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Chapter 8
Mosquitoes: their interrelationships with man

B. H. Kay, P. Sinclair and E. N. Marks

Introduction
The Aborigines built special shelters to escape mosquito attacks, and Caucasians, since their earliest encounters with the Australian environment, have complained of mosquito plagues. Although several species were described earlier, the first scientific paper recording the habits and breeding places of Australian mosquitoes was published by Skuse in 1889. He was followed by Bancroft, Colledge, Cooling, Hamlyn-Harris, Hill, Mackerras and Taylor in the period before World War II. At the British Museum, Theobald and Edwards described many species and Edwards (1924) reviewed the Australasian mosquito fauna.

Research since this period has been due to three main stimuli:
• the war generated investigation of anopheline vectors of malaria and saw the publication of an important monograph by Lee and Woodhill (1944);
• in 1950, the successful introduction of myxomatosis into the Murray Valley for rabbit control led to extensive mosquito research by CSIRO (Fenner and Ratcliffe 1965);
• the 1951 and 1974 epidemics of Murray Valley encephalitis stimulated arbovirus (arthropod-borne virus) research.

In 1965 Dobrotworsky monographed the mosquitoes of Victoria and in 1966 Marks produced the first edition of an atlas of common Queensland mosquitoes, later revised (Marks 1973a).

This chapter complements the publications cited above by updating them, where possible, with recent research findings. Basic entomological details of structure and biology as well as useful illustrations and descriptions of many species can be found in these texts.

Definition of the problem
A pest is an organism that is unacceptably abundant. For a mosquito species, unacceptability depends on the extent to which it affects the health and comfort of man and his livestock. Thus the pests to be considered here occur at times in enormous numbers and/or are capable of transmitting disease agents. With the exception of three introduced species (Aedes aegypti Linn., Culex fatigans Wiedemann, Culex molestus Forskal), Australian mosquito pests are native animals with wide natural distributions and are not limited to feeding on introduced hosts, although these may significantly influence their abundance.
Mosquitoes may transmit pathogens from one host to another either mechanically, when the organism is carried on the mouthparts (e.g. bird-pox viruses, myxomatosis of rabbits), or biologically, when the organism undergoes an obligatory period of development in the mosquito (e.g. malaria, Murray Valley encephalitis virus).

Perkins (1946) recognized three distinct mosquito problems, domestic, freshwater and saltwater, each caused by different species. Pests from these three categories will be discussed but it should be emphasized that the pest status of some species has changed over the years. Man's progress has been a major factor in both the creation and elimination of pest problems.

Mosquito-borne diseases and their vectors

Dengue fever, first recorded in Australia at Charters Towers in 1885, was reported in 1885-86 from most of the major settlements in north Queensland (Lumley and Taylor 1943) and from that time epidemics occurred every 5-15 years until the last in 1955 (Doherty 1974). Epidemics were severe (2300 cases were recorded at Townsville for the 3 months to February 1942) and some extended into northern New South Wales, and across northern Australia. The vector of the dengue virus was *Ae. aegypti* which is closely associated with human habitation. It breeds in all types of artificial containers (e.g. water tanks, tyres, tins) and sometimes in tree-holes, and is well suited to dispersal by man because its desiccation-resistant eggs are attached to the sides of containers. The decline of *Ae. aegypti* as a serious pest can be attributed mainly to the advent of reticulated water which replaced the domestic water tank. Populations of this species still occur in Queensland.

Filariasis (caused by a nematode worm, *Wuchereria bancrofti* (Cobbold)) has disappeared from Australia for reasons not fully understood. Up to 1910 approximately 10% of hospital patients in Queensland were infected. The incidence declined over subsequent years and the disease was virtually extinct by 1938 (Mackerras 1958). The vector, *Cx. fatigans*, another domestic pest, breeds in polluted pools and creeks and in artificial containers. In modern times, plagues of *Cx. fatigans* have been reduced through control measures adopted by local authorities, including covered drains and dry gully traps. This species, however, is still a major pest (p. 168).

The last major epidemics of malaria occurred in Cairns in 1942 and in Northern Territory in 1955-57. Since 1962 all but a very few of the cases reported in Australia have been infected overseas. Drainage of Cairns swamps, effective antimalarial drugs, and screening of immigrants to the Northern Territory, have contributed to the disappearance of malaria. Also, potential vector anophelines, although common, are zoophilic and feed mainly on domestic and wild mammals. *Anopheles annulipes* Walker occurs throughout Australia; *Anopheles farauti* Laveran and *Anopheles billi* Woodhill and Lee (both found naturally infected at Cairns in 1942), *Anopheles amictus* Edwards and *Anopheles bancroftii* Giles have more restricted distributions in northern Australia.

The mosquito-borne diseases of medical importance in Australia today are caused by arboviruses of which *Culex annulirostris* Skuse is the major vector. Fortunately, the problem is not a large one. Murray Valley encephalitis (MVE, Australian arboencephalitis, Australian encephalitis) has occurred in 8 epidemics since 1917. Kunjin virus has recently been implicated as causing encephalitis in man (N. F. Stanley, personal communication). Ross River virus, the agent of epidemic polyarthritis, a debilitating disease which occurs annually, is carried by several mosquito species, the most notable being *Aedes vigilax* (Skuse) on the coast and *Cx. annulirostris* and *Aedes normanensis* (Taylor) inland (Doherty 1974, 1977).
Mosquitoes are proven vectors of several animal diseases. *Anopheles annulipes* and *Cx. annulirostris* played major roles in the wide dissemination of myxomatosis through Australian wild rabbit populations in the 1950s, and other species were important in certain situations (Fenner and Ratcliffe 1965). Dog heart-worm (*Dirofilaria immitis* (Laidy)) undergoes development in mosquito hosts, which include *Cx. fatigans*, *Cx. annulirostris*, *Aedes vigilax* and *Ae. notoscriptus* (Skuse) (Bemrick and Moorhouse 1968). Bovine ephemeral fever virus has been isolated from pools of *An. bancroftii* and from mixed mosquito species (St George et al. 1976).

