Seasonal and spatial variation in *Salmonella* infections rates in quokkas (*Setonix brachyurus*) on Rottnest Island, Western Australia, in areas of human contact

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Abstract

A sampling programme to determine the seasonal incidence of *Salmonella* infections in the marsupial quokka, *Setonix brachyurus*, on Rottnest Island, was carried out in public contact areas over the period March 1984 to March 1985. The study followed an unusual rise in the frequency of *Salmonella adelaide* infections in quokkas foraging in the Thompson Bay settlement area and isolations from catchment waters and sewage effluent. A total of 670 tagged quokkas was swabbed in the island's three settlement areas, plus Kingston Barracks, Garden Lake and Lighthouse swamp. A total of 1,139 duplicate swab samples was collected from quokkas and 713 swabs from 244 animals recaptured more than once. Twenty five *Salmonella* serotypes were identified, including *Salmonella javiana* and *S. typhimurium* Phage Type 202 associated with human cases previously traced to the island. Significant differences were found in rates of infection in quokkas and these peaked at approximately 40% in the resident population at Lighthouse swamp, and at 30% in settlement areas during the summer months. Based on population estimates, a minimum of 200 infected animals are likely to frequent the Thompson Bay settlement area during the peak summer vacation period. Infection rates fell below 5% in settlement areas during the winter period but remained around 20% in the Lighthouse Swamp population. The majority of *Salmonella* infections in recaptured animals was classified as transient and few quokkas showed evidence of a carrier state, or absence of infection throughout the sampling period. *Salmonella* infections were higher in juvenile quokkas than adults in settlement areas and in adult females at Lighthouse Swamp. The large population density of quokkas foraging nocturnally for food in settlement areas maintained high levels of ground contamination with infected droppings. However, evidence of progress in long-term management strategies to promote natural behaviour in the island's wildlife and ameliorate public health problems is consistent with the absence of cases of salmonellosis traced to the island during the monitoring period and in subsequent years marked by significant increases in visitors to the island.

Keywords: Salmonellosis, zoonoses, Rottnest Island, marsupial, public health

Introduction

Salmonella isolations from wild animals in different countries was reviewed in a report on serotypes identified by the Salmonella Reference Laboratory in the United Kingdom by (Taylor 1969) and recently updated (Anon. 2006). The possibility of infections caused by wildlife spilling over to humans has been highlighted in a recent review, (Kruse Kirkemo & Handeland 2004) following on early studies in Panama (Kourany Bowdre & Herrer 1974), Trinidad (Everard Tota Bassett & Ali 1979), and India (Kaura & Singh 1968; Sambyal & Sharma 1972). In Australia, *Salmonella* infections acquired from wildlife are known to persist in non-urban aboriginal communities (Iveson 1983; Iveson Mackay-Scollay & Bamford 1969). The surprise discovery in 1972 of a major reservoir of *Salmonella* infection in the small marsupial wallaby *Setonix brachyurus*, known as the quokka, on Rottnest Island and the tracing of infections in humans to droppings from infected animals and contamination of wells and water storage tanks (Iveson & Bradshaw 1973), alerted public health authorities to the need for improved preventative measures on this small island resort in Western Australia. The findings also raised questions concerning the management of *Salmonella* infections in wildlife populations on the island, which were first addressed in a Public Health report and management

plan prepared for the then Rottnest Island Board (Iveson & Bradshaw 1978).

Over the subsequent period 1972–2000, a total of 31 laboratory-confirmed cases of human salmonellosis were diagnosed in residents and visitors to the island involving 9 *Salmonella* serotypes. These comprised *S. javiana* 16, *S. typhimurium* 6, *S. muenchen* 5, *S. saintpaul* 3, *S. chester* 1, *S. oranienburg, S. wandsbeck* 1, *S. waycross* 1, and *S. IIIb diarizonae. Salmonella javiana* has caused severe gastro-enteritis in infants exposed to quokka droppings and hospitalisation has been needed to treat the infection. Two patients were infected with multiple serotypes. *Salmonella javiana* and *S. typhimurium* Phage Type 202 have been the major strains implicated in human infections and non-human isolations on Rottnest Island have been recorded from quokkas, horses, seagulls, swallows, reptiles, water supplies and sewage (Iveson & Hart 1983). The finding of *S. javiana* infections in quokkas, horses, humans and well waters at the Riding School, resulted in its closure and the removal of horses from the Island. The undoubted virulence of *S. javiana* and its absence from the food chains of humans and livestock on the mainland also resulted in a test programme and quarantine measures to exclude infected quokkas being translocated to mainland fauna reserves (Short Bradshaw Giles Prince & Wilson 1992).

