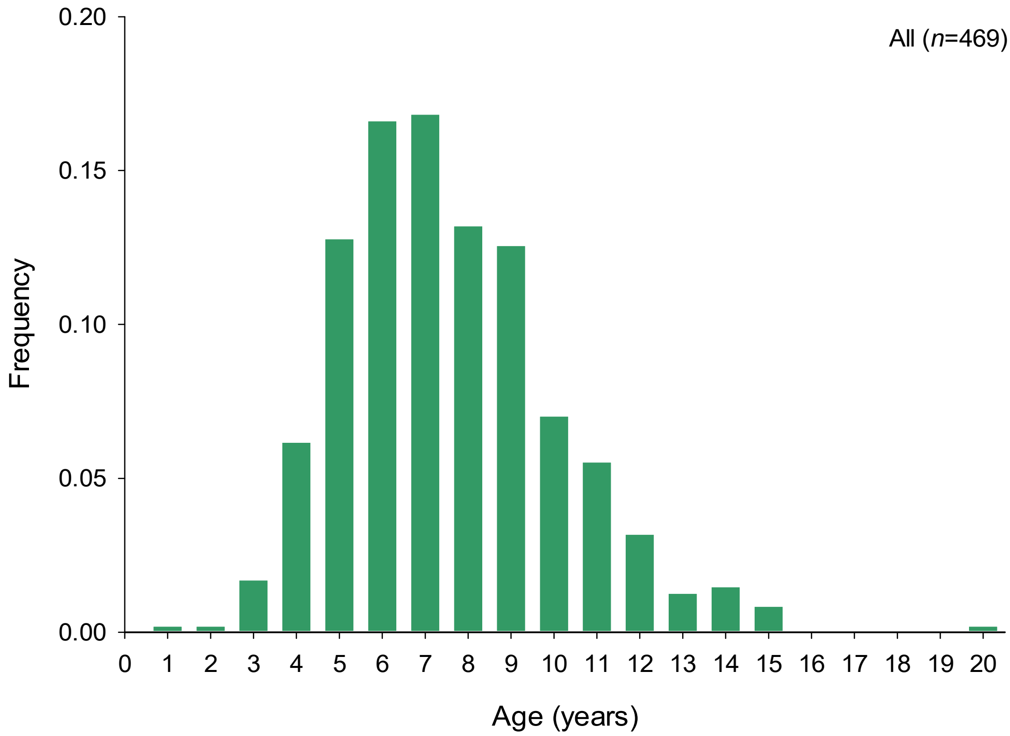

Figure 3-5. Estimated age structure of Murray crayfish across Victoria population.

Implication for recreational fishery:

- Broad (19–156 mm) and normally distributed length structure
- Estimated age range from 0.9 to 19.3 years with the majority of the sampled population were under eight years old (i.e. juveniles)

Sex ratio

The ratio between males and females within a population is a fundamental ecological indicator, which is particularly useful to explore harvest pressure experienced by recreationally fished populations that are subject to sex-selective harvesting. The natural sex ratio for freshwater crayfish is predicted to be in unity (1 : 1: males to females: Holdich 2002). Consistently, studies have revealed 1 : 1 sex ratios in unfished Murray crayfish populations (Zukowski et al. 2013) and populations subject to a period of fishery closure (Morison 1988; Barker 1992). Yet, under the present Murray crayfish fishery regulations, larger males are almost exclusively harvested given the total protection of berried females and that most females within the HSLL range are in berry (Gilligan et al. 2007; Zukowski et al. 2012).

During the present benchmarking, the sex ratio (0.58 : 1) across all sampled individuals was significantly skewed toward females (binomial test, $p < 0.001$). Within the HSLL, the female-bias was more pronounced (0.28 : 1; binomial test, $p < 0.001$) consistent with substantial pressure being placed on male Murray crayfish (Table 3-2). In contrast, the sex ratio (0.80 : 1) did not divergence significantly from unity (binomial test, $p = 0.053$) for Murray crayfish below the HSLL and thus not subjected to recreation fishing. Above the HSLL, the sex ratio was 0.06 : 1, indicating that very few males are making it through the HSLL.

Table 3-2. Sex ratios of Victorian population.

Size class	Sex ratio (males to females)	Males	Females
All	0.58 : 1	172	297
Below HSLL (<100mm)	0.80 : 1	148	182
Harvestable range (100–120mm)	0.28 : 1	24	85
Above HSLL (>120mm)	0.06 : 1	2	30

Other studies have revealed similarly female-biased sex ratios for Murray crayfish populations under the fishing regulations prevailing at that time (McCarthy 2005; Zukowski et al. 2011). Most relevantly, over the period that the present HSLL has been in place (i.e. 2014–2016), the HSLL sex ratio (0.32 : 1) for the open area on the Murray River was comparable to that of the present Victorian benchmarking as was the sex ratio below the HSLL (0.77 : 1) although slighter more males made it through the HSLL (>HSLL = 0.13 : 1: Whiterod et al. in review). It has been suggested that skewed sex ratios may not pose a threat to the population viability, as long as there are sufficient reproductively active males to reproduce with mature females (Gilligan et al. 2007; Stewart 2010); yet the critical threshold remains unknown and caution must be exercised.

Implication for recreational fishery:

- Sex ratio was significantly skewed toward females within the HSLL
- Below the HSLL the sex ratio was not significantly different from unity
- Few males were observed above the HSLL

Sexual maturity

The size of onset of sexual maturity (*SOM*) is commonly employed to guide the establishment of the lower limit of length-based harvest regulations (Gwinn et al. 2015). Sustainable lower limits aim to guard against recruitment overfishing (i.e. diminishing reproductive potential of a population) by allowing all individuals to spawn-at-least-once (Froese 2004). In the present study, we define SOM as the length where 95% of sampled females reach sexual maturity (SOM_{95}) given the asymptoting nature of the logistic equation defining SOM. However, pragmatically, the MLL is often set to provide an opportunity for 50% of the population to reach sexual maturity (SOM_{50}), with this principle guiding the recent increases in the lower limit from 90 to 100 mm for the recreational fishery in NSW (Gilligan et al. 2007; Zukowski et al. 2012) and adopted in Victoria. For instance, Zukowski *et al*. (2012) showed that in Murray River populations, only 39% of females were mature at 90 mm whereas at 100 mm almost all females were mature (SOM_{50}: 91.77 mm; SOM_{95}: 103.75 mm). Whilst the amended lower limit was adopted across the Victorian fishery, its suitability has not been assessed until the present benchmarking.

During the present benchmarking, sexually mature females ranged between 75 and 156 mm, with the largest immature female measuring 107 mm and the smallest mature female measuring 75 mm. The SOM_{50} was estimated at 87.29 mm (r^2 = 0.99, n=14 size classes) while the SOM_{95} was 104.44 mm with 93.34% of females mature at present lower limit (100 mm) (Figure 3-6). For all mature females, 93.25% were in berry with all mature females in the HSLL possessing eggs. In combination, this resulted in only 3.49% of sampled females being available for harvest (i.e. in HSLL and not with eggs). Over a similar period (2014–16) in the Murray River, the percentage of females subject to harvest was much higher (i.e. 25.00%) (Whiterod et al. in review). It will be interesting to see how the minimal percentage of females available for harvest across the Victorian population will influence sex ratios over time and if there are any consequences for population viability.

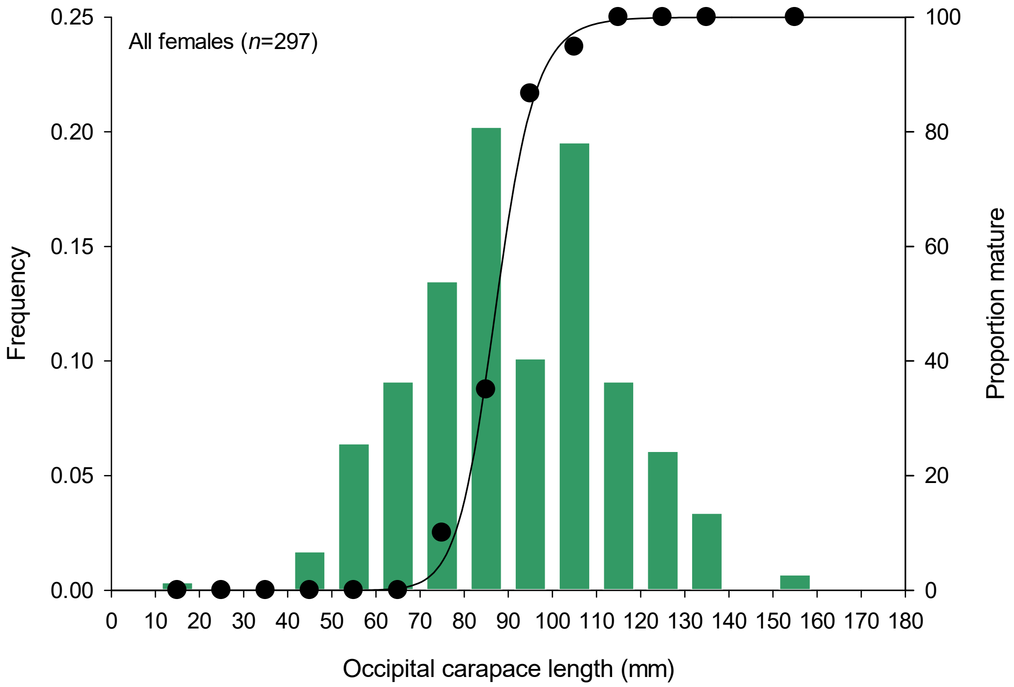

Figure 3-6. Length-frequency distribution of male and female Murray crayfish populations across Victoria.

Implication for recreational fishery:
• 50% of females mature at 87.29 mm and 95% mature at 104.44 mm • 93.34% of females mature (thus have opportunity to 'spawn-at-least-once') at lower limit of present HSLL and all mature females in the HSLL possessed eggs • On basis, only 3.49% of sampled females were potentially available for harvest (e.g. in HSLL and without eggs)

3.5.2 Catchment summaries

Goulburn Catchment

The focus within this catchment was the Goulburn River between Lake Eildon and the Murray River junction, where the river transforms from clear, cold and fast flowing to turbid and slow-flowing with a high density of woody structure across lower sections. The two impounded areas (Lake Nagambie and Waranga Basin), where the species is known to occur (Morison 1988; Barker 1992), were also sampled. The focus area included two sections (Lake Eildon to Alexandra and Murchison to Loch Garry) classified as Premier Rivers as part of the Victorian Go Fishing initiative and sections of the river within the Lower Goulburn National Park.