**Mosquitoes as biting pests**

Mosquito attacks on man can be severe at times, especially in coastal saltmarsh when *Ae. vigilax* is prevalent, or in inland areas following heavy rainfall that hatches the desiccation-resistant eggs of other *Aedes* species. In subtropical and tropical Australia,

![Graph showing prevalence of five pest species in Brisbane 1968–70 from truck-trapping data](image)

*Fig. 1. Prevalence of five pest species in Brisbane 1968–70 from truck-trapping data (Standfast et al. 1969, 1970) in coastal, urban and rural suburbs. Aa, Anopheles annulipes; Av, Aedes vigilax; Ca, Culex annulirostris; Cf, Culex fatigans; and Cs, Culex sitiens.*

species adapted to more permanent breeding places, such as *An. annulipes*, *Cx. annulirostris* and *Cx. fatigans*, breed all year round, usually becoming pests during summer when good rainfall extends breeding places and warmer temperatures allow rapid development of larvae. In Brisbane, truck trapping during the 1968–70 summers (Standfast et al. 1969; Standfast et al. 1970) showed that the major pest species were different in coastal (*Ae. vigilax*, 76% of mosquitoes trapped), urban (*Cx. fatigans*, 49.6%) and rural (*Cx. annulirostris*, 39.3%) areas (Fig. 1). *Ae. vigilax*, *An. annulipes*, *Culex annulirostris*, *Cx. fatigans* and *Cx. sitiens* Wiedemann comprised 99.7% and 94.8% of mosquitoes trapped in consecutive summers. Domestic species such as *Ae. notoscriptus* are occasionally common enough to be a nuisance in winter in Queensland.
<table>
<thead>
<tr>
<th>Species</th>
<th>Distribution</th>
<th>Larval habitat</th>
<th>Activity time</th>
<th>Biting sites</th>
<th>Resting sites</th>
<th>Host range</th>
<th>Disease vector status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anopheles bancrofti</td>
<td>Northern, Qld, N.T., W.A.</td>
<td>Rural freshwater</td>
<td>N</td>
<td>0/1</td>
<td>0</td>
<td>Mammals mainly; also birds, reptiles</td>
<td>Malaria, filariasis</td>
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<tr>
<td>Anopheles annulipes</td>
<td>Widespread</td>
<td>Rural freshwater</td>
<td>N</td>
<td>0</td>
<td>0</td>
<td>Mammals mainly; also birds, reptiles</td>
<td>Myxomatisos, malaria, filariasis</td>
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<tr>
<td>Anopheles farauti</td>
<td>Northern, Qld, N.T.</td>
<td>Fresh or brackish swamps, lagoons</td>
<td>N</td>
<td>0/1</td>
<td>0/1</td>
<td>Mammals, birds</td>
<td>Malaria, filariasis</td>
</tr>
<tr>
<td>Mansonia uniformis</td>
<td>Mainly coastal, Qld, N.T., W.A., N.S.W., Vic.</td>
<td>Freshwater swamps, lagoons</td>
<td>N</td>
<td>0</td>
<td>0</td>
<td>Mammals, birds</td>
<td>Filariaisism</td>
</tr>
<tr>
<td>Aedes camptorhynchus</td>
<td>Southern, mainly coastal, N.S.W., Vic., Tas., S.A., W.A.</td>
<td>Brackish or freshwater pools</td>
<td>N/D</td>
<td>0</td>
<td>0</td>
<td>Mammals, birds</td>
<td>Myxomatisos (minor)</td>
</tr>
<tr>
<td>Aedes normanensis</td>
<td>Northern inland, Qld?, N.S.W., N.T., W.A.</td>
<td>Temporary freshwater</td>
<td>N</td>
<td>0</td>
<td>0</td>
<td>Mammals, birds</td>
<td>Epidemic polyarthritis</td>
</tr>
<tr>
<td>Aedes sagax</td>
<td>Southern inland, Qld, N.S.W., Vic., S.A., W.A.</td>
<td>Temporary freshwater</td>
<td>D</td>
<td>0</td>
<td>0</td>
<td>Mammals, birds</td>
<td>None</td>
</tr>
<tr>
<td>Aedes theobaldi</td>
<td>Eastern inland, Qld, N.S.W., Vic., S.A.</td>
<td>Temporary freshwater</td>
<td>N/D</td>
<td>0</td>
<td>0</td>
<td>Mammals, birds</td>
<td>None</td>
</tr>
<tr>
<td>Aedes vigilax</td>
<td>Coastal, Qld, N.T., W.A., S.A., N.S.W., Vic.</td>
<td>Brackish marsh, mangrove, salt pan</td>
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<td>0/1</td>
<td>0</td>
<td>Mammals, birds</td>
<td>Dog heartworm, epidemic polyarthritis</td>
</tr>
<tr>
<td>Aedes vittiger</td>
<td>Eastern inland, Qld, N.S.W., Vic.</td>
<td>Temporary freshwater</td>
<td>N/D</td>
<td>0</td>
<td>0</td>
<td>Mammals, birds</td>
<td>Myxomatisos (minor)</td>
</tr>
<tr>
<td>Aedes notoscriptus</td>
<td>Widespread, urban/rural</td>
<td>Freshwater containers, treeholes, rock pools</td>
<td>N/D</td>
<td>0/1</td>
<td>0</td>
<td>Mammals, birds</td>
<td>Myxomatisos (minor), dog heartworm</td>
</tr>
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<td>Culex annulirostris</td>
<td>Widespread, mainland</td>
<td>Rural freshwater</td>
<td>N</td>
<td>0/1</td>
<td>0</td>
<td>Mammals, birds, reptiles, amphibians</td>
<td>Myxomatisos, MVE, epidemic polyarthritis, dog heartworm</td>
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<tr>
<td>Species</td>
<td>Location</td>
<td>Breeding Habitat</td>
<td>Hosts</td>
<td>Disease</td>
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<tr>
<td><em>Culex fatigans</em></td>
<td>Widespread, mainland, urban</td>
<td>Polluted freshwater containers, pools</td>
<td>Mammals, birds, reptiles, amphibians</td>
<td>Filarialis, dog heartworm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Culex sitiens</em></td>
<td>Northern, coastal, Qld, N.S.W., N.T., W.A.</td>
<td>Brackish marsh, mangrove, salt pan</td>
<td>Mammals, birds</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A D, day; N, night; B I, indoors; 0, outdoors.
Mosquitoes