This unusual pattern of exposure in humans to reservoirs of infection in wildlife on the island differs from the usual pattern of food-borne infections that is commonly seen in urban areas on the mainland. *Salmonella javiana* and *S. typhimurium* PT 202 are rarely isolated from humans resident in mainland Australia and have not previously been detected in domesticated animals or in indigenous fauna. A total of 10 serovars classed as exotic isolates introduced by humans and domestic animals has been discovered in the period 1972 to 2000 on Rottnest Island and comprise *S. agona, S. bovismorbificans, S. derby, S. havana, S. infantis, S. javiana, S. livingstone, S. meleagridis, S. newport* and *S. typhimurium*. The majority of these serovars has been recorded from quokkas in settlement areas and all of the serotypes were also isolated from sewage effluent, suggesting latent infections in humans either resident or visiting the island.

Although monitoring of sewage effluent provides evidence of silent carrier infections in humans on the island, symptoms of gastroenteritis in residents, visitors and, occasionally, research workers on the island have rarely been matched by collection and examination of patient specimens. Surprisingly, the 31 cases of salmonellosis and 35 isolations recorded from humans on the island were derived from only 52 faecal samples and the majority of cases was diagnosed prior to the upgrading of public facilities on the island, as recommended in the Rottnest Island Management Plan and reviewed by (Portlock 1991). Collective studies of *Salmonella* infections in settlement areas on Rottnest Island commenced in 1972 and revealed infection rates in quokkas ranging from 20–30%. Specific information on the gain and loss of serotype infections was lacking, however, and following the discovery of 20 (74%) *S. Adelaide* infections in quokkas in the main settlement area on the Island this suggested a possible epizootic in quokkas.

In view of the risks to public health, data were obviously needed on the seasonal incidence of *Salmonella* infections in quokkas inhabiting settlement areas and other contact areas on the Island. The aims of the study were thus:

to monitor infection rates in individually-tagged quokkas frequenting the settlement areas on Rottnest Island over a 12-month period, and to compare these with infection rates of quokkas resident in other parts of the Island.

To assess the health threat to tourists visiting the Island of the practice of hand-feeding quokkas at the bus stop adjacent to Lighthouse swamp.

Materials and methods

The Thompson Bay settlement and associated camping area on Rottnest Island (31°60'S, 115°30'E) occupies an area of approximately 2 km^2 and is bordered by the water-catchment area, sewage facility, golf course and Garden Lake (see Figure 1). Remnants of native vegetation provide daytime habitat for quokkas that are attracted to feeding sites in the early evening (Kitchener 1972). Distances between sampling locations ranged from 100–500 m and were subject to a degree of overlap during capture and recapture over the year.

Quokkas were caught with hand-held nets between 1800–0200 hours in the settlement and Kingston Barracks/Bickley Swamp area, and between 1100–1600 hours at the tourist feeding site, close to Lighthouse Swamp. Animals were ear-tagged individually, scored as adults or juveniles, sexed and duplicate rectal swabs were placed in 5 mL of strontium chloride B enrichment broth (Iveson 1971) and isolation procedures for serotypes are detailed in Hart Iveson Bradshaw & Speed (1982). Average times for the tourist and vacation feeding activities averaged from 15 min to 45 min on 1–4 daily visits during the peak summer period and involved hand-feeding in roadside areas littered with many droppings. A number of animals was also sampled at the alternate Longreach and Geordie Bay settlements, located on the north coast, approximately 2.5 km from the main settlement area in Thompson Bay. Samples were collected on 10 occasions over a 12-month period from March 2, 1984 to March 8, 1985. The sampling effort was deliberately concentrated over the summer months when public numbers were greatest and the infection rate in quokkas was expected to be at its highest. Capture and recapture of tagged quokkas allowed approximate estimates of local populations to be calculated, using a simple Lincoln Index, as modified by Bailey (Bailey 1952; Lincoln 1930). Most individuals were recaptured less than 100 m from the site of their original capture, but a small number of individuals was highly mobile and any quokkas that were recaptured more than 500 m from their initial capture site were classified as 'mobiles' are analysed separately.

Data on *Salmonella* infections were analysed statistically using ANOVA and Chi-squared tests with Yate's correction.

