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TOWARDS MANAGEMENT OF MOSQUITOES AT HOMEBUSH BAY, SYDNEY, AUSTRALIA. I. SEASONAL ACTIVITY AND RELATIVE ABUNDANCE OF ADULTS OF *AEDES VIGILAX, CULEX SITIENS,* AND OTHER SALT-MARSH SPECIES, 1993–94 THROUGH 1997–98

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ABSTRACT. The mosquitoes associated with 2 saline wetlands at Homebush Bay, Sydney, Australia, were investigated over 5 consecutive seasons. Twenty-one species were collected in adult traps at the 2 sites but the saline wetlands supported larvae of only 4 species: *Aedes alternans, Aedes camptorhynchus, Aedes vigilax,* and *Culex sitiens.* Of these, *Ae. vigilax* and *Cx. sitiens* were the most common, and their peak abundances generally occurred during February and April, respectively. Both wetlands were influenced by tides and rainfall–runoff, and a lack of regular tidal exchange in the mangroves and inadequate drainage of the saltmarsh provided potential habitat. Populations of *Ae. vigilax* and *Cx. sitiens* at the Newington site were greater than those at the Bicentennial Park site, because of more extensive habitat at the former, but were diminished by irregular ground-based applications of temephos during the middle 3 years of the study. Populations at the Bicentennial Park site, not subjected to the larvicide, were typically smaller but more consistently related to influences of tide and rainfall through the 5 seasons. During the final season, populations of both species in both wetlands were enhanced by exceptional tide penetration and rainfall. Helicopter applications of *Bacillus thuringiensis israelensis* larvicide were employed at both sites and effectively suppressed populations of both pest species. For future management, provision of full tidal exchange and water recirculation to reduce the area of water impounded within the mangroves and retained in depressions on the marshes should significantly suppress the pest populations and relieve reliance on control agents.

KEY WORDS Mosquitoes, *Aedes vigilax, Culex sitiens,* salt-marsh, control

INTRODUCTION

Mosquitoes breeding in coastal saline habitats of Australia can be major nuisance pests (Kay et al. 1981). In eastern Australia the most important are *Aedes alternans* (Westwood), *Aedes camptorhynchus* (Thomson), *Aedes vigilax* (Skuse), and *Culex sitiens* Wiedemann (Russell 1993). Additionally, *Ae. vigilax* is the most important coastal vector of Ross River and Barmah Forest viruses in New South Wales (NSW) and Queensland, *Ae. camptorhynchus* is the most important vector on the coast of eastern Victoria, and *Ae. alternans* and *Cx. sitiens* have also been associated with arboviruses but these are much less significant (Russell 1995, 1998).

For the state of NSW, the pest and vector species of greatest concern is *Ae. vigilax,* and it has been recorded for most estuarine areas on the coast north and south of the capital, Sydney. *Culex sitiens* is found along the north coast and can be abundant occasionally, but is rare south of Sydney. *Aedes camptorhynchus* is widespread but relatively abundant only sporadically on the NSW south coast, and is found only rarely to the north of Sydney. *Aedes alternans* is found along both the north and south coasts, and can be abundant occasionally.

In Sydney, saline wetlands on the Parramatta River, the major tributary of Port Jackson (Sydney Harbour), have a history of mosquito production. More than 70 years ago, Mackerras (1926) noted that *Ae. vigilax* was "... a pest in the Western Suburbs near the Parramatta River." In the following decades, foreshore modification, land reclamation, and industrial development along the river resulted in the continuing degradation of many of the riverside wetlands (Clarke and Benson 1988), and poorly drained mangrove and salt-marsh habitat became even more productive of mosquitoes. One relatively extensive site, Homebush Bay, became the most important salt-marsh mosquito habitat with respect to production of nuisance mosquitoes.

The recreational, educational, and environmental values of Homebush Bay were recognized in the 1980s when redevelopment of 760 ha was being planned. The saline wetlands were found to support a number of rare salt-marsh plant species (Burchett and Pulkownik 1996) and to provide important habitat for internationally protected migratory wading birds (Taylor and Hutchings 1996), and thus are considered to be environmentally sensitive.