The southern species have been best documented in Victoria, where Dobrotworsky (1965) found that the great majority of species spend the winter either as larvae or as hibernating adults and all species attain their greatest abundance during the spring or summer.

Attacks on livestock by mosquitoes (especially *Cx. annulirostris*, *An. annulipes*, *Ae. vigilax* and other *Aedes* spp.) can be particularly severe, causing distress and, occasionally, subsequent loss of condition (Standfast and Dyce 1968; Muller and Murray 1977). The milk production of dairy herds can be reduced in periods of heavy attack, as can egg production by fowls.

Ecology

Comparatively few of the 260 known species in Australia cause pest or disease problems (Table 1). Only basic information has been recorded on the biology of many species. We shall discuss here two major pests on which recent studies have been completed.

*Aedes vigilax*—(Kerridge 1971; Sinclair 1976)

*Aedes vigilax* is a salt marsh mosquito common along the Australian coast from Sydney around the north to Perth and near Adelaide. Inland at Mildura it breeds in salt pans receiving irrigation run-off. It is also found in New Guinea, south-east Asia, and some Pacific islands. This species is not merely a pest near its breeding places. At times, when salt marshes have been flooded to maximum extent by tides and/or rain, enormous populations develop, and mass adult displacements occur with specimens being recorded up to 64 km from the nearest breeding place (Marks 1969b).

Breeding is prolific in shallow, stagnant pools of brackish or salt water lying above the mean high tide level but usually filled by the highest tides of each cycle and by rain. The presence of the succulents *Salicornia australis* Sol. and *Suaeda australis* (R.Br.) Moq. or low growing salt water couch (*Sporobolus virginicus* (L.) Kunth) indicates suitable breeding areas.

Studies in the Deception Bay–Redcliffe area of south-east Queensland indicate that oviposition is concentrated adjacent to depressions retaining water after flooding, and where vegetative cover reduces moisture loss, ensuring that the desiccation-resistant eggs are seldom exposed to deleterious humidities. Eggs are laid singly or in groups of up to six in crevices in moist soil or attached to the bases of plants. Concentrations of eggs have been found along the edges of pools, on drain lips, ridges surrounding hoof prints, the sides of vegetated hummocks rising from a mud flat, and the sloping bank edging a tidal flat. Distribution of eggs across a flat is shown in Fig. 2.

Egg density at a particular site varies according to prevailing weather conditions. At Deception Bay oviposition was reduced around quickly-drying, small pools during periods of high temperature. Breeding was unusual within the mangrove zone where tidal flooding was frequent and larvivorous fish common. However, when low tidal peaks coincided with a period of low rainfall, the temporarily isolated depressions within the mangrove zone provided breeding pools during an otherwise unfavourable period. After heavy rainfall and frequent fresh water flooding, *Cx. annulirostris* replaced *Ae. vigilax* in part of the Kippa-ring swamp near Redcliffe, apparently because lush growth of grass and reeds reduced *Ae. vigilax* oviposition; *Ae. vigilax* remained the dominant species in an adjoining area subjected to the same flooding, but covered by the low-growing *Salicornia* and *Suaeda*.

Variability in hatching response leads to instalment hatching with successive floodings. First hatch of laboratory laid eggs submerged within the hour, occurred on day five and
57% had hatched by day nine. Hatching then stopped until the eggs had been dried and reflooded, or subjected to an additional artificial stimulus by evacuating air from the flooding medium. In the field, soil microorganisms provide a natural stimulus by utilizing oxygen in the water. A strong water current through breeding pools reduced hatching. In the laboratory, eggs remained viable for 116 days at 65% R.H. and 98 days at 15–20% R.H.

Fig. 2. Position and hatch of *Aedes vigilax* from soil samples collected from a *Salicornia* covered flat, Deception Bay. Entire flat is covered by the highest tides and rain.

Hatching may be greatly reduced during winter in temperate and subtropical regions. During the 1970 winter (June, July, August) at Deception Bay, below average minimum temperatures (mean 8.2°C compared with 10.2°C for the 13 year average) forced most eggs into a state of quiescence. In experimental studies, field collected eggs, conditioned by holding for a minimum of three days in increased temperatures (25°C), gave a 68% hatch on the first flooding compared with 10% for unconditioned eggs held at ambient temperatures. By the end of September (mean minimum 11.5°C) field collected eggs no longer needed conditioning, 98% of them hatching when flooded once. Very few larvae hatching in the 1970 winter survived because the development period extended to 20 days and pools frequently dried before pupation could occur. In the warmer 1969 winter larval development took 8–9 days, and in summer months only 5–6 days. In the Sydney area, Reynolds (1961) found that hatching in the field did not occur when maximum air temperature was below 18–21°C; she suggested that a facultative diapause might occur there.
At Deception Bay, salt marsh flats were flooded either by tidal peaks, heavy rainfall or a combination of both. Regression analysis of light trap records of adult female populations demonstrated a significant relationship between the combined effect of tide and rainfall on population density. The effect of tide alone was significant but the effect of rainfall depended on the state of the tide.

