Chapter 8: Ecology and management of mosquitoes

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The life-cycle and ecology of the saltmarsh mosquito

Introduction

Saltmarshes form at the dynamic interface between land and sea. This interface experiences fluxes in the biological, physical and chemical processes responsible for the density and abundance of species. As a result, saltmarshes provide important ecosystem services but also support the key habitat features necessary for breeding of some species of pestiferous and vector mosquitoes.

In Australia, the most common species of mosquitoes that breed in saltmarsh habitats are *Aedes vigilax* Skuse in the warmer tropics and subtropics and *Aedes camptorhynchus* (Thomson) in the cooler areas. *Aedes alternans* (Westwood) occurs in both regions, but less commonly. All saltmarsh mosquitoes breed in the free water that pools in shallow depressions following tidal influence or as a result of freshwater inputs.

Mosquito breeding strategies

The biology of the mosquitoes inhabiting saltmarsh was described by Russell (1993) for southeast Australia and by Liehne (1991) for Western Australia. The adaptive strategies of different species are reflected in their ability to use and preference for habitats that exploit the dynamic nature of saltmarsh. For example, the larvae of some species develop near saltmarshes during normal tidal cycles and then in them following rainfall, when the salinity of ground pools is lower. These brackish species include *Culex sitiens* Wiedemann, *Verrallina funerea* (Theobold), *Aedes procax* (Skuse), *Culex annulirostris* (Skuse) and *Aedes notoscriptus* (Skuse.).

Many mosquitoes require water for egglaying. For example *Culex sitiens* and related *Culex* species lay a raft of eggs on the water. The Anopheline (genus *Anopheles*) mosquitoes also lay eggs on water – hence water is needed for both the egg and larval stages. In contrast, aedine mosquitoes (those in the genus *Aedes*) lay eggs on the ground surface. For the saltmarsh mosquito (*Aedes vigilax*) the life cycle requires the varying conditions that occur on the saltmarsh. The eggs are laid, singly, on damp ground or plant stems, and are conditioned by drying out. Then flooding occurs and a drop in dissolved oxygen stimulates hatching. Following tidal events, hatching of Aedine species can occur almost immediately and simultaneously. This can result in very larval population high densities developing under ideal conditions.

Larval development and ecology

The life cycle is shown in Figure 7.1. After hatching, and provided water remains for sufficient time, the larvae will develop through four larval stages. A newly hatched first instar *Aedes vigilax* is less than 0.9 mm long and a 4th instar is around 4-5 mm. During the larval stages a larva breathes air directly via a syphon or by an air hole, connecting through the water surface. This means that larvae can survive in low dissolved oxygen environments, where aquatic predators may be relatively few. The larvae pupate, ceasing feeding and soon emerge as adults. Males often emerge first to await the females. After mating, females seek a blood meal for protein to help develop their eggs. However some species are autogenous, that is, they can lay one batch of fertile eggs without mating. In summer, when water temperature is warm, the larvae can complete development, pupate and emerge as adults in around five days. In winter development may take three weeks or longer. The life span in the field is probably around 2 weeks though adults can be kept alive under laboratory conditions for several months (Morris et al 2002: D6). *Aedes vigilax* can fly considerable distances, up to 50 km, though this may be influenced by favourable wind (Morris *et al.* 2002: D-7). The biology of *Aedes vigilax* is described in Sinclair (1976).

Figure 7.1. Mosquito Life cycle (Life cycle drawing adapted from Silver City Vector Control Task Force http://www.townofsilvercity.org/vector/MosquitolifeCycle.html Accessed 20 October 2006)

Detailed research based on remote sensing and field study at Coomera Island in south-east Queensland showed an interesting strategy for *Aedes vigilax* (Skuse) (Dale *et al*. 1986**)**. In the Coomera research oviposition sites were intermediate between low and high marsh in areas of mixed *Sarcocornia quinqueflora* (Bunge ex Ung.-Stern) and *Sporobolus virginicus* (L. Kunth) vegetation. Larvae were most numerous on the low marsh, with its *Sarcocornia* vegetation and on mudflats, but were also plentiful on the upper marsh, in amongst the dense *Sporobolus.* This is one of the reasons that saltmarsh mosquitoes are numerous: pools in the higher marsh that flood on high tides may often be isolated for several days. This means that access for predators such as fish is very limited and the habitat is relatively safe for larvae, though drying up is a risk. On the other hand the lower areas retain water but also have increased risk of predation.

