

Research Article

Monitoring downstream migrations of *Eriocheir sinensis* H. Milne Edwards, 1853 (Crustacea: Brachyura: Grapsoidea: Varunidae) in the River Thames using capture data from a water abstraction intake

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Abstract

The International Union for Conservation of Nature has cited *Eriocheir sinensis* as one of the world's worst 100 invasive species. Outside their native range, this alien species has had adverse impacts, both ecologically and economically, on river catchments. Understanding the life cycle of the Chinese mitten crab, especially details of the migration period, is important for the potential control of this exotic species. The mitten crab has been reported from the River Thames, London, England and in this watershed the population continues to increase in numbers, disperse in a westerly direction and reports of a downstream migration date back to 1996. Recently, regular collections from a rubbish screen at a River Thames water abstraction point were used to monitor the migration of adult crabs over three years (2008–2010). Details of size, sex and condition of the crabs were recorded as were data on the abstracted flow. The main migration period runs from August to early November with peak numbers of crabs recorded in September/early October. In all years the sex ratio of captured crabs was heavily skewed towards males, which were significantly larger than females. Furthermore there is some evidence that female crabs move later in the migration period than males and that peaks in numbers of both male and female crabs are associated with full moon periods; peak numbers demonstrating significant lunar periodicity. In addition there is a weak association between crab numbers and abstraction flow rate. The key findings are used to recommend the timing of any future control measures that might be designed to reduce the population of this invasive species in the River Thames. These recommendations could also be applied to other river catchments where the species is problematic.

Key words: Chinese mitten crab; invasive species; annual downstream migration; monitoring; river water abstraction; River Thames

Introduction

Abstraction of Thames (England) river water for cooling electricity generating plant has been a remarkable source of biological data over the last fifty years that has enabled naturalists to assess the environmental health of this London watershed (e.g., Harrison and Grant 1976; Wheeler 1979). Four power stations have featured; mainly Lots Road Power Station (LRPS) at Chelsea which until 21 October 2002 supplied electricity to the London Underground, West Thurrock Power Station (WTPS) which was closed in 1993 and later demolished, Tilbury Power Station (TPS) and, to a much lesser extent, recently, Didcot

Power Station (DPS). For the locations of the Thames power stations see Figure 1. According to Clark et al. (2008), the salinity of the Thames at LRPS varied between 0.3–1.3 psu (freshwater), WTPS between ca. 8–22 psu (brackish) and TPS is also considered to be brackish. DPS is ca. 83km west of LRPS and upstream. The Thames catchment in this area is freshwater. In order to prevent any blockages, the cooling water is screened and the resultant rubbish is temporarily stored on site before being removed and disposed of in landfill. A large amount of biological data can be obtained by sorting through this debris over a period of time. This is especially true with regard to the invasion of the Thames by the

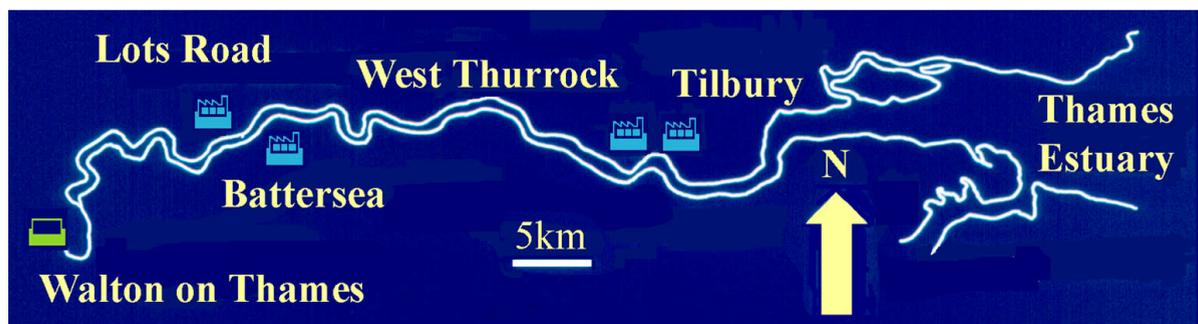


Figure 1. Locations of power stations along the tidal Thames and the Walton-on-Thames pumping station.