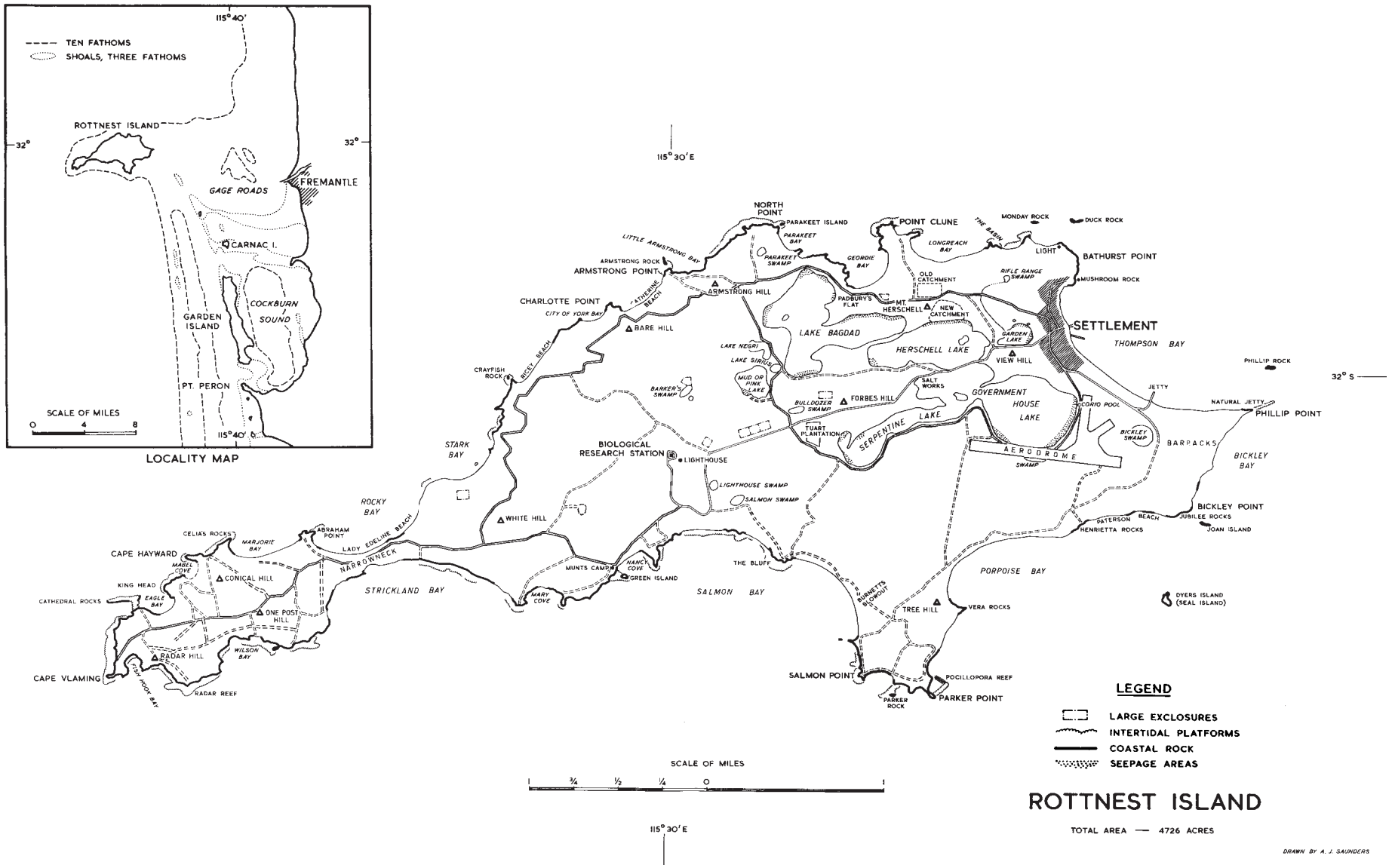

Figure 1. Map of Rottnest Island located 20km off the coast of Perth in Western Australia, showing salt lakes, the main Thompson Bay Settlement area, and other collecting sites at Kingston Barracks, Bickley Swamp, Garden Lake and Lighthouse Swamp.

Table 1

Results of a 12-month *Salmonella* recapture programme of quokkas, *Setonix brachyurus,* on Rottnest Island carried out in areas of public contact between 1984 and 1985.

Quokkas	Settlement Areas	Camping Area	Kingston/ Bickley	Lighthouse Swamp	Mobiles	Totals
No. Tagged	344	91	86	100	49	670
Males	158	62	38	43	30	331
Females	186	29	48	57	19	339
No. Positive (%)	71 (20.6)	23 (25.3)	36 (41.9)	67 (67)	10 (20.4)	207 (30.9)
Recaptures	69	25	27	75	49	284
No. Swabbed once (1)	276	66	59	25	0	426
Twice (2)	56	20	22	15	26	139
(3)	10	5	3	25	14	57
(4)	2		2	7	3	14
(5)				9	5	14
(6)				8	1	9
(7)				4		4
(8)				7		7
Total swabs	426	121	120	335	137	1139
Total Serotypes	20	8	15	14	6	25 (25)
Total Isolations	81	27	54	133	14	309
Juveniles	23	4	8	29	3	58

Results

A total of 670 quokkas was tagged at the 4 major sites comprising settlement and camping area, 435; Kingston/ Bickley Swamp, 86; Lighthouse Swamp, 100; 'mobiles', 49. *Salmonella* isolation rates over the one-year period, including recaptured animals, averaged 21% in the settlement area, 42% in Kingston and Bickley Swamp and 67% in Lighthouse swamp, with a marked seasonal pattern, decreasing over the southern winter period. A combined total of 197 (32%) animals yielded *Salmonellae* at the four locations and 25 serotypes were identified from a total of 1002 swab samples (excluding mobiles) as shown in Table 1. A small number of faeces voided during collection of swab samples from adults and pouch young yielded an MPN (Most Probable Number) ranging from 10–1000 *Salmonella* organisms per gram. The efficiency of swab procedures in isolating *Salmonella* serotypes *versus* faecal samples for *Salmonella* isolations was 67% (Hart *et al.* 1982).