Disease transmission

Saltmarsh mosquitoes transmit a variety of arbovirus diseases. Ross River and Barmah Forest viruses are the two dominant mosquito-borne viruses affecting humans in the area. They are not fatal but are debilitating and are characterised by arthritis, fever, rash and fatigue (MacKenzie *et al.*1998). The economic impact of RRv is significant with estimates of the cost of healthcare resources and productivity loss to be $AUD1,000 -

2,500 per person (Boughton 1996; Harley *et al.* 2001; Mylonas *et al.* 2002) and more recently it has been estimated to be over $AUD 1000 per person (Ratnayake 2006). Although RRv is present in all states (Miller *et al.* 2003) Queensland generally has more cases than any other state (Russell 2002). Tables 1 and 2 shows the annual incidence and rate by state/territory. From the data in Table 1 Queensland had on average 53% of the cases, ranging from 35 % in 2000 to 78% in 1994. Table 2 shows that the Northern Territory has the highest rate, though the numbers are less than in Queensland. Only Tasmania and the Australian Capital territory have relatively few cases and a low infection rate.

Table 7.1. Number of Ross River cases in Australia by state and territory, 1993-2007

Table 7.2. Rate of Ross River cases/100 000 in Australia, by state and territory 1993-2007

Ross River virus is transmitted by female mosquitoes when an infected mosquito takes a blood meal (to enable her eggs to develop). The cycle is shown in Figure 7. 2. The mosquito is infected by biting an intermediate host such as a kangaroo, wallaby or other warm-blooded animal. The virus then replicates over a period of around a week within the mosquito and so can be transmitted when next she feeds. Except under epidemic conditions it is thought that humans are a dead-end host. That is, the mosquitoes are not re-infected when biting a viraemic person. In some cases transmission may also occur 'vertically' when an infected female's eggs hatch infected larvae, resulting in adults ready to infect.

Figure 7.2. Ross River virus transmission cycle (adapted from a figure provided by the Queensland Institute of Medical Research, mosquito photo provided by Prof Brian Kay)

Because of the risk to human health, control of mosquitoes close to human settlement is important and is, for example, mandatory in Queensland under the *Public Health Act 2005.* The responsibility for mosquito control involves the local governments in the States and Territories and assistance is provided by the State/Territory Health departments, by funding as in WA or by other assistance as in Queensland.

Control methods

In Australia, control or management of saltmarsh mosquitoes is focussed on the larval stages rather than adult mosquitoes. Larviciding (control of larval mosquitoes) in saltmarsh requires a detailed knowledge of the biological and ecological features of the target animal to maximise the efficiency of measures. The main advantage of larval control over adulticiding (control of adult mosquitoes) is that measures are implemented when the target organism is still developing. The concentration of immature mosquitoes on saltmarsh is very high compared to the scattered distribution of adult mosquitoes.

Generally, saltmarsh mosquito larvae occur in transient pools located high on the marsh. These pools are filled infrequently by tidal or surface waters and control efforts target the larval habitats. Control can be can be effected via several mechanisms, under three broad strategies:

- habitat modification
- chemical treatment
- the use of biological agents.

Each has its advantages and disadvantages in terms of effectiveness, costs and environmental impacts. An integrated mosquito management program uses a variety of methods so that there is not complete reliance on any one strategy.

Salt marsh management for mosquito control was reviewed in Dale and Hulsman (1990). They identified serious information gaps in the area of impacts of control and some of these have been remedied at least in part since then. In the area of habitat modification they also identified a changing rationale for salt marsh mosquito management in Australia. This was one that attempted to modify the habitat only so far as it was needed to reduce mosquito larval populations, rather than adopt the approach that destroying the environment would also destroy mosquitoes, as had been implemented elsewhere earlier in the 20th century. The Australian rationale has been embedded in policy as demonstrated in the Australian Mosquito Control Manual (Morris *et al.* 2002) and in Queensland the Mosquito Management Code of Practice (Local Government Association of Queensland 2002).

Habitat modification

Modifying the larval habitat will affect mosquitoes. The advantage is that this is of long-term effect and reduces on-going control costs though it may take several years to recoup the costs in terms of savings by using less chemicals (Dale *et al.* 1989). The disadvantage is that it may incur a relatively large capital cost at the time of construction, as well as incurring delays because of permitting requirements. There is also the potential for environmental damage, especially with respect to modifying the physical, chemical and biological characteristics of saltmarsh.