Larvae have been recorded from a wide range of salinities and also from fresh water, where numbers are usually low. Reynolds (1961) found that larval densities in pools in a typical salt marsh were significantly influenced by pool depth and maximum daily air temperatures, whereas salinity was not a critical factor.

*Aedes vigilax* is well adapted to breeding in salt marsh areas. The variability in hatching response of eggs and their resistance to desiccation ensure that viable eggs remain after each flooding to enable repopulation of an area should adverse environmental conditions be encountered.

Although typically found in open sunlit pools, *Ae. vigilax* will also breed in the shade and larvae have been collected from such diverse sites as stone jars and hollows in mangrove trees (Bonne-Wepster 1954) and rock pools (Marks 1966, 1976a; Debenham and Hicks 1970). In saline pools *Ae. vigilax* have been found in association with *Ae. funereus* (Theobald), *Ae. albounnulatus* (Macquart), the predacious *Ae. alternans* (Westwood), Cx. sitiens, Cx. annulirostris, An. farauti and An. billi, and in fresh water habitats with Cx. annulirostris and An. annulipes.

The time elapsing between emergence of the adult female from the pupa and hatching of larvae from its first batch of eggs is influenced by a number of factors. The eggs must develop to maturity but thereafter oviposition may be delayed. The female must mate so that eggs can be fertilized by stored sperm during oviposition. The eggs must then remain moist while development of the embryo proceeds to completion. It is only when this stage is reached that eggs may hatch or resist desiccation.

Field populations of *Ae. vigilax* at Deception Bay were 0–96% autogenous (females able to mature eggs without a blood meal). The autogeny rate varied significantly between populations from adjacent pools and also between females emerging ‘early’ and ‘late’ from the same pools over a period of emergence. In the laboratory at 25°C autogenous females had matured eggs by 54 h after emergence. Females started blood feeding 8 h after emergence with the numbers feeding continuing to rise until 20 h. Oviposition generally did not occur until 72–96 h after emergence. Eggs required at least a further 54 h at 25°C before hatching would occur. Males (which cannot mate until their genitalia have rotated) matured in 12–18 h from emergence, developing faster in the hotter months.

*Aedes vigilax* has been recorded feeding on man, cattle, horses, rabbits, mice, feral pigs, dogs, kangaroos, flying foxes and birds, including domestic fowls. In New Caledonia adults are diurnal (Laird 1954) but in Australia biting occurs both day and night. Persons entering mangrove swamps providing daytime harbourage will testify to the severity of the attack. Peak biting activity follows a crepuscular bimodal pattern. Catches on cattle near Rockhampton showed that the main biting activity occurred 2 h after sunset, decreasing until first light when a second period of high activity was recorded (Standfast and Dyce 1968). At Gove, Northern Territory, peak biting occurred 20–40 min after sunset with smaller numbers biting throughout the night.

Flight activity patterns at Gove and Kippa-ring were similar, with truck traps collecting maximum numbers 20–50 min after sunset and 30–45 min before sunrise. The effect of meteorological conditions on flight needs further study. Truck trapping near the breeding areas at Kippa-ring showed that the shortest period of activity occurred one evening when temperature dropped 5°C during the hour following sunset; on evenings when temperature change was small, activity was extended. Activity occurred earlier
when relative humidity was high and there were storms within an hour of sunset. Minimum daily temperatures of 8.3°C curtailed flight activity, measured in light traps; activity increased with temperature. Hamlyn-Harris (1933) reported that large-scale movements usually took place during periods of high barometric pressure although temperature and humidity were important contributing factors. Results from a light trapping project in the Brisbane district (Marks 1968) indicated that numbers of *Ae. vigilax* taken close to breeding sites increased 6–8 days after and peaked 9–13 days after the highest tide. During 1969–70 at Deception Bay peak populations occurred 9–22 days after flooding. Dispersal usually coincides with peak activity in the coastal areas and is often obviously downwind.

The foregoing research on *Ae. vigilax* has bearing on the application of insecticides to intertidal areas with the object of reducing infestations in urban and tourist centres to tolerable levels. Adulticiding is intended to kill mosquitos before they move away from the breeding area in search of a blood meal and, to be effective, must be timed within 24–48 h of emergence, during hours of morning and evening twilight when mosquito activity is highest. In practice, this is extremely difficult as emergence extends over several days; there is also lack of synchrony because breeding areas are often flooded by different tide levels or by localized storms. Larviciding can be more effectively timed because the larval stages are present for longer periods.

*Culex annulirostris* – (Kay 1978)

*Culex annulirostris* occurs throughout mainland Australia and the Pacific, east through island chains as far as French Oceania, west to Indonesia, and north through Papua New Guinea to the Mariana Is. Some detailed studies on its ecology have been made in Queensland at Kowanyama on the western side of Cape York Peninsula and at Charleville in south-west Queensland.