Fifteen sites were sampled across the catchment (Figure 3-7), with Murray crayfish recorded at 12 of these sites - the species was not recorded at two sites in the upper catchment (Goulburn River – Point Hill; Goulburn River – Alexandra Bridge) or the lower Goulburn River – Yambuna. CPUE abundance ranged between 0 to 0.38 crayfish net^{-1} $hour^{-1}$, with strong CPUE abundances, the highest observed across the present benchmarking, confined to the section of the Goulburn River from Seymour to Cemetery Bend. In contrast, CPUE abundances <0.05 crayfish net^{-1} $hour^{-1}$ were recorded at Goulburn River sites between Lake Eildon and Seymour and Shepparton to Murray junction as well as in the Waranga Basin.

Figure 3-7. Selection of Goulburn Catchment sites: (top left) Goulburn River – Point Hill; Goulburn River – Ghin Ghin (Yea junction); Waranga Basin – Western section; and Goulburn River – Riverside Caravan Park.

A total of 275 Murray crayfish, ranging between 28 to 156 mm OCL and 12 to 1667 g were sampled across the catchment (Figure 3-8). The length structure for females (KS-test, D = 0.255, $p < 0.05$), males (KS-test, D = 0.269, $p < 0.05$) and all individuals (KS-test, D = 0.236, $p < 0.05$) varied significantly from normality. There was a slightly more pronounced female-biased sex ratio (0.52 : 1; binomial test, $p < 0.001$) observed across the Goulburn population, compai

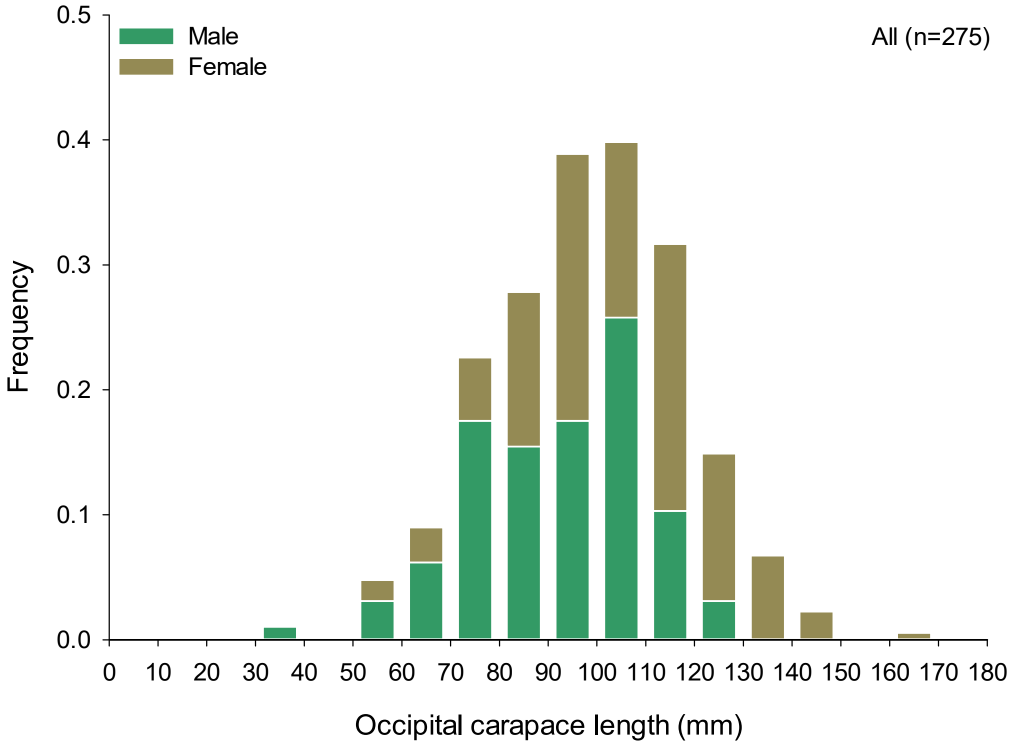

Figure 3-8. Length structure of Murray crayfish sampled from the Goulburn Catchment over the present benchmarking.

Temporal comparison of a period (1984–1990) during which the recreational fishery was closed with that of the present benchmarking revealed declines in CPUE abundance at two sites across the Goulburn Catchment. In Lake Nagambie CPUE abundance was 0.43 crayfish net lift^{-1} averaged over 1984–1988 (Morison 1988) and up to 0.59 crayfish net lift^{-1} in 1990 (Barker 1992) but considerably lower during the present benchmarking (0.29 crayfish net lift^{-1}) (note CPUE abundance presented as crayfish net lift^{-1} for comparative purposes). The present benchmarking also revealed a substantially lower CPUE abundance in the Waranga Basin compared to 1990 (0.083 vs. 0.146 crayfish net lift^{-1}). In terms of sex ratio, a greater skew toward females was evident during the present benchmarking (Lake Nagambie: 0.53 : 1; Waranga Basin: 0.53 : 1) compared to historical monitoring of Lake Nagambie (0.80 : 1) and Waranga Basin (0.84 : 1). Length structure varied significantly between the historical monitoring and present benchmarking (KS-test, D = 0.562, $p < 0.001$), both of which were not significantly different to normality (historical: KS-test, D = 0.223, $p = 0.129$; present: KS-test, D = 0.318, $p < 0.058$) (Figure 3-9). The present benchmarking revealed an older and more truncated length structure compared to the historical monitoring, perhaps reflecting restricted recruitment or simply a shift in the mean length accompanied the recent increase in the lower length limit. Taken together, it is evident that presently the Murray crayfish populations at the two sites in the Goulburn River at Lake Nagambie are less abundant, more skewed toward females with an older and truncated length structure.

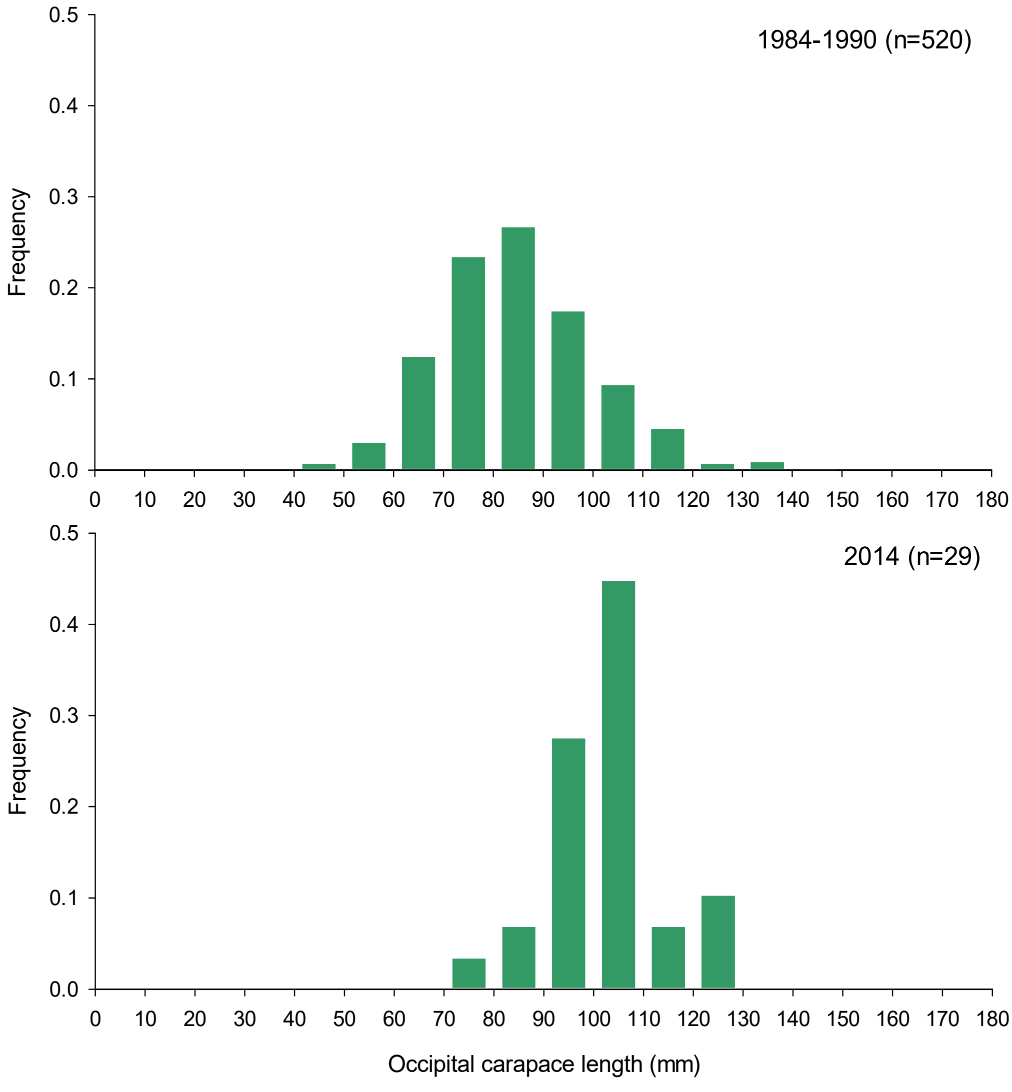

Figure 3-9. Length structure of Murray crayfish in Goulburn River – Lake Nagambie during the (a) period the recreational fishery was closed (1984–1990) and (b) present benchmarking (2014) (historical data sourced from Morison 1988; Barker 1992).