Habitat modification of saltmarshes for mosquito control was developed early in USA and has evolved into several methods that are widely used. These range from ditching the marsh, via Open Marsh Water Management which retains or restores tidal flooding (Meredith *et al.* 1985; Ferrigno and Jobbins 1986) to impounding, nowadays allowing for tidal circulation during times of low mosquito populations (Carlson and O’Bryan 1988).

The concept of minimal disturbance was developed in Australia and reported in Dale and Hulsman 1990. It led to runnelling, which is a minor form of Open Marsh Water Management. Runnelling was first implemented in New South Wales in 1984 and at Coomera Island in Queensland (S27° 51', E153° 33'), in November1985 (Hulsman *et al.* 1989).

The term runnelling was coined to clearly distinguish it from ditching. Having identified water as the critical variable in the mosquito system runnelling was designed to connect the isolated pools to the tidal source to increase the flushing potential of otherwise isolated pools and to allow greater predator access to the larvae. At Coomera Island the saltmarsh is usually only flooded by tides exceeding 2.45 m AHD (predicted at the Brisbane Bar). Thus around 7% of tides each year (around 50) flood the marsh. However if runnels are constructed to a depth of 0.25m then the tide will extend into the marsh on a 2.20 m predicted tide. This means that around 28% of tides (n=196) will flood the marsh after runnelling. This is illustrated in Figure 7.3 below.

Figure 7.3. Effect of runnelling calculated on the frequency of tidal flooding at Coomera Island (from Breitfuss 2003). Tidal cycle at the Brisbane Bar is shown for 2002. Dashed line represents height of tides (2.45 m) that would normally completely flood the marsh. When runnelled, tidal height required for inundation reduces to 2.20 m (solid line) thereby increasing the number of flooding tides. (Queensland Department of Transport 2002)

Natural channels were used as models for the structures – runnels- and so these were designed to be shallow, spoon shaped channels, three times as wide as deep and with a maximum depth of 0.30 m. The depth of runnels was determined with reference to a sandy erodible layer at that depth at the Coomera site. In retrospect, this was a wise decision, as potential acid sulfate soils are encountered throughout coastal Australia at elevations below 5 AHD. Further, careful site selection and design for runnelling should minimise the potential for encountering and exposing these soils (see Alsemgeest *et al.* 2005).

In addition, channels were located as much as possible in areas of natural water flow, determined in the field and from colour infrared aerial photographs, in which wet depressions and channels appear relatively dark. Figure 7.4. shows a view of a runnel and the runnel layout at Coomera Island

Figure 7.4. Runnel and layout at Coomera Island (1986).

That runnelling reduces mosquito populations is generally accepted and the method is used widely in southeast Queensland, New South Wales and Western Australia. In Western Australia, Latchford (1997) found runnelling to have no significant impact on a number of macro-scale features. However, the study was short-term with less than 2 years post-runnelling assessment.

The impacts of runnelling have been assessed at a range of sites but most research has been on the Coomera site. The 20-year monitoring for that site has been reported in Dale (2008). It concluded that mosquito production was reduced and that there were very small magnitude impacts on the environment to include slightly increased substrate moisture lower salinity and some vegetation change (mainly smaller and less dense plants). Other research in southeast Queensland has identified localised impacts associated with the presence of runnels on:

- sediment consolidation and soil water features (Breitfuss and Connolly 2004)
- seasonal reductions in fish abundance adjacent to runnels (Connolly 2005)
- patterns in grapsid and grapsoid crab species abundance (Breitfuss *et al.* 2004; Breitfuss *et al.* 2005)
- patterns in the density and size structure of surface-feeding pulmonate snails (Breitfuss et al. 2005)
- transport of mangrove propagules (Breitfuss *et al.* 2003)

Many of the patterns associated with the presence of runnels can be explained in terms of natural variability in the characteristics of saltmarshes. For example, there were differences between treatment and controls at runnelled sites in southeast Queensland for some crabs in a trapping experiment (Chapman *et al*. 2004; Breitfuss *et al.* 2005) and in a study of crab burrow density (Breitfuss 2003; Breitfuss 2005). The results of the crab burrow study indicated local-scale differences in the distribution and abundance of species, between sites with and without runnels, based on their preferences for different substrate conditions. Given the high degree of heterogeneity between these conditions on marshes in southeast Queensland (Breitfuss and Connolly 2004), the results tended to highlight these features rather than impacts associated directly with the presence of runnels. Nevertheless the southeast Queensland sites do have relatively few species and the impacts noted may differ for more species rich environments at higher latitudes.