Chinese mitten crab *Eriocheir sinensis* H. Milne Edwards, 1834. This species has a native distribution from south China to the western coastal region of Korea (Ingle 1976). Chinese mitten crabs are highly invasive. Its spread is almost certainly facilitated by transport in ship's ballast water and/or intentional introduction (Cohen and Carlton 1997), and the species is one of only two brachyuran species listed in the top 100 worst invasive species (Lowe et al. 2000). The biology and invasion patterns of *E. sinensis* in Europe and elsewhere are reviewed by Herborg et al. (2003, 2005) and Dittel and Epifano (2009).

Although the actual site of the first mitten crab to be found in the Thames is confused with Professor R. T. Leiper (Anon 1936a, b) stating that *Eriocheir sinensis* "... had been dredged up at Battersea Power Station while Harold (1936) reported the crab from the intake grating of Lot's Road Power Station, the date of capture 1935 is not in doubt. This initial report was followed by a relatively long hiatus before three more Chinese mitten crabs were noted by Ingle and Andrews (1976), all captured at WTPS. Andrews et al. (1981) appear to have recorded the first ovigerous mitten crab for the Thames taken at WTPS in January 1979, and a second in December of the same year. Ingle (1986) too recorded an ovigerous mitten crab from the Thames estuary and further records of Thames mitten crabs from 1986 to 1993 in the estuary were listed by Attrill and Thomas (1996). They also noted the capture of a berried female on 20 August 1990 and postulated that the pattern of mitten crabs collected at WTPS had changed during 1991–92. Adults were appearing more regularly until thirty individuals were captured on 13 November 1992. This was more than the mitten crabs caught

during the previous seven years at the power station and according to Attrill and Thomas (1996), suggested that downstream migration (first evidence in the Thames) was occurring since all the females were ovigerous. Attrill and Thomas (1996), Clark and Rainbow (1997) and Clark et al. (1998) provided evidence that the mitten crab population in the Thames appeared to have increased during the early 1990s and was continuing to rise. They all used Environment Agency mitten crab records collected from the filter screens at WTPS (1976–1993). From a relatively low constant baseline of 1–4 crabs per year the captures at WTPS suddenly increased to 18 in 1992. In the following year 15 crabs were recorded up until 31 March when electricity generation at WTPS ceased. Clark and Rainbow (1997) and Clark et al. (1998) further showed that this increase was maintained as large numbers of crabs were collected from TPS in 1994 and 1995, with at least as many in the first half of 1996 when collecting ceased. Attrill and Thomas (1996) reported the first juvenile and later Robbins et al. (2000) indicated that high numbers of juveniles were found in the river. This information suggested that *E. sinensis* was established and successfully completing its catadromous life cycle (see Panning 1939). With the successful establishment in the Thames catchment, the mitten crab had dispersed westward upstream. The most westerly Thames record was initially found in the collection of the Natural History Museum, London, from Thames Ditton, Surrey; date of capture July 1994. Since then this westerly distribution has been monitored at regular intervals; Clark and Rainbow (1997) and Clark et al. (1998) as far west as the River Colne at Staines, Surrey, November 1996; Clark et al.

(2008) Boverney Lock, just west of Windsor, Berkshire, October 2007 and DPS at Sutton Courteney, Oxfordshire, October 2010 (see <http://www.mittencrabs.org.uk>).

The invasion of the Thames by the Chinese mitten crab has caused a series of ecological and economic problems. They burrow into unprotected riverbanks which eventually collapse (Dutton and Conroy 1998; Zucco 1999). Two areas in particular where this behaviour is apparent are the *Phragmites* reed beds on Chiswick Eyot and the river bank along Syon Park, Middlesex. Native flora and fauna is threatened too (Clark et al. 1998; Gilbey et al. 2008; Czerniejewski et al. 2010), and this includes evidence of feeding on fish eggs (e.g., Culver 2005; D. Morrill pers. obs.; P. Rosewarne pers. comm.). Mitten crabs can also cause damage to static and mobile fishing gear when captured in large numbers (Ingle 1986; D. Pearce pers. comm.). Furthermore, in the future there may become a cost attached to mitten crabs blocking abstraction channels.