Implication for recreational fishery:

- Most important catchment for the species, with highest abundance of the present benchmarking recorded
- Absent or in low abundance across sections of the catchment
- Temporal comparison indicates declining abundance, skewing of sex ratio, and aging and truncating of length structure over time

Ovens Catchment

Sampling in this catchment predominately focused on the lower Ovens River (between Wangaratta and the Murray River junction, including the backwaters of Lake Mulwala) although an additional site was sampled on the King River, a major tributary flowing into the Ovens River above Wangaratta (note: the sampling of additional sites within this catchment was prevented by flooding (and high flows) and subsequent restrictions on river access). The focus section (i.e. the Ovens River below Wangaratta) is a turbid meandering river with extensive wetlands and surrounding river red gum forests and largely within the Warby-Ovens National Park and Lower Ovens River Wildlife Reserve. The lower reaches of the river are influenced by the impoundment of Lake Mulwala, which acts to create wide river channel, deep water and relatively slow flows (when the lake is at full supply). The Ovens Rivers is considered one of the least regulated rivers in the Murray-Darling Basin with regular flooding events, which support a diversity of aquatic animals and plants (Cottingham et al. 2001).

A total of 115 Murray crayfish, ranging between 19 to 133 mm OCL and 14 to 1015 g, were sampled from eight sites across the catchment (Figure 3-10 and Figure 3-11). The highest CPUE abundance (0.21 and 0.33 crayfish net^{-1} hour^{-1}) were recorded at two sites below the Murray Valley Highway. Very low CPUE abundance was recorded at the other sites (0.00–0.03 crayfish net^{-1} hour^{-1}) including two sites just upstream of the Murray Valley Highway. It is worth highlighting that inaccessibility to due overbank flooding of the lower Ovens River over open season often acts to indirect enact area closures (i.e. Parks Victoria close access tracks and high river unsuitable for hoop netting). Of sampled individuals, the sex ratio, although significantly different to unity (0.69 : 1; binomial test, $p < 0.001$) was less skewed than that of the overall Victorian population (0.58 : 1) although the HSLL sex ratio was consistent (0.30 : 1 v 0.28 : 1). The length structure for females (KS-test, D = 0.231, $p < 0.05$), males (KS-test, D = 0.283, $p < 0.05$) and all individuals (KS-test, D = 0.233, $p < 0.05$) varied significantly from normality.

Figure 3-10. Selection of Oven Catchment sites: (top left) Ovens River – Warby Range Road; Ovens River – Parolas Bend, do k.

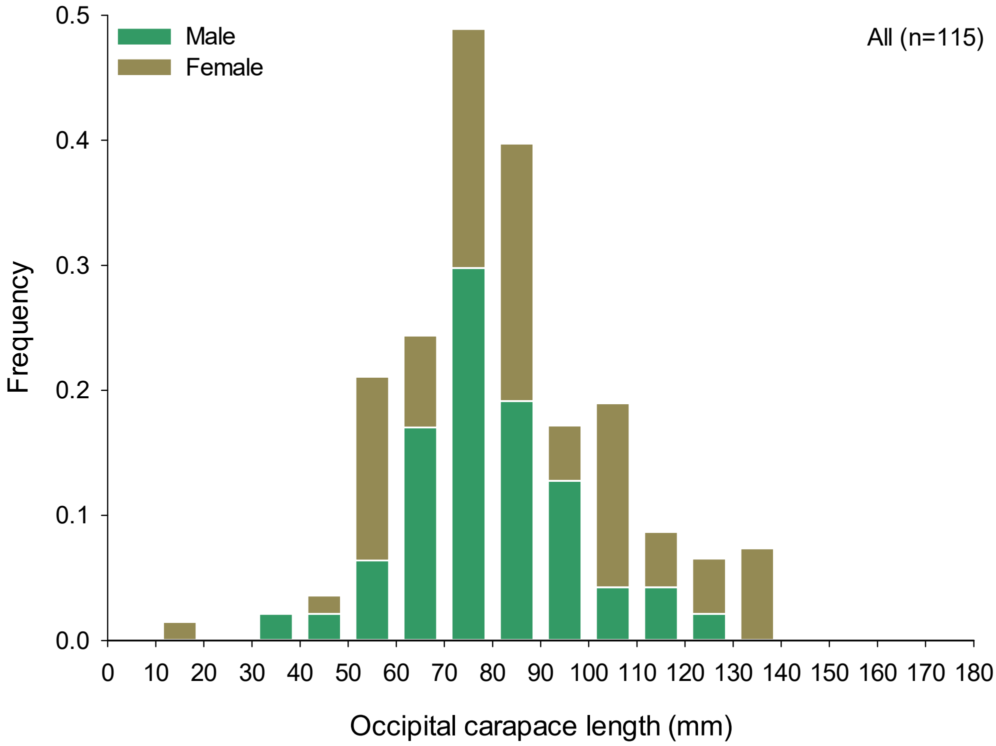

Figure 3-11. Length structure of Murray crayfish sampled from the Ovens Catchment over the present benchmarking.

The lower reaches of the Ovens River are important to assess temporal trends in Murray crayfish populations with sampling occurring more regularly (but still intermittently) than other Victorian catchments. Monitoring initially occurred during the period when the recreational fishery was closed (annually between 1984–1988 and 1990) and continued less frequently when the fishery re-opened with fishing regulation of 90 mm MLL (i.e. 1993, 1994, 1996, 1998 and 1999), and was revised to include protection of larger crayfish (i.e. only one individual above 120 mm: 2003 and the resampling by Stewart 2010). The present benchmarking reflected implementation of the 100–120 mm HSLL. Comparison across these time periods indicates that CPUE abundance (again presented as crayfish net lift^{-1} for comparative purposes) has declined over time (Table 3-3). Specifically, CPUE abundance has reduced by one third from the period of fishery closure (0.44 ± 0.07 crayfish net lift^{-1}) to the present benchmarking (0.29 ± 0.17 crayfish net lift^{-1}). When you compare the present benchmarking to the period of peak CPUE abundance (i.e. in the years following re-opening of the fishery), the decline is more pronounced (63%). It is evident that CPUE abundance varied substantially between years (not just time periods) as well as across sites of the lower Ovens Rivers (as evidenced in present benchmarking). For instance, CPUE abundance fluctuated between 1.26 crayfish net lift^{-1} in 2003 to only 0.09 crayfish net lift^{-1} in 2010. Furthermore, fewer than five crayfish were observed at four of the six sites sampled across the lower Ovens River during the present benchmarking.

Table 3-3. Summary of catch from lower Ovens River over time (data sourced from Morison 1988; Fisheries Victoria, unpublished data; Stewart 2010).

Timing of monitoring	Fishery regulation	CPUE Abundance (crayfish net lift^{-1})	Size range (mm)	Sex ratio
1984–1988	Total closure	0.44 ± 0.07	32–174	1.09 : 1
1993–1999	Re-opened with 90 mm MLL	0.78 ± 0.13	28–147	0.73 : 1
2003 and 2010	Amended to restrict harvest of larger crayfish (e.g. only one crayfish >120 mm)	0.68 ± 0.58	45–146	1.21 : 1
2015 and 2016	100–120 mm HSLL	0.29 ± 0.17	19–133	0.78 : 1

In addition, there has been a skewing of the sex ratio from the period of total closure (1.09 : 1) to the present benchmarking (0.78 : 1), although fluctuations are evident over time. Length structure did not vary varied significantly between the historical monitoring and present benchmarking (KS-test, D = 0.107, p = 0.31) despite fewer larger (>140 mm) Murray crayfish were recorded during the present benchmarking (Figure 3-12). Taken together, it is evident that presently the Murray crayfish populations across the lower Ovens River exhibit reduced abundance, possibly up to two thirds of peak abundance, more skewed toward females and fewer larger individuals are present.

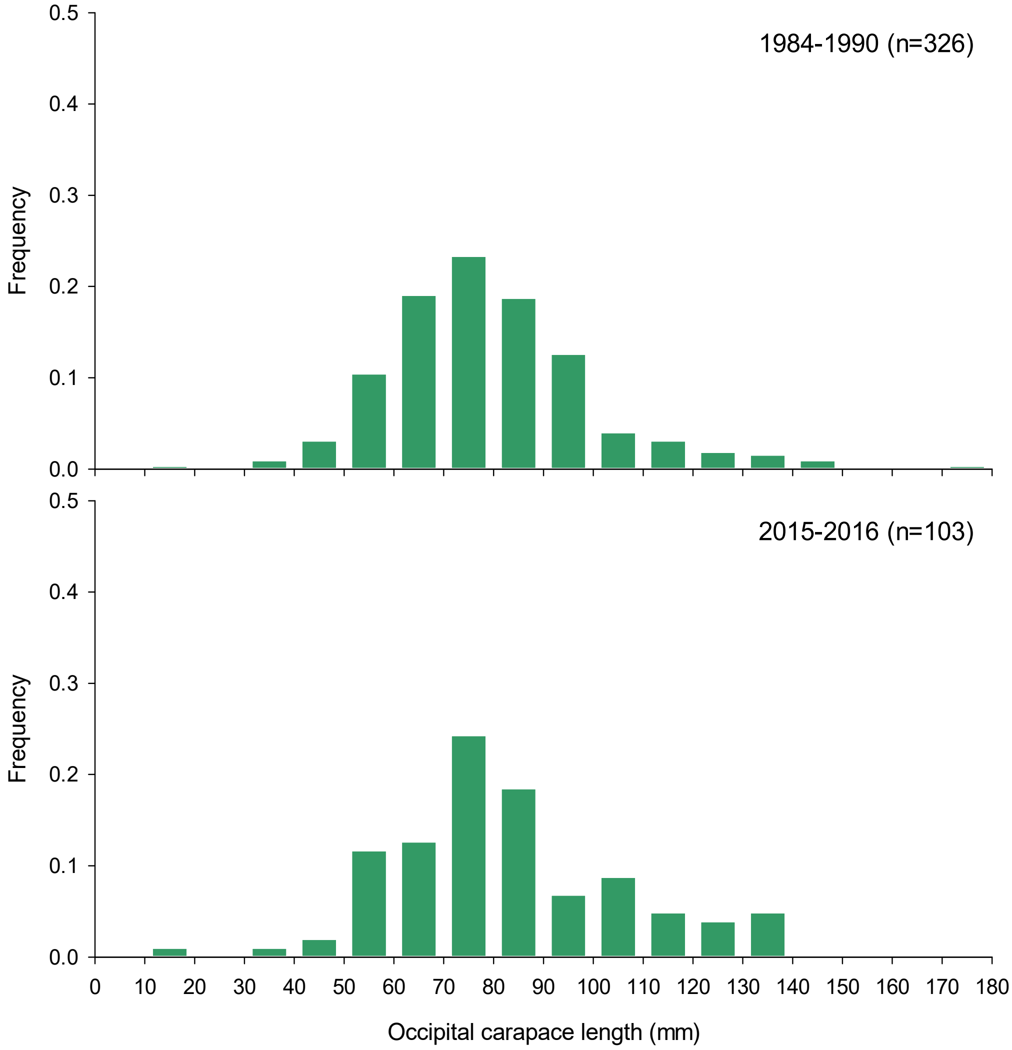

Figure 3-12. Length structure of Murray crayfish in lower Ovens River during the (a) period the recreational fishery was closed (1984–1990) and (b) present benchmarking (2014) (data sourced from Morison 1988; Fisheries Victoria, unpublished data; Stewart 2010).