Concerns have been raised over the potential for runnels to facilitate the invasion of mangroves onto saltmarsh. While runnels will transport mangrove propagules onto saltmarsh (Breitfuss *et al.* 2003) it is unlikely the propagules are deposited to locations suitable for growth and sustained development. Mangrove invasion of the salt marsh has not occurred at runnelled sites (Jones *et al.* 2004) although generally, mangrove density on saltmarsh is increasing and often at the expense of saltmarsh (Saintilan and Williams 2000).

Research at the Coomera site has shown that as a mosquito control technique, runnelling results in fewer non-target impacts (noted above) than Open water Marsh Management (Dale and Knight (2006). Most of the analyses have indicated that runnelled sites do not differ significantly from the control sites (Dale 2008) and especiallywhen considering salt marsh processes (Dale and Dale 2002; Dale *et al.* 1993; Dale and Hulsman 1988).

Chemical control

Adult mosquitoes may be targeted using a range of non-specific chemicals. In Australia, adulticiding is not the preferred method of control and is generally only implemented under emergency situations when adult mosquitoes pose a direct risk if disease transmission to human settlements.

It is usually considered more effective to control the problem of mosquitoes closer to their source; the larval habitat where the developing mosquitoes are restricted to water bodies. If the saltmarsh habitat is not modified, by runnelling OMWM or some other method, then the most effective control method is to treat larval habitats with a larvicide. The advantage is that because larvicides are used the isolated pools contained larvae, the effective kill rate aims to exceed 95%. The main disadvantages in using larvicides is the volume of product required to be distributed in the field and associated application costs. Most larviciding programs are implemented by using aerial and/or ground-based vehicles and personnel. Monitoring is required to identify the presence of larvae on the saltmarsh, as the location of larval habitat pools is not consistent with all patterns of tidal or surface water inundation. Further, monitoring is necessary to establish both whether an application has been successfully applied to a larval habitat and when the application has ceased to be effective.

Studies from overseas and in Australia have identified a number of chemicals suitable for use in Australia. Based on their limited range of non-target impacts and ability to be applied using broad hectare methods, the two most commonly used chemicals are *Bacillus thuriegiensis* var *israelensis* (B.t.i) and (s)-methoprene. Both chemicals are produced in a variety of formulations (liquid, granules, briquettes) that offer options for the type of application and length of activity required.

The mode of action of the commonly used larvicide chemicals is either through ingestion or external contact. For B.t.i products, the chemical is ingested by larvae and, due to the pH of the larval midgut, toxic proteins are released from the product that cause cell lysis and death. Only actively feeding larvae are affected by the chemical. The chemical is quite target-specific to Diptera, especially mosquitoes. Further, the potential for broad non-target impacts is reduced because the mode of action requires the release of toxic proteins based on pH. Common formulations are liquids or granules and the activity period is relatively short, less than a week in the field.

The insect growth regulator (IGR) (s)-methoprene is delivered to larval habitat pools as a contact chemical. The timing of application for (s)-methoprene is critical for effectiveness on early instars. The mode of action of the chemical is to slow development and hinder the final moult from pupa to adult. Monitoring of (s)-methoprene activity on field populations of mosquitoes is necessary for evaluating mortality and percentage reduction in emergence. Both liquid and solid formulations are available. Solid formulations may provide consistent control for up to a few months in some circumstances.

A limited number of organo-chlorine based products are used for larviciding in Australia. The managed use of these chemicals can provide effective control of saltmarsh mosquitoes, though a range of significant non-target impacts on invertebrates and vertebrates have been investigated for the field and laboratory. Although effective at killing larvae the ingredient does have adverse impacts on non-targets especially in saline wetlands and on crustaceans, either directly or by leading to increased mortality from predation (Dale and Hulsman 1990).

The products are applied to the areas to be treated either by ground-based application or by aerial spraying. For large and not easily accessible areas, aerial application is the most effective and efficient as it can be carried out rapidly. This is important as the window of opportunity may be restricted to only a few days following a tidal or flooding event. This window must also consider the field verification of a hatching event and then the flight must be arranged so that the product is applied at a time relevant to the chemical being used and the stage of development of the larvae.

In practice, the control agencies program their operations based on tidal predictions, weather conditions, knowledge of field conditions and often have arrangements with the aerial spraying company for rapid responses. The use of Global Positioning Systems to ensure coverage and calibration of dispensing equipment to assure appropriate concentration of minimises both monetary and environmental costs.