The major serotypes isolated from quokkas in the Settlement areas and the camping area were *Salmonella typhimurium* PT 202 (21), *S. muenchen* 17, *S. adelaide* 13, *S. javiana* 12 and *S. wandsbek* 11, with similar results recorded at Kingston Barracks. At Lighthouse swamp *Salmonella adelaide, S. chester, S. orientalis and S. wandsbek* were the major serotypes isolated. *Salmonella*

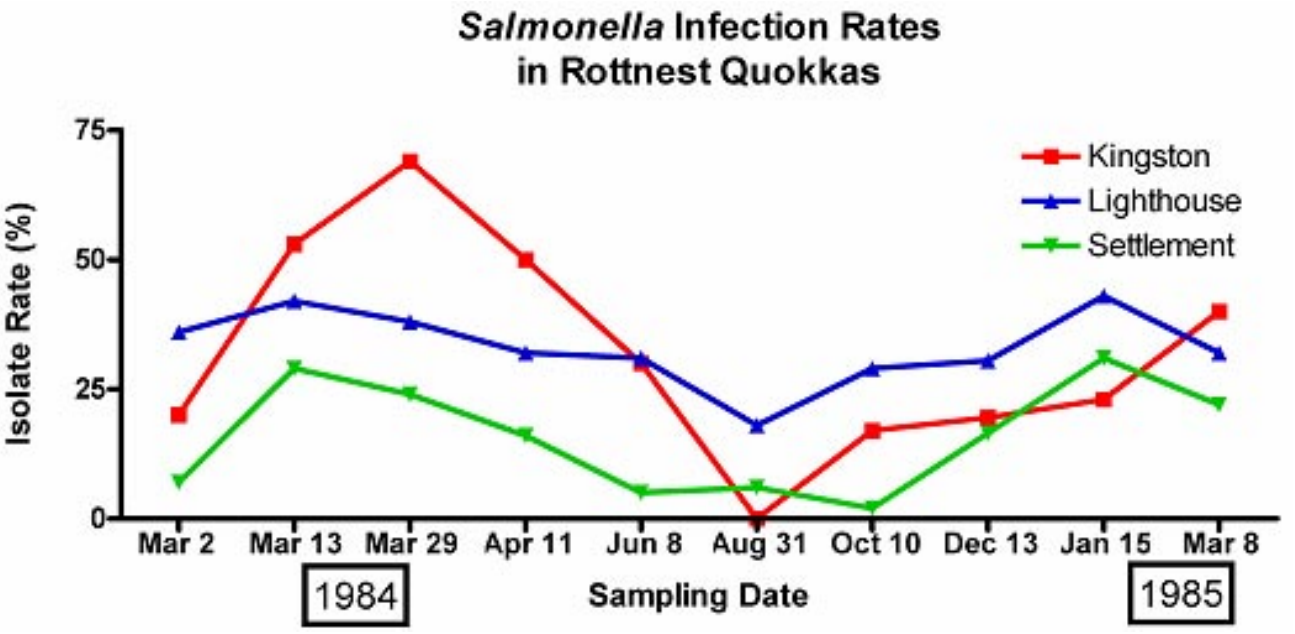

Figure 2. Seasonal variation in *Salmonella* percentage infection rates in quokkas (*Setonix brachyurus*) on Rottnest Island over a 12-month period from March 1984 to March 1985. Sampling locations shown are Kingston Army Barracks and Bickley swamp (Kingston), Lighthouse Swamp (Lighthouse), Garden Lake and the main Settlement area in Thompson Bay (Settlement).

Table 2

Salmonella isolations by serovars from tagged quokkas (*Setonix brachyurus*) in close associations with humans on Rottnest Island over a 12-month period from 1984-1985.

Salmonella **serotypes**	**Settlements**	**Camping Area**	**Kingston Barracks**	**Lighthouse Swamp**	**Mobiles**	**Totals**
adelaide	10	3	5	23	3	44
II alsterdorf			1			1
anatum	3	1	2			6
birkenhead	2			2		4
bootle	4					4
bovismorbificans	2					2
chester	1	1		16		18
decatur	3	1	1	2	1	8
infantis	1			1		2
javiana	8	4	8	1	2	23
muenchen	12	5	5	13	3	38
newington	2			6		8
oranienburg				8		8
orientalis	4		3	14	1	22
orion	3		1			4
potsdam	2					2
rottnest	1		1	7		9
typhimurium	11	10	10		4	35
II wandsbek	9	2	8	36		55
IV waycross	2		4			6
53:d:z_{42}	1		1			2
IIIb 25:l v:z_{53}	3		1			1
IIIb 50:K:z_{35}				1		1
IIIb 61 l v:z_{35}				3		3
IIIb 61:$z_{52}z_{53}$	2		3			5
Total Isolations	81	27	54	133	14	309
Total Serotypes	20	8	15	14	6	(25)
Quokkas tagged	344	91	86	100	49	670

javiana was isolated once but *S. typhimurium* remained undetected. A summary of the serotypes isolated at all sites in contact with the public, including isolations from mobile quokkas, is given in Table 2.