Implication for recreational fishery:

- High catches occur at some sites, but abundance patchy
- Broad length structure and skewed sex ratio revealed
- Temporal comparison indicates declining abundance, possibly by up to two thirds, skewing of sex ratio, and the presence of fewer larger individuals

Murray Catchment

Wodonga Creek is a small tributary of the Murray River flowing near the major regional centre, Albury-Wodonga. Despite its short length, the creek has been known to support a strong Murray crayfish population, although there have been previous concerns of low abundance and a low percentage of mature females in berry (Morison 1988; Barker 1992). During the present benchmarking, a total of 64 Murray crayfish were recorded from two sites on the creek (Figure 3-13). The CPUE abundance was slightly higher at the downstream site (0.21 crayfish net^{-1} hour^{-1}) compared to the site (0.17 crayfish net^{-1} hour^{-1}). The catch ranged between 42 to 140 mm (38 to 1347 g) with 9.38% of individuals potentially harvestable (Figure 3-14). The sex ratio was skewed toward females (0.52 : 1), and was once again more pronounced in the HSLL range (0.38 : 1). Furthermore, across the two sites all mature females possessed eggs, which ensured that half of all females were reproducing. This is counter to observations in 1990, which showed only 12.5% of all females were mature with eggs, and lead to conclusions that the population was exhibiting signs of stress and/or recruitment failure (Barker 1992).

Figure 3-13. Murray Catchment sites: Wodonga Creek – lower section (left); Wodonga Creek – Morison site (right).

Across the present benchmarking, the length structure for females (KS-test, D = 0.201, p >0.20) and all individuals (KS-test, D = 0.235, p = 0.121) did not vary significantly from normality but this was not the case for males (KS-test, D = 0.316, $p < 0.05$). Additionally, historical monitoring length structures were significantly different to normality across all years (KS-test, D = 0.289–0.351, $p < 0.001$) (Figure 3-14 and Figure 3-15). Apart from 1984, which was significantly different to all other years except 2015 (KS-test, D = 0.273–0.479, $p < 0.05$), length structures were typically consistent across years. Given its proximity to

Albury-Wodonga, this suggests relatively constant, and potentially high harvest pressure has been exhorted on this population over time.

Despite this harvest pressure, CPUE abundance at the Wodonga Creek – Morison site remained consistent between historical (1984–1987: the mean CPUE abundance was 0.51 crayfish net lift^{-1}) (Morison 1988; Barker 1992) and present monitoring (CPUE abundance was 0.50 crayfish net lift^{-1}), which is counter to temporal comparisons across the Goulburn and Ovens catchments (note CPUE abundance presented as crayfish net lift^{-1} for comparative purposes). It is worth emphasising that CPUE abundance was variable across the historical monitoring – as high 1.90 crayfish net lift^{-1} in 1986, but down to 0.04 crayfish net lift^{-1} in 1990) – indicating fluctuations in the size of the Wodonga Creek population presumably in relation to localised environmental disturbance or harvest pressure (or possibly movement between the creek and the nearby Murray River). It is important to better understand the mechanisms explaining these fluctuations as the likely lower carrying capacity of this small creek coupled witl

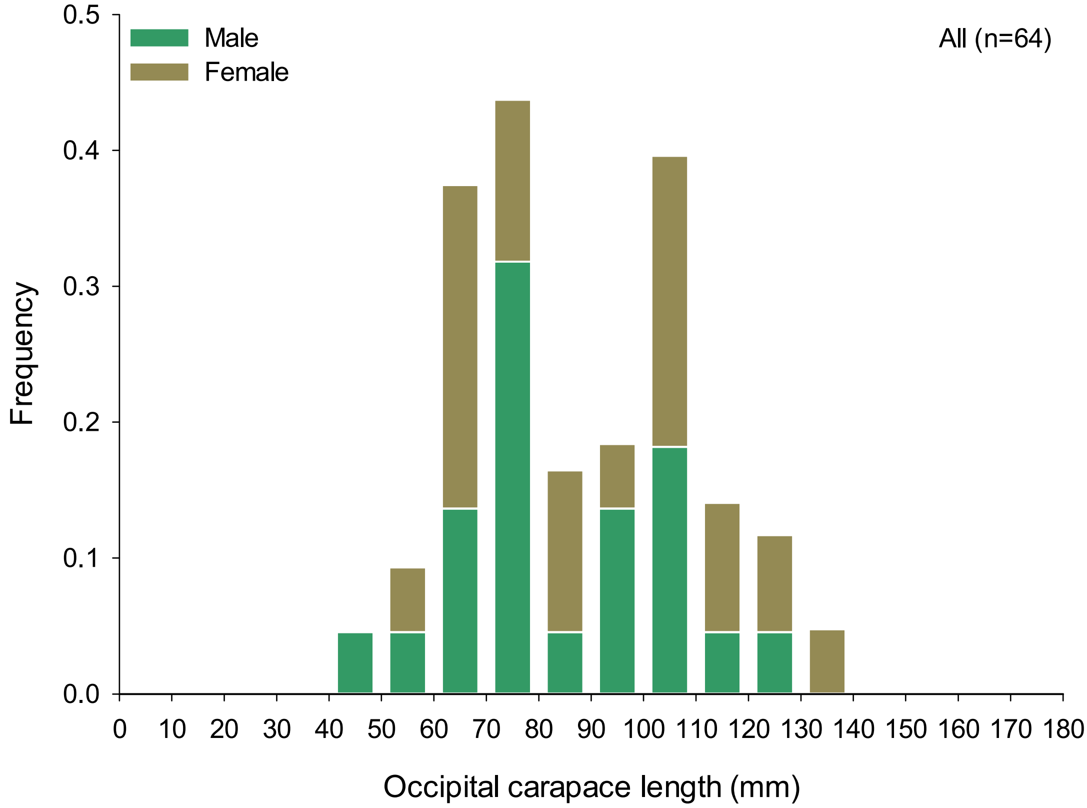

Figure 3-14. Length structure of Murray crayfish sampled from Wodonga Creek over the present benchmarking.

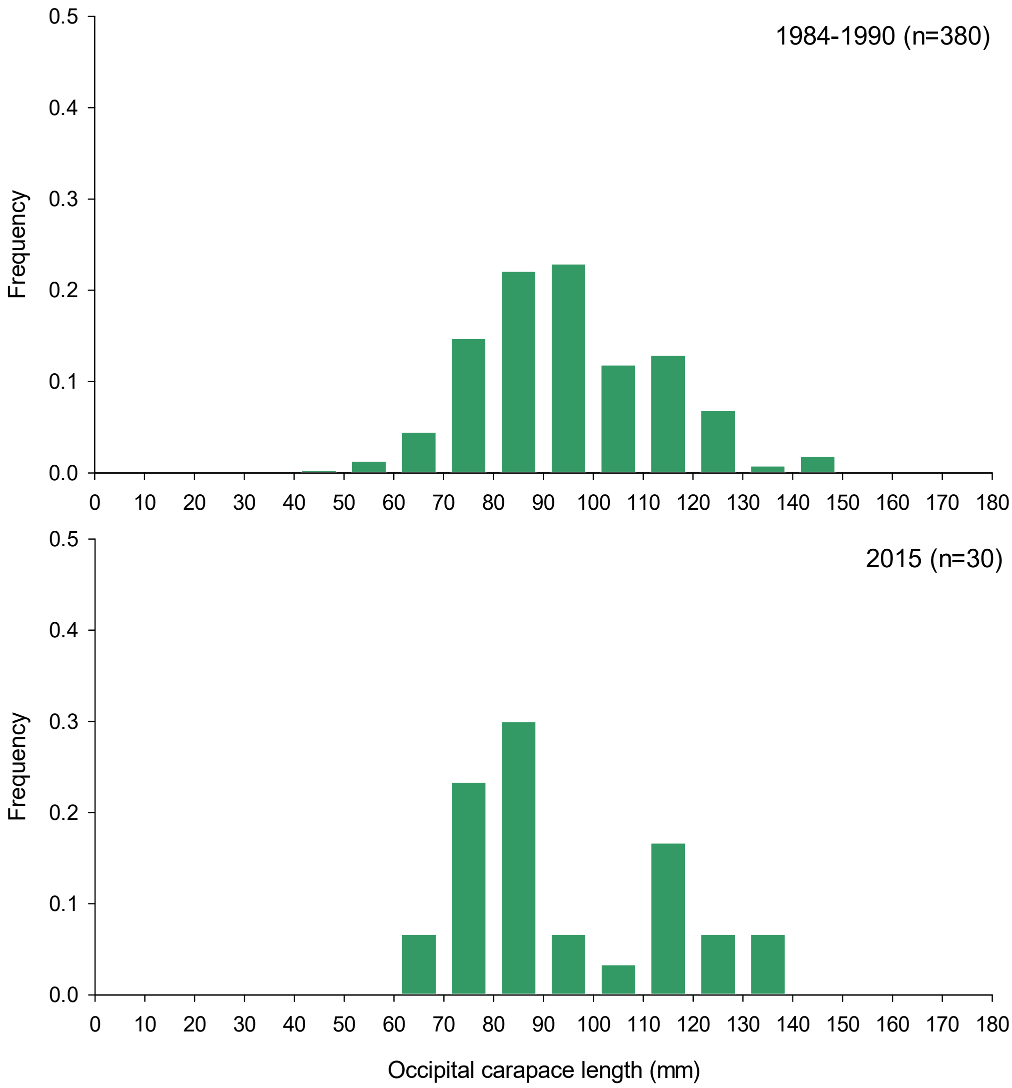

Figure 3-15. Length structure of Murray crayfish in Wodonga Creek during the (a) period the recreational fishery was closed (1984–1990) and (b) present benchmarking (2014) (historical data sourced from Morison 1988; Barker 1992).