Biological Control

Research and experimentation into the effectiveness of biological control agents for saltmarsh mosquito control are in their infancy. To-date, studies have focussed on field observation of natural systems, rather than manipulation. There has been no really effective biological control developed for salt marsh mosquitoes. While there are various organisms that are known to prey on mosquito larvae, such as copepods, insects and fish, their effectiveness for large-scale control programmes is limited.

There is still a dearth of information regarding salt marsh predators whose lifecycle may be synchronised with that of the larvae. To be effective in reducing very high densities of mosquito larvae, small predators need to be able to colonise the marsh as rapidly as the eggs hatch so as to be able to consume the small first instar larvae.

Fish have the potential to predate on larvae when they access the marsh with a flooding tide. There have been year-long studies at the Coomera Island site, conducted prior to runnelling. Morton *et al.* (1987) recorded some adult mosquitoes in the fish diet, but insects appeared to be a very minor item of diet. Morton *et al.* (1988), focussing on the mosquito issue at Coomera, found that fish did consume larvae, but not in large quantities and concluded that fish were not likely to control the mosquitoes. Shrimps may also have potential to act as a biological control in saltmarshes but more research is needed on this. A study in south-east Queensland has indicated that they feed on larvae (Morris *et al.* 2002, I-5). In addition, some mosquito larvae prey on smaller larval instars. In the saltmarsh *Aedes alternans* is one such species, but is not found in sufficient numbers to act as an effective control and moreover is another pest mosquito, although not a known disease vector.

The dynamic nature of saltmarsh larval habitats is suited to the breeding strategies of mosquitoes, but not for transient aquatic organisms that require more static conditions for survival. Saltmarsh pools are exposed to irregular periods of drought and flooding, dependant on their location from the tidal front, height on shore and proximity to other sources of water.

In addition to the intermittent presence of water on saltmarsh, its salinity characteristics vary considerably, ranging from almost fresh/brackish following rainfall to hypersaline a few days after tidal flooding in summer. Salinities in excess of 40 ppt are not uncommon in the isolated pools that provide mosquito larval habitat, compared to seawater of 35 ppt). Water table salinities of up to 80ppt have been recorded at Coomera Island (Dale unpublished data).

Conclusion

Salt marshes provide important ecosystem services, including habitat for disease vector mosquitoes. This has human health impacts and possibly longer term consequences for the ecosystems, as a result of attempts to manage the issue. Mosquito management can be carried out via a range of methods and the most developed and best resourced programs are integrated ones, relying on a mix of methods as appropriate to the nature of the problem, areas and species. In general in Australia larval control is preferred to adulticiding and that means that efforts to control saltmarsh mosquitoes focus on saltmarsh larval habitats. Not all saltmarshes are suited to habitat modification, but where they are, runnelling provides long term and cost-effective control with minor non-target impacts. Chemical control is highly effective as a short-term measure, but requires coordination, monitoring and incurs significant costs. Biological control is unlikely, in the near future at any rate, to offer the extent of management necessary for an effective reduction in vector mosquitoes.