In Australia, *Cx. annulirostris* breeds mainly in freshwater swamps, lagoons and transient grassy pools, but also in a variety of other sunlit or shaded habitats, usually where there is aquatic or emergent vegetation. It has been collected with *Cx. sitiens* from salt marsh pools, and, following prolonged heavy rainfall, sometimes displaces *Ae. vigilax* as the dominant species breeding in the flooded salt marsh (p. 162). Woodhill (1936) reported larvae from salinities (expressed as total salts in g l⁻¹) up to 16.3%. At Kowanyama, it has been found in pools of pH 5.5–10.4 but generally prefers more neutral waters. The wet season rains in northern Australia flood extensive grassland areas which often produce *Cx. annulirostris* in plague proportions. Ponded side channels of inland rivers produce large numbers. Irrigation, effluent disposal (p. 168) and other water management practices often provide breeding places in slow-flowing or stagnant shallow waters with grassy margins.

As with other *Culex* species, the eggs do not resist desiccation. They are laid on the water surface in rafts containing 50–200 eggs (mean at Kowanyama was 102±22). As hatching is not dependent on a sequence of drying and flooding, adults, larvae and pupae are usually present all year round. In summer, eggs hatch in 24–48 h, and the 4 larval instars and the pupal instar are each of 1–2 days duration. The time of development lengthens during winter. At Charleville, in pools with a water temperature of 13–18°C, *Cx. annulirostris* took 21–32 days from egg hatch to adult emergence.

Species with which larval *Cx. annulirostris* have been found in Australia include *An. annulipes* (very frequently), *An. amictus*, *An. atropipes* Skuse, *An. bancroftii*, *An. farauti*, *Aedomyia castasticta* Knab, *Aedes aboannulatus*, *Ae. albocutellatus* (Theobald), *Cx. australicus* Dobrotworsky and Drummond, *Cx. bitaeniorynchus* Giles, *Cx. cylindricus* Theobald, *Cx. fatigans*, *Cx. fraudatrix* (Theobald), *Cx. balifaxii* Theobald, *Cx. squamosus* (Taylor), *Cx. starckeae* Stone and Knight, *Cx. whitmorei* (Giles).
Mosquitoes

_Culex annulirostris_ has been recorded feeding on man, cattle, rabbits, horses, cats, dogs, domestic fowls, buffalo, sheep, mice, brush-tailed possums, _Trichosurus vulpecula_ (Kerr), and jew lizards, _Amphibolurus barbatus_ (Cuvier).

Precipitin tests of host-blood from engorged females collected at Charleville in 1977 showed that _Cx. annulirostris_ was predominantly a broad mammalian feeder; 78.2% had fed on cat, dog, man, cow, horse, sheep and/or goat, rabbit and marsupial. Although there was obviously some interchange of blood-engorged females from town and sylvan collecting sites, the blood-feeding patterns reflected the abundance and availability of hosts within each area (e.g. reptile, cow, rabbit, and macropod reactors were common outside town, whereas fowl, dog and cat reactors were more common within town). Dogs (452) were equally important hosts as fowls (about 2500) in town. Man was seldom attacked, possibly because many were indoors in screened houses when _Cx. annulirostris_ was active, or because the townspeople (3800) were well aware of the risk of mosquito-borne disease and acted accordingly.

At Kowanyama between 1974 and 1976, 86.1% of blood-engorged _Cx. annulirostris_ reacted to mammals (feral pig, cow, cat, dog, man, horse and marsupial), 12.9% to birds of several orders and 1% to reptiles and amphibians. The presence of dogs in the village may divert _Cx. annulirostris_ from feeding on humans as 44.6% and 9.5% fed on the 100 dogs and 800 humans respectively. An experimental trapping study demonstrated that dogs were excellent bait in relation to relative weights of other animals used. A calf was preferred, and pig and dog were superior to man and kangaroo; two fowls were poor bait. Although Standfast and Barrow (1968) suggested a shift in host preference from man in the dry season to birds in the wet season, no evidence of this could be found in later studies. Reduced feeding on marsupials in the wet season was attributed to the protection from mosquito attack afforded by long grass and to the effects of the wider availability of water on the dispersal of marsupials and mosquitoes.

_Culex annulirostris_ feeds nocturnally with an early evening and pre-dawn peak in activity. It will also bite in sheltered situations during the day. Feeding occurs mainly outdoors although females readily bite indoors in the Murrumbidgee Irrigation area (Dyce, personal communication) and on occasion in Brisbane. Quantitative studies of man–vector contact at Kowanyama demonstrated that _Cx. annulirostris_ fed primarily outdoors but occasionally indoors, preferring dark to illuminated rooms. This behaviour was consistent throughout all seasons.

During the day adults rest mainly outdoors in vegetation. They have been taken amongst water hyacinth (_Eichhornia crassipes_ (Mart.)) and grass, as well as in outhouses and fowl sheds (O’Gower 1960), on insect screens (Lee _et al._ 1954) and in rabbit burrows (Marks 1972). In southern New South Wales, Myers (1956) found that by day near Albury _Cx. annulirostris_ rested in the copious ground vegetation, mainly _Polygonum_ sp., whereas at Urana, in very dry conditions and the absence of ground vegetation, they rested in the tree canopy. At Charleville in 1977, large numbers were collected from paddy lucerne (_Sida rhombifolia_ L.). In 1978 even larger numbers were resting in poison pratis (Pratia concolor Druce) and, in contrast to 1977 findings, flood debris along the Warrego River harboured mosquitoes.

In the Murray Valley, _Cx. annulirostris_ overwinters as adults which often rest in flood debris in trees. They will fly if disturbed, which suggests that a true diapause or hibernation does not occur. The species is active throughout winter in localities studied in Queensland – Kowanyama, Charleville, Cunnamulla, Lake Bullawarra near Thargomindah, Innisfail and Brisbane. At Kowanyama temperatures remain warm enough in winter (July, mean temperature range 14.8–30.9°C) to lengthen the developmental times only slightly; blood-engorged females mature ova within 4–5 days instead of the 3–4 days of the summer period (November temperature range 23.6–34.7°C). However, at
Charleville in midwinter (July range 3.5–19.4°C) maturation of ova takes 8–9 days. No evidence of autogeny was found at Kowanyama nor in the QIMR colony from Mildura, Victoria.