Differences in infection rates between areas

Examination of all field data reveals three major groupings based on the infection rates in the 670 quokkas examined. These are Kingston Barracks, Lighthouse Swamp and the settlement areas and variation over time in infection rates at these sites is graphed in Figure 2. A marked seasonal pattern is evident in all 3 sites, with infection rates falling to between 0 and 20% in winter and reaching a peak in late summer/autumn. A one-way ANOVA shows significant variation between the infection rates in the 3 sites with $F_{2,27} = 4.813$ and $P = 0.0163$. Bonferoni's *posteriori* Multiple Comparison Test shows that infection rates in the Settlement areas are significantly lower than both Kingston Barracks and Lighthouse Swamp with $P < 0.05$.

Differences in infection rates based on age and sex

The number of juveniles sampled was generally too small for statistical analysis except in the case of the settlement areas where the infection rate in juveniles was significantly higher than in adults ($X^2 = 5.06$, $P = 0.02$, see Table 3). A sex difference was only found in adults from the Lighthouse Swamp sample where a higher infection rate was seen in females ($X^2 = 4.349$ $P = 0.037$) as shown in Table 4. This difference was not due to a seasonal bias in sampling of the two sexes as a total of 67 quokkas was positive at least once of which 30 were males and 37 females.

Changes in infection rates in individual quokkas

Only at Lighthouse Swamp were individuals recaptured frequently and thus was it possible to observe changes in infection status in a single animal over both the short and long term. Data from 19 quokkas that were

Table 3

Comparison of *Salmonella* infection rates in adult and juvenile quokkas, *Setonix brachyurus*, from settlement areas on Rottnest Island, with percentages in parentheses

Quokkas	**Positive (%)**	**Negative (%)**	**Totals**
Adults	101 (15.4)	555 (84.6)	656
Juveniles	15 (28.3)	38 (71.7)	53
Totals	115 (16.2)	594 (83.8)	709

Table 4

Comparison of *Salmonella* infection rates in male and female adult quokkas, *Setonix brachyurus*, from Lighthouse Swamp on Rottnest Island, with percentages in parentheses

Quokkas	**Positive (%)**	**Negative (%)**	**Totals**
Males	36 (27.5)	95 (72.5)	131
Females	63 (39.9)	95 (60.1)	158
Totals	99 (34.3)	190 (65.7)	289

Table 5

Salmonella infection records for individual quokkas over a 12-month period of sampling at Lighthouse Swamp on Rottnest Island.

Quokka	March 2 1984	March 13 1984	March 29 1984	April 11 1984	June 8 1984	August 31 1984	October 10 1984	December 13 1984	January 15 1985	March 8 1985	No. Times Sampled
102 ♂	-ve	-ve	-ve	-ve	-ve	-ve	-ve				7
103 ♂	-ve	-ve	-ve	-ve	*berkenhead*	-ve			-ve	-ve	
107 ♀	-ve		*orientalis*	-ve	-ve		-ve	-ve	-ve	*wandsbek*	8
109 ♂	-ve		-ve	-ve				-ve	-ve	*muenchen*	6
176 ♂	-ve			-ve	-ve		-ve	-ve	-ve		6
179 ♂	-ve	-ve	-ve	-ve				-ve	-ve	-ve	7
180 ♂	*adelaide, orientalis*		-ve	*orientalis*			-ve		*orientalis*	-ve	6
183 ♂	*rottnest*	*rottnest*	*rottnest*	-ve	-ve	-ve	-ve	-ve			8
196 ♀		-ve	*wandsbek*	-ve	*oranienburg*			*chester*	*chester*	*javiana decatur*	7
198 ♂		*chester*	*chester*	*chester*	-ve	-ve		*chester*	*wandsbek*	-ve	8
203 ♀		*muenchen wandsbek*		-ve 6	*muenchen*	-ve	*adelaide,*				
284 ♂		-ve	-ve	*newington*	-ve		-ve	-ve	*rottnest*	*wandsbek*	8
288 ♂		-ve	*muenchen adelaide*	*orientalis*	-ve			-ve		-ve	6
292 ♀		-ve	-ve	-ve			-ve	-ve	*adelaide*	*wandsbek*	7
303 ♀			*adelaide*	*adelaide*	-ve	-ve	*wandsbek*	-ve			6
308 ♀			-ve	-ve		-ve	-ve	*wandsbek*		-ve	6
310 ♂			-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve	8
311 ♂			-ve	-ve	-ve	*wandsbek, adelaide*					
389 ♂			-ve	*oranienburg*	*oranienburg*	*oranienburg*		*oranienburg*	*oranienburg*		6
No.+ve	2/8	3/10	6/17	6/19	4/14	2/10	2/12	5/15	7/14	5/13	42/132

caught and sampled a minimum of 6 times are presented in Table 5. Infections were predominantly transient, involving 10 different serotypes. Only 2 quokkas (male 198) infected with *S. chester* and (male 389) infected with *S. oranienberg* showed evidence of infections exceeding a period of 6 months. Conversely, 9 animals showed evidence of being free from infection for several months. It is possible, however, that when low numbers of organisms are present per gram of faeces, i.e. < 10, the standard swabbing procedure may fail to detect *Salmonella* (Hart *et al.* 1982).