Implication for recreational fishery:

- Proximity to major regional centre and considerable harvest pressure likely
- Yet, CPUE abundance has remained relative constant from historical to present monitoring, although annual fluctuations evident

Other lowland catchments

Sampling occurred across four other catchments where the species is known to occur based on the Fisheries Victoria Inland Angling Guide (Tunbridge and Rogan 2010). Across the 18 sites sampled in these catchments (Figure 3-16), the species was either not recorded or in low abundance (0–0.043 crayfish net^{-1} hour^{-1}) and thus detailed interpretation was not possible; yet brief summaries are provided below.

Figure 3-16. Selection of sites sampled in the Kiewa, Mitta Mitta, Broken and Campaspe catchments: (top left) Kiewa River — Kergunyah Bridge (top left); Mitta Mitta River – Keenans Bridge (top right); Broken River – Dip Bridge (bottom left); and Campaspe River — Murray junction (bottom right).

In the Kiewa Catchment, low numbers (*n*=8; CPUE abundance, 0–0.043 crayfish net^{-1} hour^{-1}) were recorded across five sites located between Mount Beauty and the junction with the Murray River (note: the lower section was not sampled due to winter flooding over the study period). The species was broadly distributed across the focus area, and mature females were observed but the length of sampled individuals (45–90 mm) was below the existing HSLL range. Whilst the section is classified as a Premier River as part of the Victorian Go Fishing initiative, catchment degradation (land clearance, introduced weeds) and flow modification through hydro-electricity generation (the river is part of the largest hydro power generator in Victoria) act to reduce its suitability for the species.

In the Mitta Mitta Catchment, only four crayfish (CPUE abundance between 0–0.013 crayfish net^{-1} hour^{-1}) were recorded across the six sites sampled between Lake Dartmouth to where it flows into the Hume Dam. Catchment modification and flow modification coupled with recent drought conditions are believed to have impacted Murray crayfish across this catchment. It is worth noting that it was difficult to sample sites across this catchment due to high flows, which act to lessen river access and in turn recreational harvest pressure.

Six sites were sampled across the Broken Catchment, including in the Broken River between Lake Nillahcootie to its junction with the Goulburn River as well as the Broken Creek from where it branches off the Broken River to the Murray River junction. Across these sites, only three individuals were recorded (from one site) with the species not detected in the Broken Creek and the lower Broken River. Sampled individuals were large (93 to 107mm) with the largest individual being an immature female.

The species is not considered endemic to the Campaspe Catchment (Morgan 1986; Gilligan et al. 2007) and was not recorded from the single site sampled in the catchment during the present benchmarking. The Fisheries Victoria Inland Angling Guide (Tunbridge and Rogan 2010) suggests the species is present in the catchment, so small populations may persist.

Implication for recreational fishery:

- Populations across small catchments are patchily distributed, with low CPUE abundances and few individuals within the HSLL
- Whilst not contribute greatly to recreational fishery, harvesting could have localised detrimental impacts

Upland catchments

A total of 792 Murray crayfish were recorded opportunistically during Sustainable River Audit and Murray-Darling Basin Fish Survey (Tarmo Raadik and Lauren Dodd, Arthur Rylah Institute, *unpublished data*, 2004–2016) monitoring across 130 upland Victorian sites between 2004−2016 (Figure 3-17). Sampled Murray crayfish ranged between 5–84 mm (except for a single individual at 146 mm; length provided for n = 615), indicating almost all individuals across upland areas are below the present HSLL (and previous MLL) and not subject to legal recreational harvesting (Figure 3-18). The sex ratio of sampled individuals (1.06 : 1) did not vary significantly from unity (binomial test, $p = 0.58$), suggesting that harvest pressure is minimal. Broad genetic connectivity exists across majority of the range of the species, including the major catchments of the Victorian population (Whiterod et al. 2017), but it remains unclear how these upland populations interact with those of lowland areas.

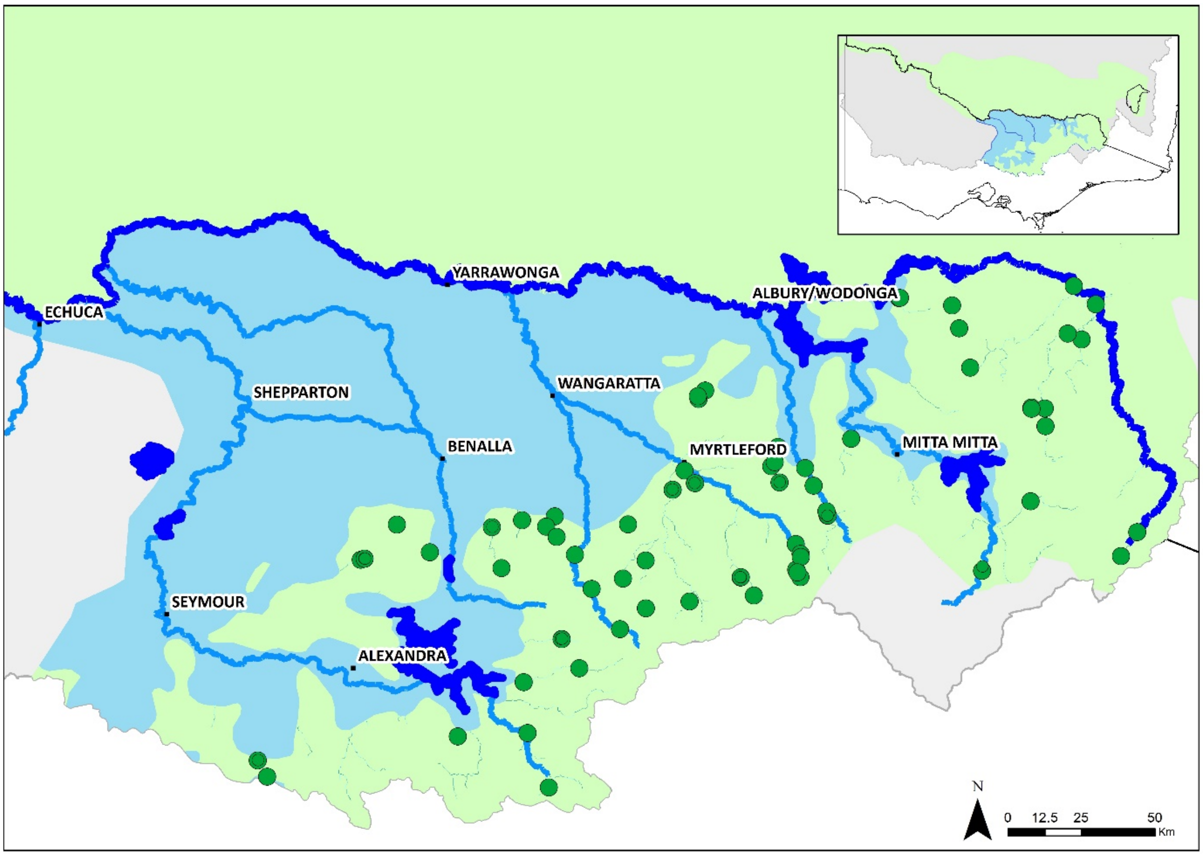

Figure 3-17. Upland sampling sites where Murray were opportunistically sampled during Sustainable River Audit and Mur

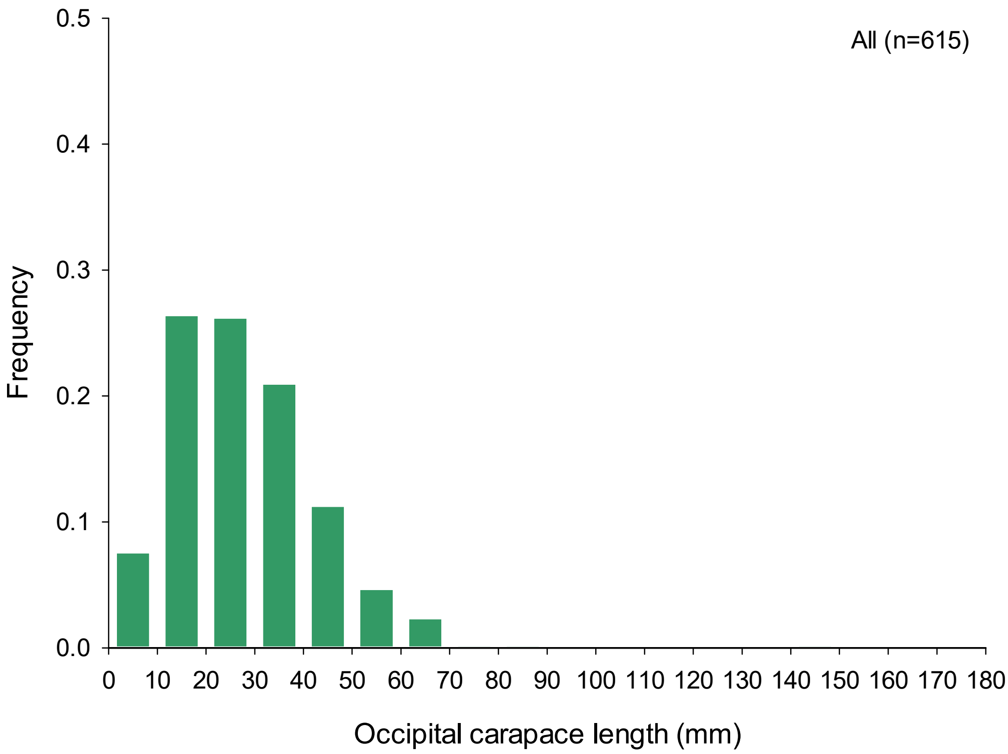

Figure 3-18. Length structure of Murray crayfish sampled from the upland areas.