Although age-grading methods have not been completely validated for this species, seasonal studies at Kowanyama and Charleville demonstrated that *Cx. annulirostris* was only moderately long-lived with daily survival generally between 70–85% (Table 2). This implies an average survival of 3–7 days. Experimental studies suggest that transmission of Murray Valley encephalitis virus is effected by most females on the third blood engorgement, approximately 8–9 days after the initial infected meal. The percentage surviving to transmission age varied considerably and was as high as 45% during February 1976 at Charleville; 12–18% was more usual. Few females oviposited more than three times.

| Table 2. Percentage daily survival rate of *Culex annulirostris* at Kowanyama and Charleville |
|---------------------------------------------|-------------------------------------|-------------------------------------|-----|-----|-----|
|                                          | Kowanyama                           | Charleville                         |
| February                                 | 79.4  |       |       | 74.4  |       | 90.6  |
| March                                    |       | 49.3  | 71.8  |       | 71.9  |       |
| April                                    | 54.4  | 75.2  |       |       |       |       |
| May                                      | 66.0  |       |       |       |       |       |
| June                                     |       | 74.8  |       |       |       |       |
| July                                     | 85.7  |       |       | 82.3  |       |       |
| August                                   |       | 72.3  |       | 75.2  |       |       |
| September                                | 82.7  |       |       |       | 62.0  |       |
| October                                  |       |       |       |       |       |       |
| November                                 |       |       |       |       |       |       |
| December                                 |       |       |       |       |       |       |

It is considered that the key to the importance of *Cx. annulirostris* as a vector in Australia lies with its great abundance in addition to its broad host range.

*Culex annulirostris* is common or predominant in many parts of Australia: Murray Valley, Ord Valley, Beatrice Hill, N.T. (Standfast, personal communication), and inland Queensland towns. In 13 collections made at Charleville from 1974–76, *Cx. annulirostris* comprised 56–99% of mosquitoes taken. The lower percentage occurred following major rainfall when the temporary ground-pool breeding *Aedes* were present. In collections at Kowanyama from 1960–76, *Cx. annulirostris* comprised 27.1±10.6% (1 standard deviation) and 43.5±16.7% of wet and dry season collections respectively.

Definitive studies on the relation of rainfall to *Cx. annulirostris* densities have yet to be done. In a light trap program within 80 km of Brisbane, distinct increases in abundance were noted in some localities 2–4 weeks after rainfall (Marks 1968). Only general information is available for Kowanyama and Charleville owing to the sporadic nature of collections. Standfast and Barrow (1968) commented on the marked differences in population size that occurred at Kowanyama from year to year but also recorded a sharp rise in population from a late dry season low, to a mid-late wet season peak. More recent studies suggest that the magnitude of the wet season is less important, as the mean catches for 1973–74 and 1975–76 which were years of prolonged early and above average rainfall were not appreciably higher than for 1972–73 and 1974–75, years of average wet seasons. Enormous numbers of *Cx. annulirostris* were collected during February to March 1967 (Doherty *et al.* 1971) following one of the driest dry seasons in history and below average rainfall in the month before collection. Gradual prolonged wet seasons at Kowanyama may allow the equilibrium between mosquitoes, food and predators to continue whereas short, moderate to heavy wet seasons may favour heavy early production of mosquito larvae which temporarily outstrips the predator population.
Whereas *Ae. vigilax* breeding places are predominantly restricted to the intertidal zone, the natural breeding places of *Cx. annulirostris* are scattered through the countryside. After heavy rains or floods, plague populations of *Cx. annulirostris* are likely to develop. An estimate of larval population may be useful for prediction of adult numbers, or for assessing the effectiveness of insecticide applications. Larvicides were applied on a large scale in the Murray Valley in the summers succeeding the 1974 encephalitis epidemic. Preliminary attempts to develop methods to estimate larval populations showed the need for a much sounder knowledge of the distribution of larvae within the breeding places (R. Laughlin, personal communication).

Some man-made pest problems

In Australia, mosquito control is generally the responsibility of local government. Present knowledge of the ecology of some species and of their adaptability to altered environments, is sufficient for entomologists to identify practices that are likely to promote mosquito plagues. However, a major difficulty is to achieve interdisciplinary communication between entomologists and health surveyors on the one hand and engineers and planners on the other. *In most cases entomologists are asked not how to prevent, but how to cure pest problems.*

**Polluted effluents**

Mosquito infestations are often associated with sewage disposal measures. Two introduced species, *Cx. fatigans* and *Cx. molestus* (which occurs in southern Australia and Tasmania), thrive in imperfectly sealed septic tanks. Whenever large numbers of night-biting mosquitoes are found resting indoors by day (a habit of these two species), possible close-at-hand sources should first be sought. However, particularly where many households are involved, an infestation may have originated further afield, as in the following case which is described in some detail to illustrate the complexities that may be encountered.

In February 1968, about 50 residents petitioned the Roma Town Council, Queensland, for action against a mosquito plague. Biting, resting, and light-trap collections in mid-March showed that the infestation was due to *Cx. fatigans* and *Cx. annulirostris* and was heaviest in the southern part of the town. Prolific breeding was found close to the Sewage Treatment Works situated on a low hill, 2600 m south-east of the town centre (Marks 1968). The works were of a type common to many towns but the method of disposal of effluent is peculiar to each site.