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Useful website

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Fig 7.1

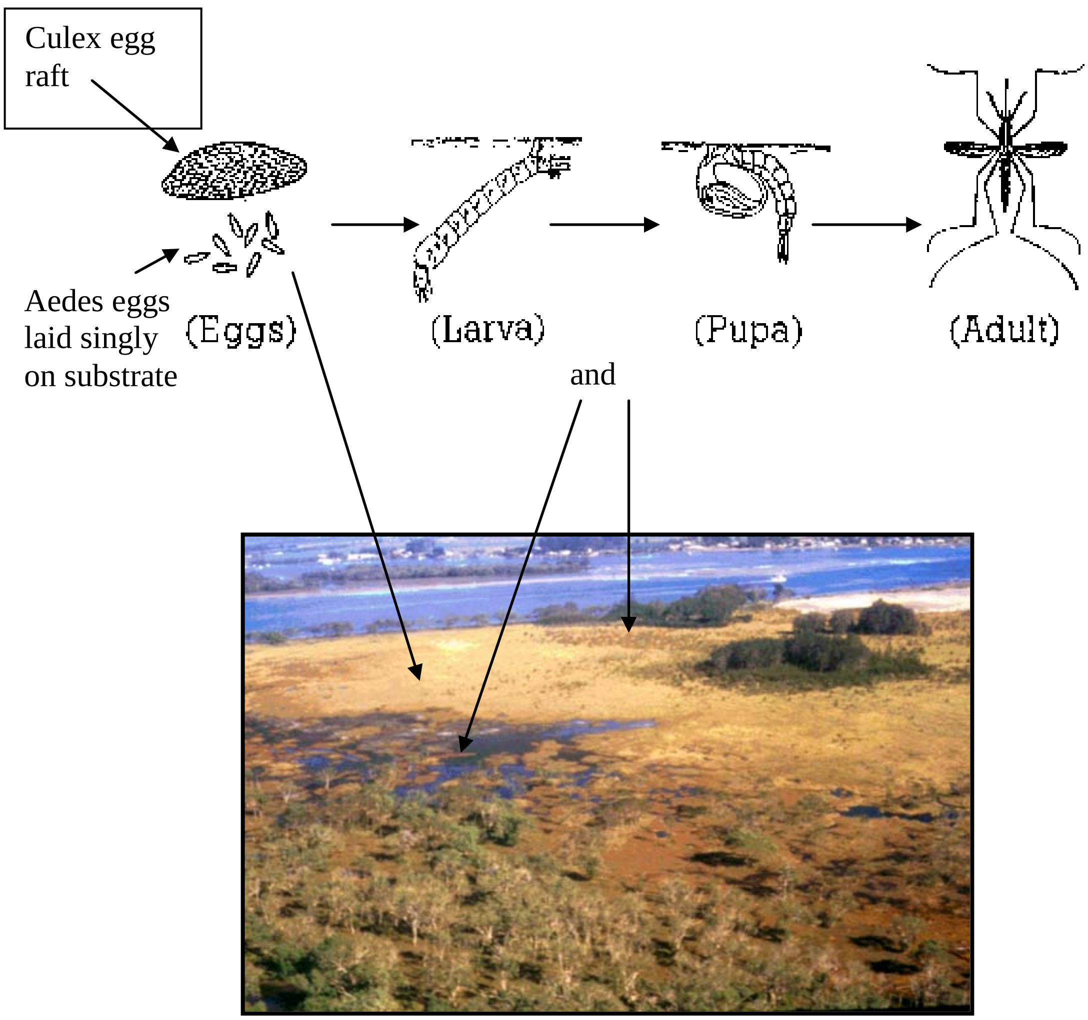

Culex egg raft
Aedes eggs laid singly on substrate
(Eggs)
(Larva)
(Pupa)
(Adult)
and

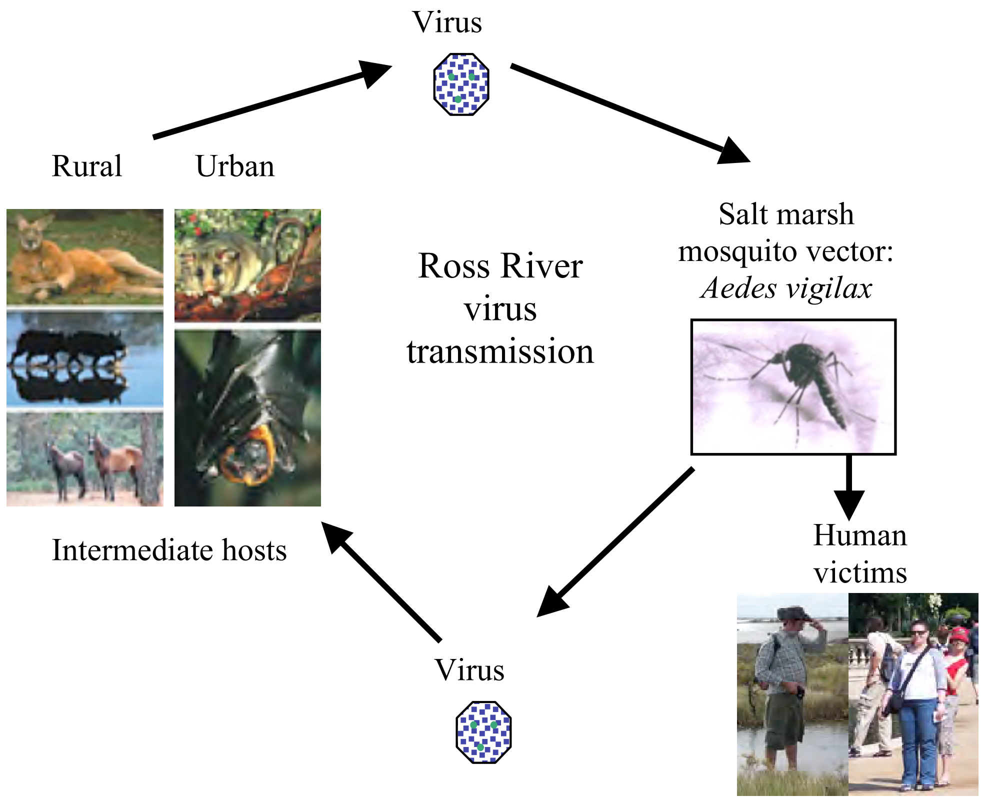
Table 7.1. Number of Ross River cases in Australia by state and territory, 1993-2007. (Source: Communicable Diseases Intelligence, Australia)