Implication for recreational fishery:

- Upland individuals rarely reach sizes larger than the present HSLL
- The sex ratio across upland areas does not vary significantly from unity

3.6 Conclusions

Murray crayfish was patchily distributed and abundance was variable across lowland sites sampled during the present benchmarking. In fact, moderate to high relative abundance was only revealed in three areas – the mid-Goulburn River (from Seymour to upstream of Shepparton), the lower Ovens River (downstream of Wangaratta to Murray junction) and Wodonga Creek. This reconfirms these areas as supporting stronghold populations, where greatest intensity of recreational fishing effort is anticipated. However, comparison of long-term monitoring at key sites in these stronghold areas indicate declines in abundance over the past 25 years, emphasising that conservative management is required.

The sampled Murray crayfish population (n = 469), exhibited a broad and normally distributed length structure (19−156 mm occipital carapace length, OCL), with corresponding ages ranging between 0.9 to 19.3 years but the majority of the population was estimated to be less than eight years old (applying previously developed length-at-age relationships). The overall sex ratio was significantly skewed toward females (0.58 : 1, males to females), with a more pronounced female-bias in the present HSLL range (0.28 : 1) although was almost in unity (0.8 : 1) for individuals below the HSLL. The size at onset of sexual maturity of 50% of females (SOM_{50}) was estimated at 87.28 mm, whereas 95% of females (SOM_{95}) were mature at 104.44 mm. Finally, complementary data revealed the species was broadly distributed across upland areas, yet almost all individuals observed were smaller than 84 mm, and therefore do not form part of the recreational fishery.

Section 4 POPULATION MODELLING

This section was prepared with the assistance of Charles Todd (Arthur Rylah Institute).

4.1 Introduction

In the present section we utilised a population model recently developed for Murray crayfish (Todd et al. in review) to evaluate management scenarios relevant to the Victorian recreational fishery. These models are constructed using understanding of life history and population processes (density-dependence) to provide a quantitative link between the individual and the population-level dynamics (Todd et al. 2011). These models are important management tools as they provide a robust framework to evaluate the consequence of natural and anthropogenic pressures as well as scenarios relate to fishery management (Koehn and Todd 2012; Gwinn et al. 2015; Lorenzen et al. 2016). For Murray crayfish, we assessed scenarios related to historical, previous and present fishery regulations as well as a number of alternative regulations that may be enacted in the future. Modelling scenarios were assessed against population sustainability and harvest potential indicators, with the specific aim to identify the most appropriate fishery regulations for the Victorian recreational fishery.

4.2 Modelling approach

4.2.1 Model structure and simulations

The population model had a stochastic length-based age structure that summarises the life history of male and female Murray crayfish by explicitly representing 25 age classes based on estimates of survival (across life stages), growth, fecundity and density-dependence across the species' lifespan (i.e. set at 25 years) (Todd et al. in review). The model was constructed using best-available information and general knowledge on processes such as density dependence, whilst acknowledging uncertainties involved in the modelling process. The model incorporates stochastic processes to allow for variation in parameter estimates, thus attempting account for this uncertainty as well as natural environmental variability. For more details on the population model, see Todd *et al*. (in review).

4.2.2 Fishery management scenarios

The population model has capacity to explore scenarios relating to mortality from disturbance events (e.g. blackwater), reintroductions and habitat change, but the present project focused solely on fishery management scenarios. These scenarios related to historical, previous and present fishery regulations as well as an unfished (no impact) scenario and alternative regulations that may be implemented in the future (Table 4-1).

Table 4-1. Summary of management scenarios for Murray crayfish assessed during modelling simulations.

No	Fishery management scenario		Scenario description
1	Unfished (no impact)		No impact of fishing; baseline measure for comparison
2	Historical	No length limit	No length limit (MLL or HSLL) but assumed that adults are targeted; Victorian regulation up until 1983
3		80 mm MLL	80 mm MLL with no upper limit; NSW regulation from 1989 to 2003
4		90 mm MLL	90 mm MLL with no upper limit; Victorian regulation from 1991 to 2001
5	Previous (90 mm MLL, with 120 mm upper limit)	+ low harvest	90 mm MLL (with 120 mm upper limit); Victorian regulation from 2001 to 2013 and NSW regulation from 2003 to 2013; +10% take of legal-size crayfish
6		+ moderate harvest	90 mm MLL (with 120 mm upper limit); Victorian regulation from 2001 to 2013 and NSW regulation from 2003 to 2013; +30% take of legal-size crayfish
7		+ high harvest	90 mm MLL (with 120 mm upper limit); Victorian regulation from 2001 to 2013 and NSW regulation from 2003 to 2013; +50% take of legal-size crayfish
8	Present (100–120 mm HSLL)	+ low harvest	100–120 mm HSLL; Victorian and NSW regulation since 2013; +10% take of legal-size crayfish
9		+ moderate harvest	100–120 mm HSLL; Victorian and NSW regulation since 2013; +30% take of legal-size crayfish
10		+ high harvest	100–120 mm HSLL; Victorian and NSW regulation since 2013; +50% take of legal-size crayfish
11	Alternative	70–90 mm HSLL	Lower HSLL with view to protect greater numbers of larger crayfish
12		80–100 mm HSLL	Lower HSLL with view to protect greater numbers of larger crayfish
13		100 mm MLL (no upper limit)	Present regulation, but with no upper length limit to allow harvest of 'trophy' crayfish

The historical scenarios accounted for fishery regulations imposed across both states (i.e. no length limit (but assumed to only target adults) and 80 and 90 mm MLL) prior to regulations (90 mm MLL with only one crayfish above 120 mm; which for modelling purposes was defined as an upper length limit) that were enacted in both states during the early 2000s (Victoria in 2001; NSW in 2003). The present scenario describes the HSLL (100–120 mm) that has been in place across both states since 2013. A range of variations were also evaluated, which aim to lessen the harvest pressure on larger crayfish (i.e. lowering HSLL) or alternatively allowing harvest of larger trophy crayfish (removing upper length limit from HSLL). Additionally, the previous and present scenarios were assessed with differing fishing harvest pressure (i.e. low: 10; and high: 50% take of legal-sized crayfish) to compare against the default harvest pressure (moderate: 30% take of legal-sized crayfish).

All modelling simulations were implemented using the lowland sub-model of the Murray crayfish population model, with a starting carrying capacity of 50,000 individuals and executed for 50 time steps (i.e. 50 years) using 1000 model iterations of the scenario. For simplicity, immigration and emigration were not included in the model. The fishing harvest was set to 30% take of legal-sized crayfish (default), except were harvest pressure was specifically explored (e.g. unfished, low and high harvest pressure). The population model was developed and implemented in the simulation software package ESSENTIAL v2.15 (Todd and Lovelace 2014).

4.2.3 Assessment indicators

Each simulated fishery management scenario was evaluated in terms of population sustainability and harvest potential (Harvest potential represented the mean number of crayfish harvested (both kept and released) and the time in which crayfish were vulnerable to harvest (based on length limit and length-at-age relationship). All assessment indicators were estimated after 25 years of model simulation with percentage change assessed against the unfished (no impact) scenario, except for the mean number of crayfish harvested (which was assessed against the present regulation with moderate harvest pressure).

Table 4-2). Population sustainability was defined by population risk, sex ratio and spawning potential. Population risk was characterised by changes in the cumulative distribution of minimum population sizes (i.e. minimum population size from each model iteration), also known risk curve (Burgman et al. 1993). The risk curve is representative of the probability of falling to or below a given population size (or threshold population size) under the assessed scenario. Sex ratio was the ratio of males to females in the population whereas spawning potential was defined as the total number of eggs produced under the relevant scenario relative to the no impact scenario, providing an indication of the probability of spawning failure in the population (Allen et al. 2013).

Harvest potential represented the mean number of crayfish harvested (both kept and released) and the time in which crayfish were vulnerable to harvest (based on length limit and length-at-age relationship). All assessment indicators were estimated after 25 years of model simulation with percentage change assessed against the unfished (no impact) scenario, except for the mean number of crayfish harvested (which was assessed against the present regulation with moderate harvest pressure).

Table 4-2. Assessment indicators used to evaluate fishery management scenarios for Murray crayfish.

Assessment indicator		Description
Sustainability potentially	Population risk	Defined expected minimum population size (EMPS) after 25 years
	Sex ratio	The male : female sex ratio after 25 years
	Spawning potential	Ratio of the potential number of eggs produced by the population relative to the unfished scenario after 25 years
Harvest potential	Mean no. of individuals potentially harvested	Mean number of harvested crayfish (kept + released) after 25 years
	Time vulnerable to harvest (years)	The number of years that crayfish are vulnerable to harvest, based on length limits and length-at-age relationships

4.3 Results and discussion

Modelling simulations revealed considerably different population sustainability and harvest potential across assessed fishery management scenarios (Table 4-3 and Figure 4-1). When assessing the scenarios in the order in which they were in force, it is evident that the population sustainability has been enhanced considerably over time. Under no length limit or 80 mm MLL scenarios (which were in place in Victoria up until 1993 and NSW until 2003), population sustainability was lowest across assessed scenarios with population risk (no length limit: 69.61%; 80 mm MLL: -48.31%), sex ratio (no length limit: 0.60 : 1; 80 mm MLL: 0.63 : 1) and spawning potential (no length limit: 44.45%; 80 mm MLL: 69.85%) deviating considerably from the no impact scenario. These impacts on population sustainability ensured that despite crayfish being vulnerable to harvest for much longer (no length limit: 20 years; 80 mm MLL: 19 years), harvest potential was restricted, with the mean number of harvested individuals -35.65% (no length limit) and -25.72% (80 mm MLL) lower than compared to the present regulations. Increasing to a 90 mm MLL acted to improve population sustainability (population risk: -27.24%; sex ratio: 0.67 : 1; spawning potential: 91.52%), whilst allowing greater harvest potential (-7.39%). Implementing an upper limit length to this MLL (i.e.

90−120 mm HSLL), only marginally improved population sustainability (i.e. population risk: -20.79%) as the majority of harvested individuals were occurring in the HSLL range with few crayfish growing larger than the upper limit. The harvest potential under the 90−120 mm HSLL was similar (-7.26%) to that the 90 mm MLL scenario, despite crayfish only being vulnerable to harvest for a much shorter period (i.e. 4.1 years).