To date, abstraction of Thames water for cooling power stations has not been a problem because of the elaborate mechanisms initially installed to screen all river rubbish prior to the invasion of mitten crabs. However, the screens currently installed at pumping stations abstracting water for drinking are, in comparison with those at power stations, simple; a steel grill. Blocking of these screens has recently become a problem for the pumping station at Walton-on-Thames, Surrey. This pumping station is ca. 26 km west of LRPS and upstream (see Figure 1). Two main problems are now evident, firstly keeping the intake channels open and the second is the disposal of large numbers of mitten crabs. Both could have significant economic implications because two men are now employed during the mitten crab migration season to clear the steel grid of crabs and debris.

The current study undertaken at Walton-on-Thames abstraction site was designed to review the established annual migration pattern of mitten crabs in the Thames and assess the usefulness of rubbish screens as a sampling tool for monitoring this behaviour. More specifically this study set out to test a number of hypotheses. Are equal numbers of male and female crabs caught during the migration period? Is there a difference in the peak movement of males and female crabs? Do different sized crabs move at different times? Is the number of crabs sampled related to the flow rate in the intake channel? Is

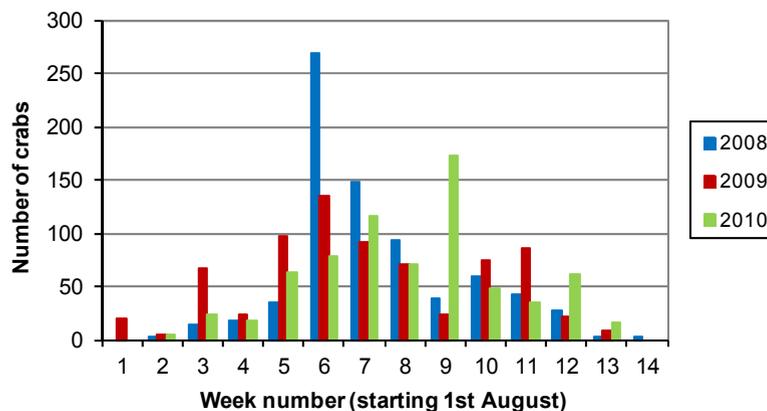
there a relationship between crab movement and the phase of the moon? The results are discussed with reference to the possible implementation of control measures for *E. sinensis* (for discussion see Clark 2011) in the River Thames and other river systems. As the watershed at Walton-on-Thames is freshwater, no ovigerous crabs were expected to be captured during this survey.

Materials and methods

Crabs were collected by Thames Water (TW) operatives using long-handled rakes from the rubbish screen bars (approx. gap 52 mm) situated across the channel carrying water abstracted directly from the River Thames at the Walton-on-Thames site, West London (51°24.1962'N, 0°23.6912'W). Collections were made at regular intervals, usually mid-morning, during the autumn migration period and crabs collected on each day were placed in separately labeled, covered plastic tanks. TW staff also kept daily records of peak flow rate (megalitres/day) and these were recorded for every day on which crabs were collected. Crabs were subsequently sexed by direct observation of the abdominal segments which form a narrow triangular shape in males and a much broader flap in females. Carapace width between the tips of the posterior lateral spines (spine 4) was then measured, using Vernier scale callipers to the nearest 0.1mm. Additional data were collected for many, but not all, crabs over the three years of the study. These data included recording limb loss and fresh weights as well as notes of whether crabs were alive and also the presence of shell lesions. Fresh weight data are not presented here as these data were found to be extremely variable depending the state of the crab, degree of hydration and level of damage. Carapace width is a far more reliable indicator of crab size. Following processing crabs were killed (if not already dead) and disposed of in accordance with the Wildlife and Countryside act for dealing with invasive species. No mitten crabs were returned to the water.