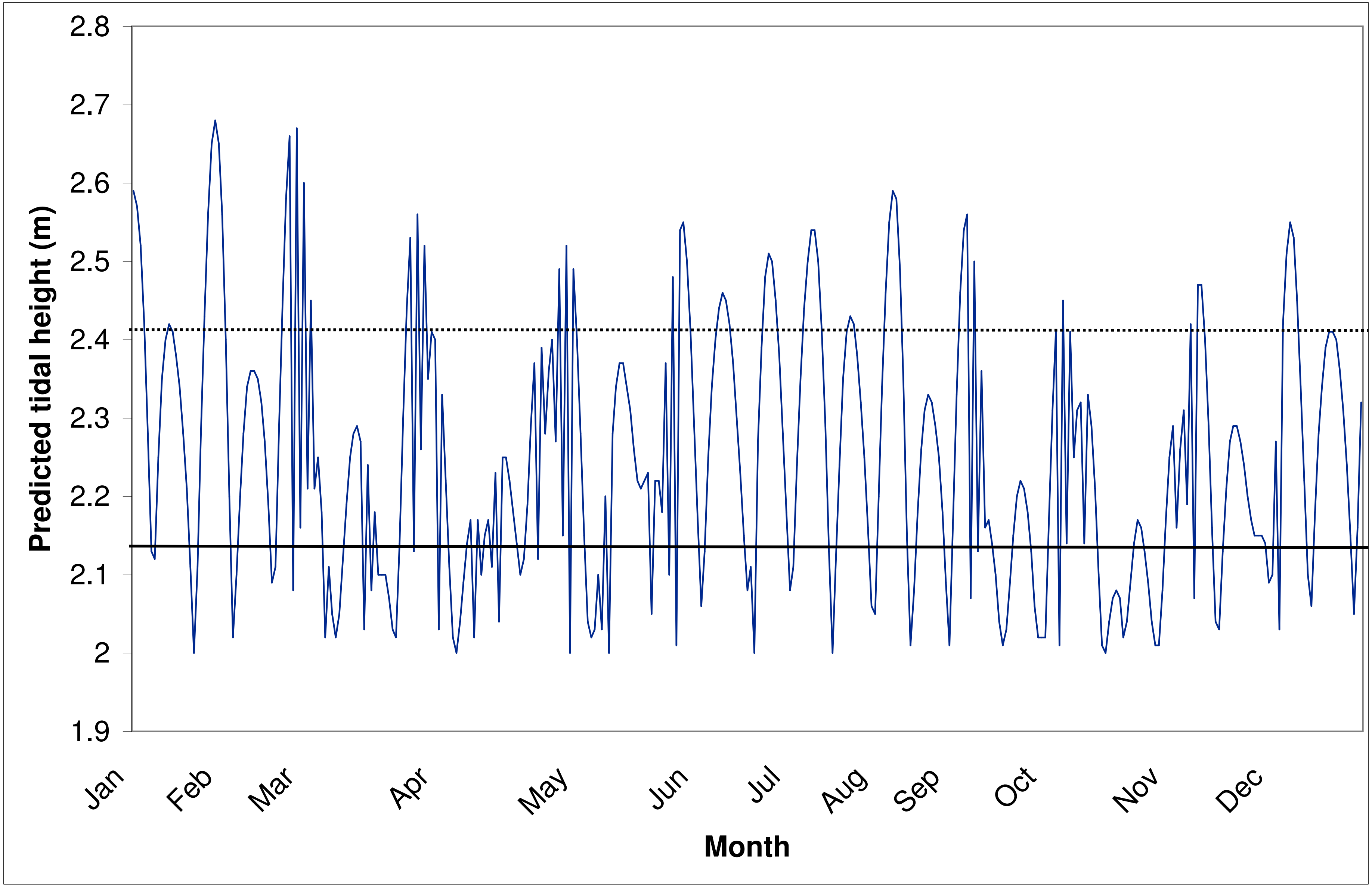
Year	ACT	NSW	NT	Qld	SA	Tas	Vic	WA	Aust
1993	4	599	264	**2252**	773	10	1198	153	5253
1994	1	332	312	**2998**	28	24	58	95	3848
1995	2	235	369	**1643**	21	28	32	303	2633
1996	1	1032	137	**4881**	56	76	152	1445	7780
1997	9	1598	218	**2363**	635	12	1042	717	6594
1998	6	581	127	**1946**	67	9	136	288	3160
1999	8	953	157	**2305**	40	67	223	624	4377
2000	16	750	145	**1481**	416	8	319	1089	4224
2001	10	716	225	**1568**	141	13	351	202	3226
2002	0	180	63	**886**	42	117	37	131	1456
2003	1	494	121	**2518**	33	4	16	663	3850
2004	6	699	233	**2006**	53	20	91	1102	4210
2005	6	579	209	**1181**	155	5	98	311	2544
2006	10	1123	279	**2616**	328	14	212	820	5502
2007	12	828	300	**2145**	265	6	92	510	4158