The greatest population sustainability was achieved under the present regulation (HSLL = 100−120 mm) scenario, with the population risk (-13.46%), sex ratio (0.85 : 1) and spawning potential most similar to the no impact scenario. Further, Murray crayfish were only vulnerable to harvesting for 2.9 years under this scenario, but harvest potential was highest amongst scenarios with 30% harvest pressure. These findings reinforce the benefit of HSLL to ensure population sustainability whilst maintain harvest potential (Koehn and Todd 2012; Gwinn et al. 2015).

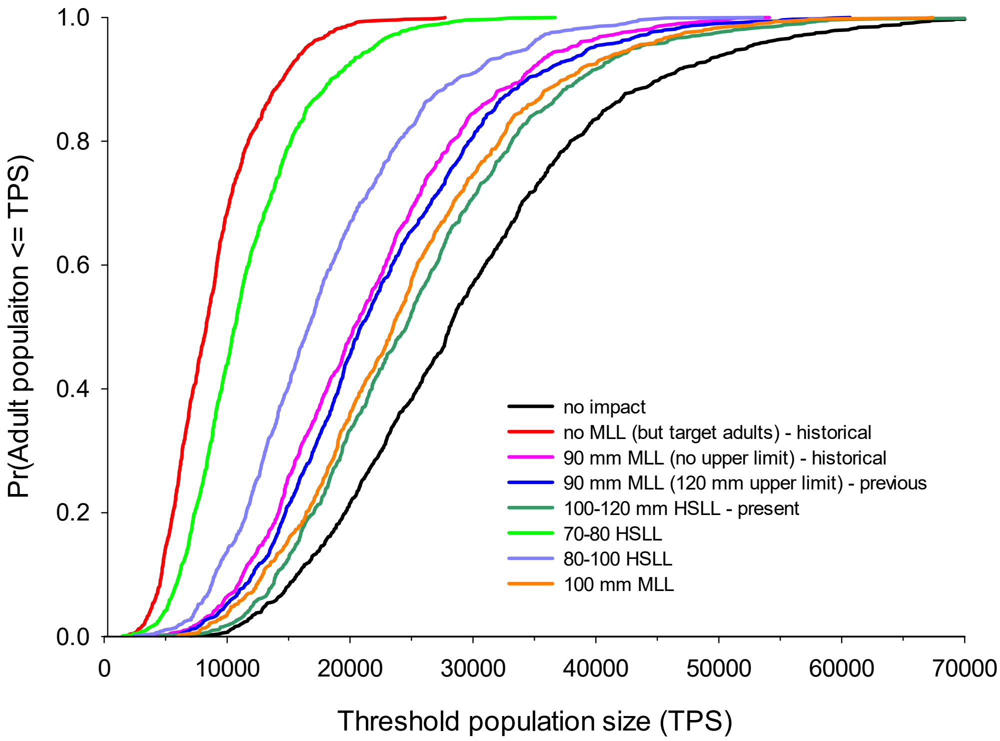

Figure 4-1. Population risk curves associated with modelling scenarios specifically relevant the Victorian Murray crayfish recreational fishery (note: risk to a population increases as the risk curve shifts toward the y-axis).

The alternative scenarios assessed did not result in improved population sustainability or harvest potential. In fact, lowering the HSLL (to either 70−90 mm or 80−100 mm) increased population risk (-60.86% and -39.11%, respectively) and lessened spawning potential (49.06% and 70.85%, respectively) although sex ratio remained similar to the 100−120 mm HSLL. Interestingly, the harvest potential under these scenarios were also suppressed compared to present regulation scenario. These findings are consistent with others (Froese 2004; Gwinn et al. 2015) who indicate that allowing harvest of individuals before they reach sexual maturity (e.g. SOM_{50} = 87.28 mm for Victorian Murray crayfish population) greatly intensifies the risk of overfishing.

Table 4-3. Modelling outcomes of scenarios relating to Victorian Murray crayfish fishery regulations. Assessment of each scenario was based on population sustainability and harvest potential indicators estimated across 25 years of model simulation. The unfished scenario (scenario 1) was used as the baseline for comparative assessment of population sustainability indicators, whereas harvest potential was compared against the present scenario with moderate harvest pressure (scenario 9).

No	Fishery regulation		Population sustainability				Harvest potential		
			Population risk (expected minimum adult population size)	Percent change (%)	Sex ratio (M : F)	Spawning potential	Mean no. of harvested crayfish (kept + release)	Percent change (%)	Time vulnerable to harvest (years)
1	Unfished (no impact)		29628.73	-	1 : 1	100.00%	-	-	-
2	Historical	No length limit	8914.30	-69.91%	0.60 : 1	44.45%	12256.51	-35.65%	20.0
3		80 mm MLL	15313.74	-48.31%	0.63 : 1	69.85%	14147.98	-25.72%	19.0
4		90 mm MLL	21558.87	-27.24%	0.67 : 1	91.52%	17638.65	-7.39%	17.9
5	Previous (90 mm MLL, with 120 mm upper limit)	+ low harvest	26480.95	-10.62%	0.87 : 1	97.51%	6647.52	-50.45%	4.1
6		+ moderate harvest	22590.35	-20.79%	0.70 : 1	91.29%	17662.35	-7.26%	
7		+ high harvest	19413.81	-34.48%	0.50 : 1	87.07%	27593.29	44.88%	
8	Present (100–120 mm HSLL)	+ low harvest	27685.91	-6.56%	0.92 : 1	99.96%	6779.45	-64.40%	2.9
9		+ moderate harvest	25640.30	-13.46%	0.77 : 1	98.44%	19045.75	-	
10		+ high harvest	24095.20	-18.68%	0.71 : 1	96.75%	30785.69	61.64%	
11	Alternatives	70–90 mm HSLL	11596.60	-60.86%	0.88 : 1	49.06%	11108.74	-41.67%	2.1
12		80–100 mm HSLL	18039.97	-39.11%	0.77 : 1	70.85%	14940.15	-21.56%	2.3
13		100 mm MLL (no upper limit)	24581.93	-17.03%	0.74 : 1	97.95%	18721.27	-1.70%	16.7

Similarly, implementing a 100 mm MLL without an upper length limit lead to decreased population sustainability with greater population risk (-17.03%) and skewed sex ratio (0.74 : 1) although spawning potential remained similar (-97.95%). Harvest potential was also slightly lower (-1.70%), despite the species being vulnerable to harvest for a much greater duration (16.7 years). Changes in harvest pressure under the previous and present scenarios moderately influenced population sustainability and harvest potential.

Implication for recreational fishery:

- The present regulations (100–120 mm HSLL) provide the greatest population sustainability, whilst maintaining harvest potential

4.4 Conclusions

The Murray crayfish population model provided a logical framework to assess population sustainability and harvest potential associated with fishery management scenarios. Several conclusions can be reached regarding the effectiveness of the present regulations imposed on the recreational fishery. Firstly, all scenarios involving harvest pressure imposed a level of impact on the species compared to the unfished scenarios, with this impact expected to be more pronounced if not for the protection of berried females. Secondly, historical scenarios, that imposed no or minimal restriction of adult harvest, resulted in lowest population sustainability and limited harvest potential. Thirdly, the present regulations provided the greatest population sustainability and harvest potential. Lastly, changes in harvest pressures assessed in the present study influenced the outcomes of modelling, which should be considered when assessing fishery regulations. Taken together, the present fishery regulations for Murray crayfish appear most sympathetic to the life history of the species, and are predicted to afford greatest population sustainability whilst maintaining harvest potential in the future.

Section 5 GENERAL DISCUSSION

5.1 Assessing stock status

5.1.1 *Summary*

The present study represents the most comprehensive assessment of the status of the Victorian Murray crayfish recreational fishery ever conducted. This multifaceted assessment relied on a combination of population benchmarking of lowland areas, the exploration of long-term trends at key sites as well as compilation of data obtained from upland areas. In addition, population modelling of management scenarios was used to assess the effectiveness of fishery regulations. The key outcomes of present study are consolidated in Table 5-1 to allow assessment of the stock status.

Table 5-1. Summary of the key outcomes of the present study and implication for management of the species.

<table>
<tr><th>Parameter</th><th>Outcomes</th><th>Implication in relation to fishing regulations</th></tr>
<tr><td rowspan="2">Distribution and abundance</td><td>Patchily distributed with variable relative abundance (i.e. not detected at 15 sites)</td><td rowspan="2">Indicates the recreational fishery is largely focused on three sections across the whole Victorian population, but need to acknowledge that these populations are reduced compared to historical levels</td></tr>
<tr><td>Only three sections (mid-Goulburn River; lower Ovens River; Wodonga Creek) maintained moderate to high relative abundance, yet long-term declines are evident (declined over the past 25 years)</td></tr>
<tr><td rowspan="2">Length (and estimated) age structure</td><td>Broad (19–156 mm) and normally distributed length structure, although variation between sites.</td><td rowspan="2">Healthy structure across the Victorian population
Low numbers of older individuals may be indicative of harvest pressure on older animals within fishing regulations</td></tr>
<tr><td>Majority of the sampled individuals estimated to be less than eight years old</td></tr>
<tr><td rowspan="3">Sex ratio</td><td>Significantly skewed toward females (0.28 : 1) within the HSLL</td><td rowspan="3">Indicative of substantial harvest pressure within the HSLL (with few males getting through); possible effects on numbers of berried females in population (needs further investigation)</td></tr>
<tr><td>Did not vary significantly from unity (0.80 : 1) below the HSLL</td></tr>
<tr><td>Pronounced skew above HSLL (0.06 : 1)</td></tr>
<tr><td rowspan="3">Sexual maturity</td><td>SOM_{50} = 87.28 mm; SOM_{95} = 104.44 mm</td><td rowspan="2">HSLL affords majority of females the opportunity to spawn-at-least-once whereas 63.90% mature at previous MLL</td></tr>
<tr><td>93.34% of females mature at HSLL</td></tr>
<tr><td>93.25% of mature females with eggs; although variable (71–100%) across size classes</td><td>Almost all berried females are protected with HSLL but has led to a mainly male-only fishery</td></tr>
<tr><td rowspan="2">Upland populations</td><td>Broadly distributed</td><td>Healthy and connected populations</td></tr>
<tr><td>Contracted length structure (5–84 mm; except one individual at 146 mm)</td><td>Almost all individuals below present HSLL so not forming part of the recreational fishery</td></tr>
</table>