After anaerobic digestion of raw sewage in two Imhoff tanks, the supernatant liquid passed in series through two of six open earth-sided sewage lagoons, undergoing aerobic decomposition before being chlorinated. The effluent was disposed of to a farmer for pasture irrigation. It flowed via an earth drain to a holding dam at the foot of the hill. Before irrigating, the farmer pumped water from this dam to a raised earth tank where it was mixed with bore water; however, he had not irrigated for at least nine months.

The Council's health inspector had reported heavy mosquito breeding in the dam in June and, when the area under water was greatly extended in November, the level was then lowered by pumping. In December breeding was prolific where the 400 m earth drain was obstructed by grass and weeds, and in February a new shorter drain was cut. In mid-February *Cx. fatigans* and *Cx. annulirostris* larvae were found in the dam and adults were found sheltering in the marginal grass; *Cx. fatigans* predominated.

The area was examined in detail in mid-March. Vegetation had been burnt from the steep earth banks of the sewage lagoons (each about 2000 m² in area); there was a few *Cx. fatigans* larvae in backwaters. *Culex fatigans* and *Cx. annulirostris* larvae were
numerous in swampy pools associated with the old disused drain, as were adults resting in the long fringing grass. The flow in the new drain was too fast for mosquito breeding.

The dam, about 4 ha in area, was formed by a low earth bank built across a wide shallow watercourse; in places, under dense marginal grass, *Cx. annulirostris* larvae were numerous. The banks of the mixing tank had been trampled by stock; *Cx. annulirostris* larvae were plentiful in seepages and hoofprints, with fewer *Cx. fatigans*. Many adults of both species rested in the grass. *Anopheles amictus* bred here and in the old drain pools.

Several factors contributed to this mosquito problem. The nutrient-rich effluent, either directly or through the microorganisms it supported, provided an abundance of food for larvae. *Culex fatigans* can breed in more highly polluted water than can *Cx. annulirostris* and changes in the degree of pollution would lead to dominance by one or other species. The effluent also promoted dense grass growth. Emergent grass provides shelter from insect and fish predators and from wave action which can damage egg rafts and drown adults emerging from pupae; as already discussed, shallow water among grass is a favoured breeding site of *Cx. annulirostris*. When irrigation ceased, the amount of water and of nutrients held in the dam increased. The design of the dam maximized the area of water and both the length and width of the marginal strip of grass growing in water. A deeper dam with steep sides could hold the same volume of effluent in a reduced area; the shorter and narrower marginal strip suitable for emergent vegetation would make this easier to control, and reduce the favourable shelter. Cattle grazing on the mixing tank enclosure kept down the grass but damaged banks, with resulting seepages and hoofprints providing for increased mosquito breeding.

When the surrounding countryside was dry, most adult mosquitoes probably remained in humid sites close to the breeding area; Fenner and Ratcliffe (1965) observed that *Cx. annulirostris* is sensitive to low atmospheric humidity. Good summer rains (122 mm in October–November, 218 mm in December–January) not only extended the dam across its shallow grassy banks but also provided green vegetation and damp soil in the shallow watercourses between it and the town, along which mosquitoes would tend to travel.

Today there is no mosquito problem associated with Roma's sewage treatment works. The golf course uses most of the effluent to water its greens, and farm requirements are piped direct to the mixing tank. The earth drains have been filled in, the dam, no longer polluted, supports natural predators, and the sewage lagoon banks are regularly treated with weedicide.

Package sewage treatment plants, which occupy a small area, can also give rise to problems, as exemplified at Gladstone, Queensland, in October 1977. Malfunctioning of the plant servicing a new suburb resulted in its discharging highly polluted effluent into a freshwater teatree-fringed creek; prolific breeding by *Cx. fatigans* occurred for 1 km downstream.

An administratively more complex problem arose in Warwick, Queensland, in October 1965 (Marks 1966). The City Council disposed of the effluent from its sewage treatment works to a landholder in an adjoining shire for pasture irrigation. Great numbers of *Cx. australicus* entering houses near the treatment works, almost certainly came from those pastures. Fortunately this species does not attack man, and was merely attracted to lights. City Councils have no authority to look for, or control, sources outside their own boundaries. Similar problems may be associated with meatworks, wool scours, canneries and other industries discharging effluents rich in organic matter.
Engineering projects in the intertidal zone

Large-scale industrial complexes can also cause problems. Earth works have given rise to pest mosquito infestations which might have been avoided by taking account of saltmarsh mosquito ecology.

Activities that allow periodic flooding with salt or brackish water are likely to favour Ae. vigilax. For a decade the Queensland government has gradually reclaimed low-lying land and mud flats along the lower reaches of the Brisbane River (Marks 1969a). Areas of several hectares were enclosed by earth banks and a slurry of mud, sand and saltwater pumped in by hydraulic dredge. Excess water drained off on the landward side across a grassy flat and into a teatree swamp, killing the trees. The periodic flooding of this former freshwater swamp has provided conditions for prolific breeding by Ae. vigilax. Much of the trouble might have been avoided by draining the water back to the river.

Fig. 3. Kippa-ring swamp. Mangroves backed by salt marsh border Deception Bay, Qld. Very high tides enter the swamp at its eastern end (upper left) but normal drainage west is blocked by the spoil bank of the Redcliffe Airport drain (lower left). Aedex vigilax then breeds in plague numbers amongst the mangroves as well as in the open marsh pools. (Photo: E. N. Marks.)

The Kippa-ring swamp, on the southern shore of Deception Bay, Queensland (Fig. 3), comprises salt marsh succeeded by mangroves. Normal tides enter the swamp at its western end. The Redcliffe airstrip, constructed on the western part of the salt marsh, is drained by a deep ditch cut north through the mangroves. Spoil from the ditch thrown up along its eastern bank cuts off normal tides from the eastern part of the swamp. However at least five tides a year are high enough to enter the eastern end of the mangrove swamp. The bank blocks this water from its normal westward drainage and the flooded
mangroves and adjacent marsh produce huge populations of *Ae. vigilax* (Marks 1969a). If the spoil had been thrown on the west side of the ditch this problem would not have occurred.