Data are expressed as numbers per week starting at 1st August as this date was before the earliest record of mitten crabs in Walton in all three years of the study (2008–2010 inclusive). However, whilst it was intended to collect data in 2011 this was not possible due to the unusual weather conditions/exceptionally dry autumn which affected the amount of water abstracted by TW at the sampling site. Anecdotally it also appeared to be an unusual year for mitten crab

Figure 2. Total number of mitten crabs caught at Walton-on-Thames (Thames Water) intake screen during the autumn migration period (2008–2010).



migration (D. Clifton-Dey pers. obs.; D. Pearce pers. comm.) which may have similarly been linked to the unusual climatic conditions.

Thus data for any crabs removed from the screens during any of the seven days in week 3, for example, were pooled and used in subsequent analysis. It should be noted, however, that in a few cases detailed data were not collected on crab dimensions (first part of the migration period) although crab numbers were recorded. In all years crabs stopped appearing on the screens by the last week in October/first week in November.

Counts for both male and female crabs were subject to harmonic regression analysis to determine whether there was any periodicity. In all cases a Poisson GLM model was applied where the count (male / female as appropriate) was fitted against $\sin + \cos + \text{week} + (\text{week} \times \text{week})$ where \sin , \cos , week and week^2 are the multipliers and \sin , \cos , week , week^2 are the explanatory variables. $\text{Sin} = \sin((2\pi/4) \times \text{phase})$, where $\text{phase} = 0, 1, 2, 3$ and 0 is 100%. $\text{Cos} = \cos((2\pi/4) \times \text{phase})$, where $\text{phase} = 0, 1, 2, 3$ and 0 is 100%. The sine and cosine functions were included as the harmonic component of the lunar phases. Thus:

$$\log_e(\text{Count}) = \text{Sin}((2\pi/4) \times \text{phase}) + \text{Cos}((2\pi/4) \times \text{phase}) + \text{week} + \text{week}^2$$

Data were analysed using Microsoft Excel, IBM SPSS Statistics Version 19 and Genstat.

Results

Crab numbers: The total number of crabs recorded was remarkably similar for each of the three years of the study, ranging between 710 in 2010 to 751 in 2008 and whilst the peak numbers of crabs were recorded in week 6 (mid-September) in both 2008 ($n = 269$) and 2009 ($n = 135$) this peak ($n = 173$) was three weeks later (early October) in 2010 (Figure 2). In terms of percentages these data show that 35.8% of all the migrating crabs in 2008 and 18.7% in 2009 moved during this September peak. In 2010 some 24.4% of all the migrating crabs moved during the early October peak. In both 2008 and 2009 there is some evidence for a secondary peak of crab movement some four weeks later than the main peak (week 10–11), this being less evident in 2010.

When considering the different sexes, in 2008 the peaks in the numbers (and percentages) of the individual sexes mimic those shown for the overall totals. In 2009 there is evidence that there were a greater proportion of females moving during the secondary peak of activity in October. This was also true, to a lesser degree, in 2010. Consequently there seems to be some evidence that proportionately more female mitten crabs may move later during the migratory period, certainly in 2009 and 2010. This is perhaps illustrated more clearly with reference to Table 1.

Table 1. Proportion of crabs (percentage of overall catch for the year) of each sex caught during defined periods, total number of each sex and mean carapace widths of each sex during the autumn migration period (2008–2010).

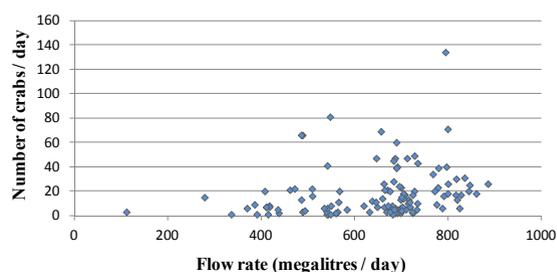
Weeks (from 1st Aug.)	Males	Females	Males	Females	Males	Females
	2008	2008	2009	2009	2010	2010
1-4	4.7	4.6	19.0	5.9	7.6	2.7
5-8	71.8	74.4	56.5	48.5	48.4	38.4
9-12	23.1	20.1	23.6	43.8	41.7	56.8
13-14	0.4	0.9	0.9	1.8	2.3	2.1
Total number	532	219	552	169	564	146
Mean carapace width/mm (\pm SD)	65.0 \pm 6.7	60.3 \pm 4.9	65.5 \pm 7.0	59.5 \pm 4.8	67.9 \pm 7.3	62.5 \pm 4.8

Table 2. Summary of harmonic regression analyses in a Poisson GLM. Sine and cosine functions are included as the harmonic component of the lunar phases where $\log_e(\text{count}) = \sin((2\pi/4) \times \text{phase}) + \cos((2\pi/4) \times \text{phase}) + \text{week} + \text{week}^2$.