Restoration of degraded saline wetlands in the eastern precinct partly improved the situation for

Bicentennial Park (100 ha) in 1988. With the announcement in 1993 that Sydney would be hosting the Olympic Games in the year 2000, and with the Homebush Bay area selected as the principal site, plans for further development of the area were brought forward to cater to construction of new sporting facilities and residential developments. Additionally, extensive remediation was proposed for the saline wetlands to enhance environmental conditions for fauna and flora, and provide education and passive recreation areas for Sydney residents and tourists.

Early in the planning and development process, mosquitoes were an issue for the remediation of the saline wetlands. Sporadic surveys of the mosquito fauna were undertaken during the 1980s, associated with the Bicentennial Park and proposed developments; 6 genera comprising 17 species were recorded (Russell, unpublished data). With further developments for the Olympic Games, investigations of mosquito populations associated with the wetlands were commissioned to provide for an environmentally sensitive mosquito management strategy. This paper presents surveillance data on adults produced by the saline wetlands during the first 5 years of the investigation.

MATERIALS AND METHODS

Study areas

Homebush Bay is on the southern side of the Parramatta River, 12 km west of the Sydney central business district. The area included saline wetlands with foreshore mangroves (*Avicennia marina* var. *australasica*), and salt-marsh (primarily *Sarcocornia quinqueflora, Sporoboblus virginicus* and *Suaeda australis*) and mudflats. Two major freshwater courses, with associated saline and freshwater marshland, drained into the bay—Powells Creek from the south through Bicentennial Park in the east, and Haslams Creek from the southwest below the Newington precinct (previously a Royal Australian Navy armament depot) to the west.

The principal mosquito habitats were the saline wetlands in northern Bicentennial Park and northern Newington. Areas of the mangroves and salt-marsh existed along the 2 creek lines, but these were not significant mosquito habitats because of their comparably small size and relatively effective drainage. All of the above wetland areas were influenced by tidal inundation and by rainfall and freshwater runoff, and were within 1.5 km of the proposed Olympic sporting facilities and residential development (Fig. 1).

The Newington wetlands (approximately 45 ha) comprised extensive mangrove and salt-marsh areas, mudflats, and a relatively shallow lagoon. The wetland was separated from the Parramatta River by a seawall, through which limited tidal exchange was possible via a small culvert. Siltation had affected the major drainage channels beneath the mangrove canopy, and they had become colonized by mangroves and no longer functioned effectively; many of the channels had become a series of pools, and there were extensive areas of permanently impounded water were present. The salt-marsh had many small depressions with dense coverage of *S. quinqueflora,* and after tidal penetration or rainfall inundation the depressions provided extensive mosquito habitat.

The Bicentennial Park wetlands (approximately 60 ha) comprised mangrove forests, salt-marsh, mudflats, and a large lagoon (approximately 10 ha). Beneath the mangrove canopy were channels, small shallow pools, and areas of impounded water caused by siltation or other blockages. The construction of a raised walkway through the mangroves for visitors inhibited drainage of tidal water and rainfall runoff, and other disturbances, siltation, and incomplete canopy cover had led to salt-marsh becoming established in areas around channels and pools within the mangroves. The external salt-marsh area of Bicentennial Park was considerably smaller than in Newington and the habitats were penetrated by only the highest of tides; generally these habitats were only completely inundated when high tides coincided with heavy rainfall. The open impoundment was steep sided, contained fish, was windswept, and generally did not provide significant mosquito habitat.

Mosquito sampling

Sampling of adults was usually undertaken weekly from October through June each year over 5 seasons from 1993 to 1998, with encephalitic vector surveillance (EVS)-type dry ice-baited light traps (Rohe and Fall 1979) set during the afternoon and retrieved the next morning. Over the 5-year period, various numbers of traps and sites (up to 26 per week) were used for the overall investigation throughout the entire development area, but 8 fixed core sites were maintained for the saline wetlands. These comprised 4 sites in Bicentennial Park and 4 sites in Newington (Fig. 1), and only the data from these 8 core sites are included in this paper.

Larval surveillance was undertaken using a dip-sampling technique (Service 1993). Comprehensive surveys were undertaken throughout the saline wetlands in both Bicentennial Park and Newington on a weekly basis throughout the study period, to characterize larval associations with environmental circumstances and determine the effect of control measures; these data are to be the subject of a companion paper.