In the Thompson Bay settlement areas, including the camping area, Longreach Bay and Geordie Bay, 435 individual quokkas were captured and 93 of these recaptured one or more times. Ninety five of these recaptures were within a 30-day period and could be subjected to analysis. Fifteen of these were positive initially and 14 on the second occasion. In the first group of 15, 8 were subsequently negative, 4 were positive with a different serotype and 3 (20%) were positive with the same serotype. Seven quokkas were negative at the first sampling but showed as positives during sampling in the following months. Of all the 93 animals recaptured in the settlement areas, only 4 were ever positive with the same serotype twice.

In the Lighthouse Swamp population there were 100 individual quokkas tagged and swabbed with a total of 310 swabs from 75 recaptures. Of the 62 quokkas found to be positive at the first sampling time, 38 were subsequently negative, 7 were positive with a different serotype and 17 (27%) were positive with the same serotypes.

In the Kingston Barracks/Bickley Swamp sample there was a total of 86 individuals tagged and 27 recaptures (second sampling) and 13 more recaptures at subsequent times. Of the 8 quokkas that were positive on the first sampling, one was negative subsequently, 4 were positive with a different serotype and 3 (38%) were positive with the same serotype.

Movement of Animals

There was movement of quokkas between Kingston Barracks, Bickley Swamp and the Settlement. These individuals, and any others moving more than 500 m, were scored as 'mobiles' on reaching the settlement. There were frequent movements by quokkas of over 50 m between sampling sites within the settlement but the majority of animals was captured only on few occasions in the camping area, as well as in the main settlement area. Within the settlement and Kingston Barrack/Bickley Swamp sites, 114 individuals were recaptured only at the same site as their initial capture, showing evidence of high philopatry, whilst 48 individuals were recaptured in at least one other site. There was great variation in the length and frequency of movements recorded in the mobile groups with some individuals being recaptured in other sites and then reappearing at the initial site of capture. Only a few quokkas, however, were captured at more than two sites, even when adjacent or nearby.

The frequency of movements and approximate distances travelled by quokkas are presented in Table 6 with 50% of these under 100 m, highlighting the basically sedentary nature of the quokka. Only 14% of the records were in excess of 500 m, five being recorded at 2100 m between Kingston Barracks and the camping area.

Table 6

Frequency of movement and distances travelled by tagged quokkas, *Setonix brachyurus*, on Rottnest Island.

Distance Travelled	Number	Frequency (%)
<100 m	29	50
100-200 m	12	20.5
200-500 m	9	15.5
>500 m 'Mobiles'	8	14
Totals	58	100%

Table 7

Estimates of population size at various capture sites for the quokka, *Setonix brachyurus*, on Rottnest Island. For the location of sites, refer to the text.

Capture Site	Population Estimate
Camping Ground and Lodge	360
Garden Lake	175
Police Station	64
South Settlement	75
Lighthouse Swamp	98
Kingston Barracks and Bickley Swamp	101
Total	873

Population Estimates

Very approximate estimates of population size for the various capture sites, based on mark-and-recapture efforts, are summarised in Table 7. The main settlement area at Thompson Bay, comprising Bathurst Point, the camping ground, Lodge, Garden Lake, Police Station and South Settlement supports an estimated population of 674 quokkas which translates to an extraordinarily high density of approximately 21 animal.ha^{-1}. The Lighthouse Swamp site suggests that a discrete population of approximately 100 individuals is receiving supplementary feeding from tourists. The Kingston Barracks/Bickley Swamp population is roughly of the same size but quokkas are not fed by tourists.

Human Transmission and Public Health Issues

During the study period, patients exhibiting symptoms of gastro-enteritis rarely submitted faecal samples and *S. typhimurium* PT 202 was isolated from one patient. Monitoring of the sewage system revealed 26 serotypes and *S. Adelaide, S. chester, S. javiana, S. muenchen* and *S. typhimurium* PT 202 were detected in coastal waters, catchment sumps and water storage tanks. One hundred and twenty samples of seagull droppings collected from *al fresco* dining areas popular with the public were tested and resulted in the isolation of 11 serotypes including *S. adelaide, S. javiana* and *S. typhimurium* PT 202.