Year	Female	Male
2008	F = 11, d.f. 4,9, P = 0.002	F = 17.37, d.f. 4,9, P < 0.001
2009	F = 6.48, d.f. 4,9, P = 0.01	F = 5.53, d.f. 4,9, P = 0.016
2010	F = 6.58, d.f. 4,9, P = 0.009	F = 10.17, d.f. 4,9, P = 0.002

Sex ratio: During all three years of the study, many more male crabs were captured than females with the sex ratio deviating markedly from the expected 1:1 (Table 1). The sex ratio (M:F) ranged from 2.4 in 2008, through 3.3 in 2009 to 3.9 in 2010. As expected, no ovigerous females were captured during all three years of the study.

Crab size: Sizes of both male and female crabs were normally distributed (Kolmogorov-Smirnov Test $P \geq 0.05$). There was no consistent pattern in change of mean size of either sex with time during the migration period. In 2008 the mean size for both males (ANOVA: F = 1.75, d.f. 11, 520, $P > 0.05$) and females (ANOVA: F = 0.95, d.f. 12, 207, $P > 0.05$) was not significantly different throughout the migration period. In 2009 whilst this pattern was the same for females (ANOVA: F = 0.85, d.f. 10, 152, $P > 0.05$) there was a significant change in size in males (ANOVA: F = 2.95, d.f. 10, 438, $P < 0.05$) with smaller males moving later in the migration period. A similar pattern was seen in 2010 with females showing no significant difference (ANOVA: F = 1.34, d.f. 11, 134, $P > 0.05$) and smaller males apparently moving later (ANOVA: F = 2.63, d.f. 10, 548, $P < 0.05$). What is clear, however, is that the mean carapace width of male crabs was consistently greater than mean female carapace width. This relationship was seen in all three years of the study. Table 1 shows that, over the three years of the study, male crabs caught on the intake screen were generally larger than female crabs (Pooled values: male = 66.22 ± 7.13 mm, female = 60.68 ± 4.97 mm; $t = 19.62$,

**Figure 3.** Graph illustrating daily crab counts against mean flow rate for pooled data from all three years (2008–2010) at Walton-on-Thames.

d.f. 1314, $P < 0.001$) and interestingly the mean size of crabs was higher in 2010 than in the previous two years (ANOVA: F > 45.08, d.f. 2, 2066, $P < 0.001$; SNK 2010 > 2008 = 2009).

Effect of flow rate: There were weak (but statistically significant, $P < 0.01$) correlations between the numbers of both sexes per day and flow rate (Spearman correlation coefficients: Male = 0.319, Female = 0.274, Pooled = 0.327). As the flow rate increased so did the number of crabs captured on the screen. This significant correlation is illustrated for pooled data for both sexes in Figure 3.

Effect of the phase of the moon: There is a suggestion that peak numbers of crabs may be related to the phase of the moon with the peak seemingly associated more or less with the two periods of full moon that occur during the main

migration period (Figure 4A-C). Generally the number increases as the week number increases, declines and then increases. Analyses using harmonic regression in a Poisson GLM demonstrate that peak counts for both sexes demonstrate significant lunar periodicity in all three years with highest numbers at around the time of full moon (Table 2).