Two other saltmarsh species, *Culex sitiens* and *Anopheles hilli*, do not have desiccation-resistant eggs and thus find most favourable conditions in permanent or semi-permanent bodies of water. Large populations of *Cx. sitiens* can develop rapidly. The alumina refinery at Gladstone, Queensland, disposes of its very finely particulate red mud by pumping it in saltwater into large enclosed areas (red mud ponds) for settling. By constructing a diversion channel and dam walls, a loop of South Trees Inlet associated with extensive tidal mud and saltwater couch flats and groves of low mangroves was converted to a landlocked basin about 600 ha in area. The water level remained low until 250 mm

Fig. 4. Gladstone Power Station, Qld. Water with fly-ash washings flows (from left to right) through a series of impoundments constructed in the inter-tidal zone before discharging into the Calliope River. Prior to a regular flow being established, *Culex sitiens* and *Anopheles hilli* bred in high numbers in brackish water amongst dead mangroves in the impoundments. (Photo: E. N. Marks.)

rain in October 1975 caused a rise of 0.5 m, flooding about 200 ha. Mangroves with roots continually under water began to drop their leaves, which winds concentrated around the dam margin. The decomposing leaves provided a rich substrate for microorganisms and hence food for mosquito larvae. *Cx. sitiens* bred in enormous numbers (Marks 1976b) and, within three weeks of the rain, residents of Gladstone and of Calliope Shire were complaining to their local authorities. Aerial and manual applications of Abate insecticide granules were required to control breeding until the water level rose further and red mud was pumped to this pond. This plague of *Cx. sitiens* could have been predicted from a similar experience in the district in 1973 about which the refinery engineers had not been told.
Development of the Gladstone Power Station site was associated with a plan for reclamation of about 500 ha of tidal flats and mangroves between the mouths of Auckland Creek and the Calliope River. The initial stage involved construction of a series of rock and earth walls or bunds. In May 1973, a very large flooded impoundment enclosing many dying mangroves supported an enormous population of *Cx. s. sitiens* larvae and Gladstone experienced a mosquito plague (Marks 1973b). This problem was solved by opening the bund to allow access by tides.

A series of smaller impoundments was designed to receive fly ash washings from the power station, with the water flowing in series through them before discharge to the river (Fig. 4). In December 1976, before flow started, each impoundment contained stagnant brackish water with many standing mangroves, long dead, and shedding bark. The stable conditions had allowed dense growth of subsurface algal mats and some seagrass. Although the impoundments were well stocked with fish, these could not penetrate the thick subsurface vegetation and the shallow water over the alga and seagrass supported very large numbers of *Cx. s. sitiens* and *An. billi* larvae (Marks 1977). Abate insecticide was used to control breeding in these impoundments until they came into use by the power station. Then the water level rose, brackish water flowed through the series, the algal mats disappeared, and mosquito breeding was no longer a problem.

These mosquito problems at Gladstone were associated with the death and decomposition of mangroves in areas destined for irreversible alteration. It is likely that complete destruction or removal of the mangroves before the impoundments were closed to tidal access would have prevented or greatly reduced the problems.

**General implications for control**

Our knowledge of the ecology of mosquito pests enables us to take steps to reduce mosquito/man encounters. It should not be forgotten that the individual can often deliberately avoid such encounters, or alleviate them by personal protection.

Control of domestic mosquitoes is both possible and practicable, given the collaboration of householders, industries and local authorities in screening, emptying or destroying water-holding containers such as tanks, tins and tyres, and in treatment and disposal of polluted effluents.

Fresh and saltwater mosquito breeding is extensive and whether or not control is attempted will be influenced by regional or local economics and public health needs, as well as practicability. Successful control is likely to depend on the integration of a variety of biological, physical (source reduction) and/or chemical methods following a thorough biological investigation of the target species in relation to the environment. In Australia only the initial steps have been taken in such studies.

Hamlyn-Harris (1929, 1930) evaluated numerous native fish species, aquatic insects and other invertebrates as 'larval destructors', and investigated the physical and chemical characteristics of some breeding sites in the Murrumbidgee irrigation area and in Queensland. Subsequently there was little scientific study of the potential of biological control agents in Australia (although Laird (1956) described several parasites of mosquito larvae). In 1975 Sweeney and coworkers began evaluating a fungus, *Culicinomyces*, pathogenic to mosquito larvae.

Chemical control measures are usually undertaken on an *ad hoc* basis because few local authorities have the facilities or personnel to evaluate them scientifically. At least an initial step towards rational chemical control of saltmarsh mosquitoes has been taken (Kay *et al.* 1973). However, even basic questions on the susceptibility of pest and vector species to insecticides remain largely unanswered.
Reduction of breeding sites would seem a practical long-term approach to many fresh and saltwater mosquito problems. Better water management through the application of engineering practices, recognition and improvement of poor land preparation or layout for agriculture, improved farm and livestock management, and controlled irrigation will reduce the problem. This requires much greater organization, finance and expertise than are at present applied to mosquito control in Australia. Significant advances are unlikely until there is assured continuity of substantial funds to support such work. Nevertheless, better communication between engineers and entomologists could help to prevent some mosquito problems.

Perhaps the answer in Australia would be in the organization of Mosquito Abatement Districts similar to those which operate successfully in most parts of the U.S.A. These specialist control agencies, initiated by public petition to state governments, are funded through small levies on taxpayers and may have different boundaries from local authorities.

References


Mosquitoes