Discussion

Salmonella in wildlife

There is an increasing appreciation of the widespread occurrence of *Salmonella* serovars in wildlife species, and

of the possibility of zoonotic infections (Kruse *et al.* 2004) with Taylor Latham & Woolhouse (2001) estimating that of 1,415 known human pathogens, 62% are of zoonotic origin. An early paper by Bool & Kampelmacher (1958) reported that wild animals were carriers of *Salmonella* and Kourany Myers & Schneider (1970) identified amphibians and reptiles as common carriers. Everard *et al.* (1979) isolated 20 serovars of *Salmonella* from 44 out of 219 animals in Trinidad and Grenada with the toad, *Bufo marinus*, being the most frequently infected. Evidence of transmission of *Salmonella typhimurium* O: 4–12 from wild passerine birds from to humans was reported in Norway in 1998 (Kapperud Stenwig & Lassen 1998). A total of 33 *Salmonella* serovars was isolated from 34 symptom-less reptilian species in Indiana County, Pennsylvania, adding support to the contention that *Salmonella* is a natural member of the intestinal flora of herpetofauna (Chambers & Hulse 2006; Minette 1984). Fifty nine different serotypes of *Salmonella* were isolated from 25 species of wildlife, including crocodiles, in Queensland over a 20-year period but the major serotype infecting humans in north Queensland was absent from the reptiles (Thomas Forbes-Faulkner Speare & Murray 2001). Recent publications have documented the occurrence of *Salmonella* infections in moose (*Alces alces*) in Norway (Aschfalk Hundertmark Bendiksen Arnemo & Elchen 2003), the New Zealand endangered passerine bird, the Hihi (*Notiomystis cincta*) (Ewen Thorogood Nicol Armstrong & Alley 2007) and a wide range of wildlife species in the Nairobi National Park (Gitter & Brand 2005).

Salmonella in the quokka

The first isolation of a *Salmonella* serovar from the quokka was in 1972 (Iveson & Bradshaw 1973) and the fact that it was a rare south-east Asian serotype (*S. javiana*), unknown on the mainland of Australia, prompted the initial investigations of its ecology on Rottnest Island Hart Iveson & Bradshaw 1987; Iveson & Bradshaw 1978). The differences between infection rates found in the present study are consistent with the results of general area comparisons by Hart Bradshaw & Iveson (1985); and Iveson & Bradshaw (1973). This early work established that quokkas in the settlement area were in the best physical condition of animals on the island and exhibited the lowest rates of infection of approximately 20% in all seasons compared with rates of 40–70% from other sites. Thus, paradoxically, infection rates are lowest in areas of greatest human contact, but this would appear to be due to the supplementary feeding that the quokkas receive from tourists in the settlement and the tourist site at Lighthouse Swamp, which helps to maintain their body condition during the adverse summer period, and resistance to infection. Hart *et al.* (1987) similarly established that quokkas collected at the Island rubbish disposal site had low infection rates year round and high physical condition, measured with a meristic condition index relating body mass to bone length (Bakker & Main 1980).

Variation in infection rates

Over most of the island, away from settlement and recreation areas, there is a dramatic change in the infection rate, which cycles seasonally, approaching 70% in summer and falling to 0–30% in winter. Hart (1980) found that Bickley Swamp, which is near the Kingston Barracks, was intermediate. Lighthouse Swamp is also intermediate, reflecting probably the impact of daily feeding by tourists on the condition of the quokkas at this site. The lower results for the late summer of 1985 included in the analyses are considered atypical because of unseasonable rains that fell on the island in the summer of 1984–85. No evidence of the marked rise in infections and epizootic of *S. adelaide* recorded earlier in the settlement area and at Lighthouse Swamp was found in subsequent studies and *S. adelaide* infections declined in incidence to previous levels. *Salmonella javiana* was isolated on 21 occasions in the combined settlement, Kingston Barracks and campsite area, but only once at Lighthouse Swamp. A similar pattern of isolations occurred with *S. typhimurium*. The vast majority of these strains were Phage Type 202 in quokkas inhabiting settlement areas, the camping area and Kingston Barracks. Analysis of infection rates in males, females and juvenile quokkas showed that only at one site, Lighthouse Swamp, was there any evidence of discrimination on the basis of sex and it was concluded that Public Health procedures should not focus on any particular age group or sex when collecting samples.

Recapture rates

Analysis of the fate of infections in recaptured animals revealed that infection rates conformed to the seasonal pattern and was estimated at 20% for the settlement, 28% for Lighthouse Swamp and 38% for the Kingston/Bickley Swamp population. These estimates are fairly consistent, despite differences in infection rates between the study areas. All of the *Salmonella* isolations and re-isolations recorded for comparative purposes were made in summer and the majority were within a two-week period following the primary isolation. The possible bias involving failure to detect small numbers of organisms and subordinate strains in mixed infections by the swab procedure has been investigated by Hart *et al.* (1982) and applying the minimum level of recovery it is estimated that only 50% of serotypes detected are still present after 2 weeks. The numbers of organisms excreted are thus below the dosage likely to pose a significant hazard to humans, assuming contamination of foodstuffs, water supplies and coastal waters is avoided.