Discussion

The current study demonstrates that adult Chinese mitten crabs, intercepted by the intake screen at Walton-on-Thames, have a migration period in the River Thames lasting approximately two and a half to three months, from early/mid-August to late October. During this period the peak activity is seen from mid-September to early October (depending on year). In the related species, *E. japonica*, adult downstream migration occurs between September and December in their native range (Kobayashi and Matsuura 1995) although interestingly there is evidence for two groups of females with gonads maturing at different times (Kobayashi 1999). Many more male crabs were caught than females in the present study, with the sex ratio in all years of study being markedly skewed from 1:1, and male crabs were consistently larger than females. Interestingly these findings differ from previous data collected from 1995–1997 at LRPS by Robbins et al. (2000). Whilst these authors described a similar, but somewhat extended, migration period for adult crabs (September-January), the sex ratio was only marginally skewed towards males (M:F, 1.38). The fact that adult crabs were recorded well into the winter months compared to the current data may be due to the fact that LRPS is further downstream than Walton-on-Thames. In a more recent fyke-netting study on invasive *E. sinensis* in the Guadalquivir estuary in Spain Garcia-de-Lomas et al. (2010) reported a sex ratio which, whilst not varying significantly between months, over a seven year period tended to be female biased. These authors also recorded peak numbers of larger crabs in the Seville port region in October and November which probably reflects increased capture during the adult downstream migration. Similarly in a study using crab pots to monitor *E. japonica* in Japan, Kobayashi and Matsuura (1995) described a female-biased sex ratio in large crabs during the breeding season although noted that the sex ratio varied markedly with size of crab and location

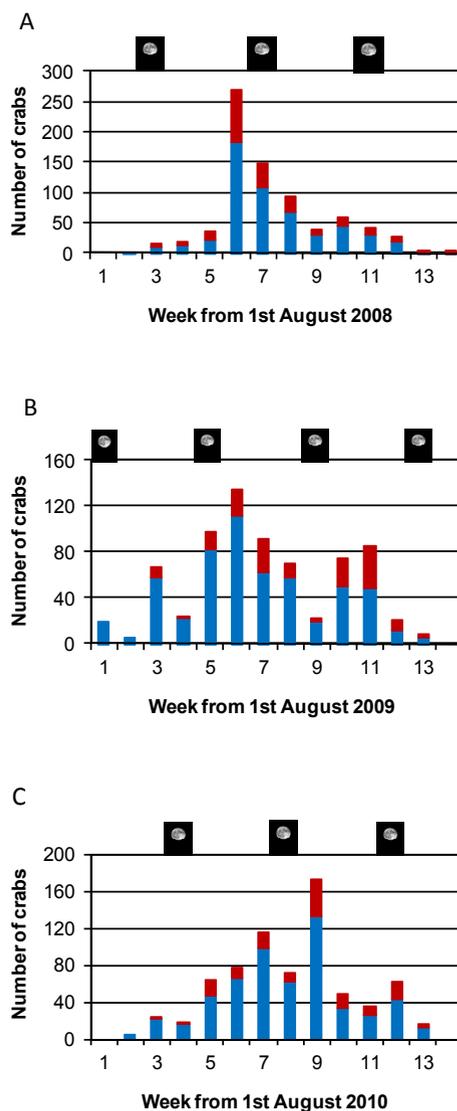


Figure 4. Crab numbers during the adult migration periods in 2008 (A), 2009 (B) and 2010 (C) at Walton-on-Thames. Male crabs are shown in blue and females in red. The weeks including the full moon period are indicated.

in the river. Indeed these authors suggest that some of the breeding population comprised smaller male crabs migrating from lower in the river system.

The reason for the skewed sex ratio, which seems to be a consistent feature in the current data set, is not immediately obvious although

this may be related to the spacing of the bars on the intake screen. It is possible that larger male crabs are more likely to be retained on the screen than smaller females. There may also be a behavioural explanation. For example, in a study on the common shore crab, *Carcinus maenas*, it was demonstrated that larger crabs, albeit adults versus juveniles, were more active and more likely to be caught in pit-fall traps (Almeida et al. 2008). It may also reflect a sex-related difference in activity levels or sexes moving in different parts of the river bed such that males are more likely to be entrained onto rubbish screens. For example male sand crabs, *Portunus pelagicus*, were described as being significantly more active than females (Sumpton and Smith 1990) during a series of laboratory experiments investigating temperature effects on activity in this species. The difference could, of course, also be a true reflection of the numbers of each sex migrating.