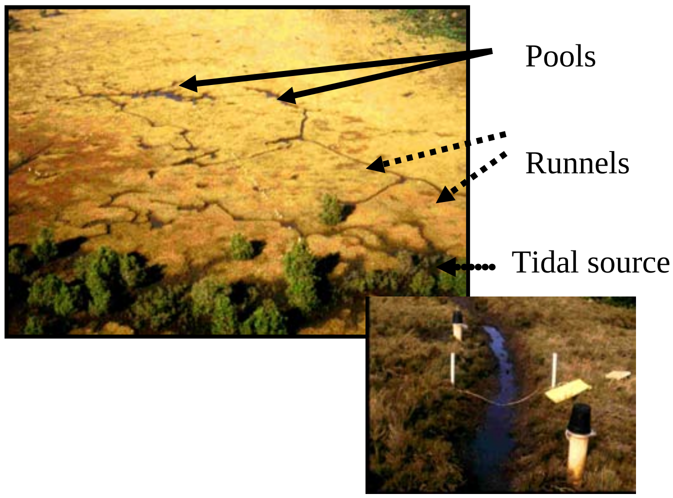
Table 7.2. Rate of Ross River cases/100 000 in Australia, by state and territory 1993-2007. (Source: Communicable Diseases Intelligence, Australia)

Year	ACT	NSW	NT	Qld	SA	Tas	Vic	WA	Aust
1993	1.3	9.9	**152.3**	70.7	52.7	2.1	26.7	9	29.4
1994	0.3	5.4	**175.7**	91.8	1.9	5.1	1.3	5.5	21.3
1995	0.6	3.8	**202.9**	49.2	1.4	5.9	0.7	17.2	14.4
1996	0.3	16.5	**73.3**	143.7	3.8	16.1	3.3	80.4	42
1997	2.9	25.2	**114.8**	68.4	42.7	2.5	22.4	39.2	35.2
1998	1.9	9.1	**65.8**	55.4	4.5	1.9	2.9	15.5	16.7
1999	2.5	14.7	**80.3**	64.6	2.7	14.2	4.7	33.1	22.8
2000	4.9	11.3	**72.5**	40.7	27.5	1.7	6.6	57.1	21.7
2001	3.1	10.8	**113.3**	42.3	9.3	2.8	7.2	10.5	16.4
2002	0	2.7	**31.8**	23.3	2.7	24.5	0.8	6.7	7.3
2003	0.3	7.3	**60.5**	64.9	2.2	0.8	0.3	33.4	19.1
2004	1.8	10.3	**114.9**	50.6	3.4	4.1	1.8	54.8	20.7
2005	1.8	8.3	**100.7**	28.6	9.7	1	1.9	14.9	12.1
2006	2.9	17.8	**129.8**	62.6	20.7	2.8	4.1	38.9	26.2
2007	3.5	12	**139.6**	51.3	16.7	1.2	1.8	24.2	19.8

`http://www9.health.gov.au/cda/Source/CDA-index.cfm`


Virus
Rural
Urban
Ross River
virus
transmission
Salt marsh
mosquito vector:
Aedes vigilax
Intermediate hosts
Human
victims
Virus


Predicted tidal height (m)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


Pools
Runnels
Tidal source