There is some evidence that serotypes do persist in carrier animals over long periods of time. Quokkas No. 198 with *S. chester* and No. 389 with *S. oranienberg* at Lighthouse Swamp, for example, each retained a given serotype for 9 months. Evidence that these infections represent a carrier state in maintaining hosts is that the serotypes are relatively uncommon and are unlikely to be isolated repeatedly as transient infections. These results are consistent if the great bulk of infections recorded represent short-term transient episodes of infection. The few long-term infections may also be maintained by recycling in high infection areas such as contaminated seepage areas and other surface water used by quokkas and cohabiting wildlife converging for drinking. Quokkas have been shown to supplement their meagre supplies of water by drinking brackish water that seeps into the various salt lakes on the island (Jones Bradshaw Fergusson & Watts 1990). During the summer months these seepage areas are heavily contaminated with droppings and 24 different serotypes have been

identified from a total of 219 isolations, suggesting contact with other reservoir hosts, such as reptiles or seagulls (*Larus novaehollandiae*) (Iveson & Bradshaw 1978).

Movements of quokkas

The record of animal movements confirmed that most quokkas were highly sedentary, moving only short distances to foraging areas close to diurnal rest sites (Kitchener 1972). A small number of individuals, however, showed evidence of high mobility, being recaptured at distances over 1 km on the small island. Five quokkas, for example, moved between Kingston Barracks and the camping ground. Forty nine animals (29 males and 20 females) were classified as 'mobile' and 10 of these (20%) were positive and infected with *S. adelaide, S. javiana* and *S. typhimurium* PT 202. Movements were mainly in the settlement areas and included quokkas moving from the beach to the camping area, from Bathurst Point to the Police Station, and from Garden Lake to Bickley Swamp – this latter displacement being approximately 1 km. There was no evidence, however, of quokkas moving short or long distances acting as carriers of *Salmonella* infections to new locations. One quokka sampled in the settlement classified as 'sick' and in poor condition showing evidence of wasting and scouring was positive for *Campylobacter jejuni*, an important zoonotic pathogen. *Edwardsiella tarda,* an opportunistic human pathogen, was also isolated from quokka droppings at Garden Lake.

Population and density estimates

The estimates of population sizes are of necessity only approximate, merging close sites and different collecting dates in order to overcome the problem of small sample sizes. They nonetheless give some idea of the extraordinarily high density of the quokka population in the settlement area. Estimates of the total number of quokkas on Rottnest Island are vague but the figure of 12,000 is accepted by most commentators (Iveson & Bradshaw 1978; Miller & Bradshaw 1979; Pen & Green 1983), giving an average density of 6.3 animals ha^{-1} for the 1912 ha island. This needs to be contrasted, however, with the figure of 21 animals ha^{-1} in the confined settlement area. The settlement area, because of its proximity to humans and supplementary sources of food, is obviously a preferred site for quokkas and this almost certainly adds to the likelihood of their acquiring and recycling infections. Animal densities in the wild of greater than 2 ha^{-1} are unusual – for example in the Niassa Reserve in Mozambique this only occurs in small localised areas with densities of 0.5–2.0 individual ha^{-1} being much more common (Gibson 2000). Population densities at Kingston Barracks/Bickley Swamp and the Geordie Bay and Longreach settlements were lower, but still well above what would be needed to nullify the risk of recycling and re-infection between quokkas.

Implications of the study

Guidelines for the management of salmonellosis on Rottnest Island were established prior to the present study (Iveson & Hart 1983) and quokkas in subsequent year have been effectively excluded from the settlement area that is most frequented by members of the public. This has been done primarily by denying quokkas access to spaces beneath houses and buildings where they previously sought refuge during the daylight hours, emerging to feed at night. The one exception is the tourist bus stop at Lighthouse Swamp which the present study suggests does not pose a significant health risk to the public, as visitors to the site are supervised. These measures appear to have been very effective, with no documented recurrences of human cases of salmonellosis on the Island since 1991.

The study provides insights into the potential hazards of tourist-type facilities that focus on close encounters with wildlife species. Rottnest Island is an iconic resort for West Australians, where escape from the pressures of modern living are sought specifically by a temporary retreat, and rejuvenating contact with nature is a primary aim of the visit (Seddon 1983). The prevalence of a large number of serotypes in a natural population of animals such as the quokka, with infection rates reaching 70% in some areas in the summer months, serves, however, to highlight the inherent dangers of too-close contact with wild species. Outbreaks of salmonellosis that can be traced to wildlife are quite common (e.g. an outbreak of *Salmonella saintpaul* in Queensland that was traced to frogs and mice (Taylor Sloan Morton & Hunter 2000)) and there is a need to educate the public of the importance of respecting wildlife and not treating it as a natural extension of household pets. There is also a need to better understand the source of *Salmonella* infections in mammalian species, where they appear to be at least potentially pathogenic, whereas in some vertebrates, such as reptiles, they appear to be natural members of the gastrointestinal flora.

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