There is some limited evidence for smaller male crabs moving later in the migration period (in two of the three years of the study) and this may be a simple reflection of the fact that smaller animals take longer to move over the same distance during the migration. Female crabs tend to be slightly, but significantly, smaller than male crabs so there may also be a similar explanation for why it appears that proportionately more females move later on during the migration period (in two of the three years studied). It is worth noting that the mean size of both male (65–67.9 mm) and female (59.5–62.5 mm) carapace widths in the present study are broadly similar to those reported for adult *E. japonica* caught in brackish water areas in the breeding season in Japanese waters (Kobayashi and Matsuura 1995) although a greater size range was reported for the Japanese crabs. The crabs in the present study were larger than those recorded (40–50 mm mode carapace widths) in the Lots Road study (Robbins et al. 2000). It should be recognised, however, that samples obtained from different localities on the Thames, using different methodologies, may represent different elements of the crab population that may be migrating at different times of the year. In contrast Robbins et al. (2000) did not report a difference in numbers of males and females moving at different times of year although did suggest that juveniles moving in the opposite direction, upstream, do so at periods outside the peak adult breeding migration. As the females can potentially produce several hundred

thousand eggs (Panning 1939; Hao Guo unpub. obs.) then concentrating efforts to preferentially intercept and remove these animals from the catchment during a later time window during the migration period would be advantageous.

There is a weak, but significant, relationship between crab numbers and daily flow and this correlation, coupled with the fact that numbers were low in 2011 when TW were only operating pumps at limited capacity, suggest that the effectiveness of using abstraction points to monitor crab migration may be at least partly influenced by inflow rates. This is perhaps not surprising as increased pumping (= higher flow rates) will inevitably result in increased entrainment of migrating crabs, and debris, onto rubbish screens.

There is good evidence that the peaks in crab migratory activity may be linked to the phase of the moon with higher numbers being recorded at or around full moon. Indeed the peaks in the numbers of both male and female crabs demonstrate significant lunar periodicity and this pattern was observed in each of the three years of the study. It is well known that many aspects of the biology, including reproductive cycles, of marine organisms are tightly linked to tidal or lunar cycles (see Naylor 1985; Palmer 1995 for reviews). It is therefore not surprising that *E. sinensis* may also synchronise its migration with the lunar cycle although it is important to note that the collection site at Walton-on-Thames is beyond any tidal influence. Based on laboratory observations, Herborg et al. (2006) described a semi-lunar periodicity in mating frequencies (coinciding with full and new moon spring tides). Interestingly these authors also described a peak in mating activity in November which fits well with the present observations: by November the majority of migrating Thames crabs will have moved down to brackish conditions (approx. 25 psu) where they are thought to mate. Certainly ovigerous females have been recorded in the upper Thames estuary in early November (D. Morrill, P. Clark pers. obs.). Also in the Thames, Gilbey et al. (2008) reported that juvenile *E. sinensis* demonstrated maximum activity levels during nocturnal high tides, possibly facilitating tidal stream transport, in the opposite direction, up river to the adult freshwater habitats. The possible link to lunar cycle is potentially important as it may indicate that any targeted control method, e.g., netting, may be most cost-effective during the full moon periods during the autumn migration. Furthermore, if limited resources are available, it may be best to

specifically target the later part of the migration period when it would appear, from the data presented here, that a higher proportion of reproductively active females are migrating. Removing these animals from the migrating population is arguably more effective in controlling future population numbers than removing males.

In conclusion, using screens to collect biological data at abstraction sites, such as Walton-on-Thames, is an extremely productive approach to monitoring seasonal patterns and numbers of mitten crabs migrating downstream in the River Thames. The concerns regarding the possible selective effect of the gap between bars on the trash screen and the influence of flow rate of abstracted water do mean that absolute counts should be treated with a degree of caution. This does not detract from the fact that this method is a useful way to monitor the timing of the migration (which does differ slightly between years) and identifying possible peak periods for migration for each sex. The present study recommends the continued use of such monitoring, where practical, as a valuable source of information for informing future discussions on the management of Chinese mitten crabs in the River Thames and in other watersheds where this invasive species is problematical.

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