	Sex ratio did not vary significantly from unity	Sex ratios align closely to those in unfished areas confirming harvest pressure is minimal
Population modelling	All scenarios (involving harvest pressure) imposed a level of impact on the species compared to the unfished scenarios	The present HSLL is the most appropriate fishery regulation for the species
	Historical scenarios (e.g. 90 mm MLL) resulted in lowest population sustainability and limited harvest potential	
	The present HSLL provided the greatest population sustainability whilst maintaining harvest potential	
	Changes in harvest pressure strongly influenced the outcomes of modelling	Should be considered when assessing fishery regulations

5.1.2 Broader context

The consistency of fishery regulations now enacted across both Victoria and NSW represents a major step toward the objective of multi-jurisdictional management of the species (Gilligan et al. 2007). Within this objective in mind, it is prudent to place the outcomes of the present study in context with the status of the species across the other jurisdictions it occurs. Following substantial declines in its range and abundance the species is now considered locally extinct or in low abundance across much of its natural range (e.g. the Murray River and its tributaries (Edward and Wakool rivers) below Tocumwal (including SA), the lower and upper Murrumbidgee River in the ACT), with recreational fishing totally prohibited in these areas. As such, recreational fishing is now only permitted in Victoria along with two sections of the Murray and Murrumbidgee rivers. The contraction of area open to fishing presents a number of potential threats to the Victorian recreational fishery, including intensification of fishing effort on stronghold populations in Victoria and increased illegal fishing activity due to recent regulation amendments (which has been noted in NSW: NSW DPI 2014). These potentially threats could be mitigated through maintenance and enhancement of compliance efforts as well as collaboration and engagement with recreational fishers.

A range of environmental disturbances have been implicated in the decline of the species, including river regulation and habitat degradation, pesticide and pollutions (Gilligan et al. 2007). Given the biology and ecology of Murray crayfish – late maturing (i.e. 8–9 years), long-lived (potentially up to 28 years), likely restricted movement – these ongoing environmental disturbances, coupled with past commercial and present recreational harvest pressure, can cause significant risk to present and future populations. In this context, it is therefore critically important to the long-term viability of the species that the Victorian recreational fishery is effectively managed.

5.2 Management recommendations

The assessment reveals that Murray crayfish occur patchily across Victoria, with the recreational fishery likely to be largely restricted to three stronghold areas, which have undergone declines in abundance over the past 25 years. On this basis, the following recommendations are made.

- **Retain 100–120 mm HSLL** – this length limit is most sympathetic to the life history of the species, and is predicted to afford greatest population sustainability whilst maintaining harvest potential in the future. Importantly, retaining the present HSLL would continue the consistency of regulation across both Victoria and NSW,
- **Evaluate area closures** – it is evident that several sections of the Victorian population (e.g. lower Goulburn River) have declined to extremely low abundances. As such, area closures may be necessary to promote population recovery,
- **Evaluate quota system** – the present regulations manage fishing effort but do not regulate overall harvest imposed by the recreational fishery. It is therefore conceivable that even with sympathetic fishery regulations that harvest pressure may continue to impose an unsustainable threat to the Victorian population. Implementation of a quota system, where the total allowable catch (TAC) across the state or catchments could be regulated, may be more suitable. The TAC could be determined, based on annual monitoring surveys and population modelling (e.g. Todd et al. in review), prior to each fishing season (or pragmatically every three to five years). It is acknowledged that considerable stakeholder input would be required to evaluate the merit of any such quota system but successful implementation is anticipated to result in better management of the recreational fishery – this could be considered a test case for quota systems across other recreational fisheries,
- **Explore stock enhancement** – whilst previously historical employed (Gilligan et al. 2007) and considered as a viable strategy to combat population declines (Geddes et al. 1993), contemporary reintroductions of the species have not been undertaken. Yet, reintroductions will take place, as part of a complimentary project in NSW, over coming years in an attempt to assist the recovery of blackwater impacted populations in the Murray River. Thus, an opportunity presents to leverage resources and expertise to evaluate and implement strategic reintroductions into suitable sections of the Victorian range of the species (e.g. lower Goulburn River),
- **Maintain/enhance compliance** – given the recent amendments to the fishing regulations (which have seen increased illegal activity in NSW) as well as the potential intensification of fishing effort on Victorian populations, it is recommended to review

efforts of surveillance, informative signage at fishing sites and community awareness to ensure adherence to fishery regulations, and

- **Collaboration and engagement with recreational fishers** – Fisher Local Ecological Knowledge (LEK) can provide long term and up-to-date information on recreational fishery species, such as Murray crayfish (Zukowski et al. 2011). This type of engagement could be helpful to address several the research needs detailed in the next section (see below) and thus benefit fisheries management. Further, collaboration and engagement provides recreational fishers with a sense of ownership, thus decreasing the likelihood of illegal harvesting, as does increased information about the species through increased signage and community education and awareness of biology/ecology and the importance of fishing regulations.

A number of management recommendations, summarised by the review of Gilligan *et al.* (2007), are yet to be addressed. The recommendations most relevant to the management of the recreational fishery include improving environmental conditions (i.e. effective environmental flow management and habitat protection/rehabilitation), strengthening the regulation of the trade of crayfishes, and establishing a national Murray crayfish working group to provide multi-jurisdiction management. It is anticipated that implementation of the recommendations specific to the Victorian recreational fishery as well as those broader in nature will assist management of the species.

5.3 Research and monitoring needs

The present assessment, along with other recent studies, have emphasised the importance of robust monitoring and research to inform the management of the species. On this basis, the following research and monitoring recommendations are made.

- **Implement long-term monitoring strategy** – the present study has shown the benefit of monitoring across a broad spatial coverage as well as long-term monitoring of key sites to assess the status of the species. Clearly, it is necessary to implement a future monitoring strategy to allow for regular assessment of the recreational fishery. Briefly, we recommend annual monitoring of 5-10 key sites (i.e. 1-2 sites in each catchment) interspersed with comprehensive monitoring covering a broader spatial extent (i.e. similar site list to the present study) every five years. Sampling should follow the methodology employed here and in NSW to allow multi-jurisdictional assessment,
- **Year-round catchability (and timing of females coming into berry)** – the present study provides the necessary spatial assessment for the recreational fishery, yet temporal aspects of the fishing regulations are yet to be evaluated. The recent amendment of the

open season, for instance, was based on the peak abundances and the timing of females coming into berry across NSW populations of the species (Zukowski et al. 2012). However, it is unclear if they are appropriate for the Victorian population – it may be that a later (and potentially extended) open season may afford greater reproductive potential whilst maintaining harvesting of the species. Following the methodology of Zukowski *et al.* (2012), monthly monitoring of key sites on an annual basis would help to resolve this issue and could incorporate recreational fishers,

- **Estimation of population sizes** – present monitoring for the species provides relative estimates of abundance (i.e. crayfish net^{-1} h^{-1}), but overall population sizes remain largely unknown. Clearly, an understanding of the population sizes is valuable to managing any recreational fishery. Recently, Zukowski *et al*. (in review) undertook a mark-recapture study, in collaboration with recreational fishers, which allowed for the estimation of population sizes in the Edward River in NSW. A similar mark-recapture study is recommended to provide estimates of population size at key sites (i.e. Goulburn and Ovens rivers and Wodonga Creek) across the Victorian recreational fishery. This study could be combined with the year-round catchability monitoring, and again involve collaboration with recreational fishers, to maximise benefits to management,
- **Determine fishing effort and economic value** – A clear understanding of the extent of recreational fishing (and harvesting) as well as associated value to local economies is required. The estimates of Henry and Lyle (2003), annual catch of 551,047 Murray crayfish (across both Victoria and NSW over 2000–01) suggest a considerable recreational fishery, but the influence of the recent regulation amendments are unknown. Further, the estimates of Henry and Lyle (2003) formed a component of national survey, so more robust estimates could be achieved through targeted surveying of Murray crayfish recreational fishers, and
- **Insight into movement patterns and habitat use** – limited information exists on the movement and habitat use of Murray crayfish, with previous understanding gained from small upland sections of the Murrumbidgee River (Ryan 2005). A targeted acoustic telemetry study, focusing on lowland areas of the Victoria population, will help to determine habitat requirements and recolonise potential of depleted populations. This information will help to better manage the recreational fishery in Victoria.

Whilst some of the knowledge gaps identified in the review of Gilligan *et al.* (2007) have been resolved, the habitat and biology of juvenile (<40 mm) Murray crayfish (see, the impact of a range of disturbance types (e.g. river regulation, habitat degradation, eutrophication and salinity, introduced species and pesticides) remain deficiencies in our understanding for the species. Thus, implementation of a long-term monitoring strategy, working with recreational fishers (to determine overall fishing effort) as well as addressing research priorities will be critical to the ongoing sustainability of the Victorian Murray crayfish recreational fishery.

5.4 Conclusions

The present study represents the most comprehensive assessment of the status of the Victorian Murray crayfish population ever conducted. The assessment indicates that Murray crayfish occur patchily across Victoria, with the recreational fishery likely to be largely restricted to three stronghold areas, which have undergone declines in abundance over the past 25 years. Given this status assessment and the outcomes of modelling simulations, the main recommendation which can be put forward is retaining the present HSLL. It is acknowledged that whilst these present regulations manage fishing effort, they do not regulate overall harvest imposed by the recreational fishery; it is recommended to assess overall harvest through collaboration with recreational fishers, and it may ultimately be necessary to explore the suitability of a quota system (i.e. regulating overall harvest) for the species. It is also acknowledged that the potential closure of areas (e.g. such as lower Goulburn River) and reintroductions where low abundances and environmental disturbances persist may be warranted. Retaining the present HSLL would continue the consistency of regulation across both Victorian and NSW recreational fisheries, and supports moving toward a coordinated management approach across the whole range of the species. Implementation of a long-term monitoring strategy, working with recreational fishers (to determine overall fishing effort) as well as addressing research priorities (including understanding movement patterns, population sizes and age structures) will be critical to the ongoing sustainability of the Victorian Murray crayfish recreational fishery.

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