Environmental data

Data on temperature and rainfall were supplied by the NSW Department of Meteorology from the nearby Parramatta station, until 1997 when a station

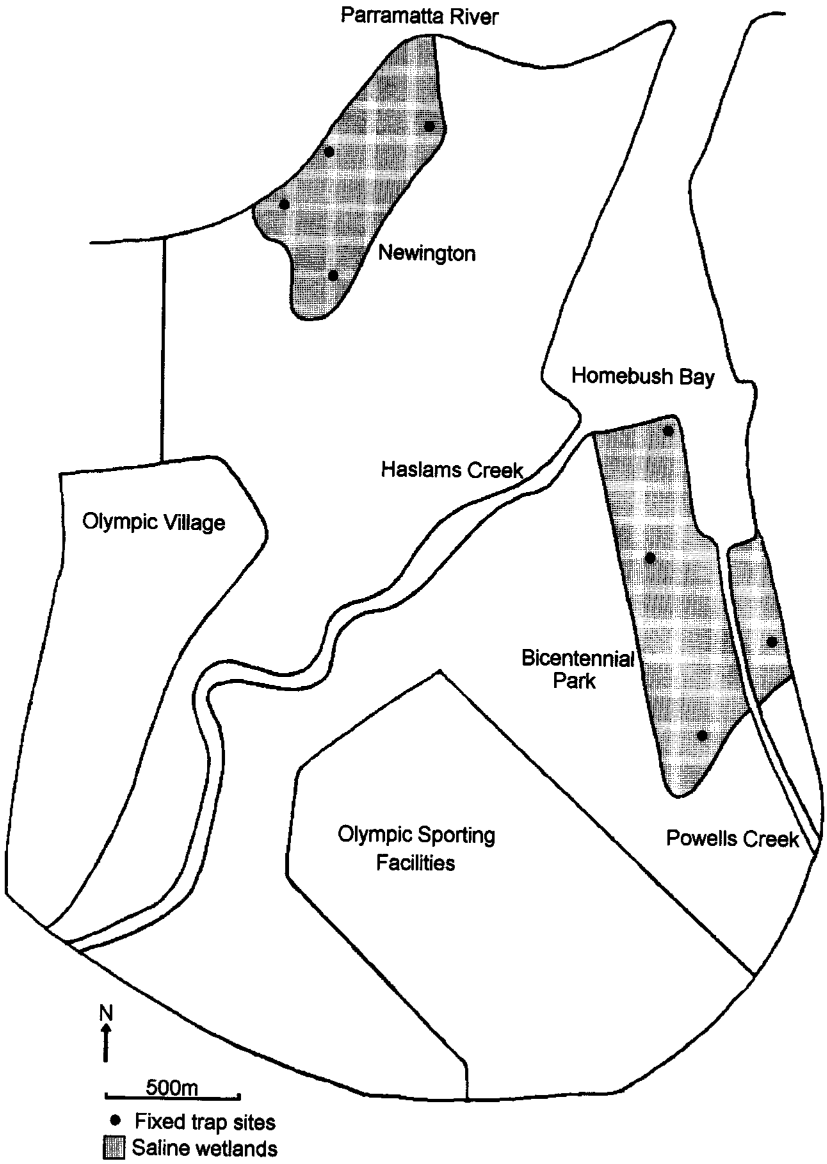

Fig. 1. The 4 fixed adult mosquito trap sites in the 2 major wetland areas, Newington (N) and Bicentennial Park (BP), showing the Olympic Sporting facilities and Olympic Village and residential development.

was opened at Homebush Bay. Tide data were obtained from the NSW Department of Public Works and Services.

Mosquito control efforts

After the 1st year (1993–94) of sampling, the Newington authorities employed contractors to reduce mosquito populations with ground-based applications of temephos sand granules. These applications occurred during the 2nd, 3rd and 4th seasons (1994–95 to 1996–97). No larvicidal treatments were undertaken in the saline wetlands at Bicentennial Park the 1st 4 years (1993–94 to 1996–97).

For the 5th season (1997–98), the temephos applications for Newington were withdrawn, and no control was planned for either of the wetlands. However, in late February 1998, extraordinary populations of *Ae. vigilax* brought demands for control and led to aerial (helicopter) applications of a liquid formulation of a *Bacillus thuringiensis israelensis* (*B.t.i.*) product being applied over the mangrove and salt-marsh wetlands of both Newington and Bicentennial Park. The applications continued as required through April as the wetlands were inundat-

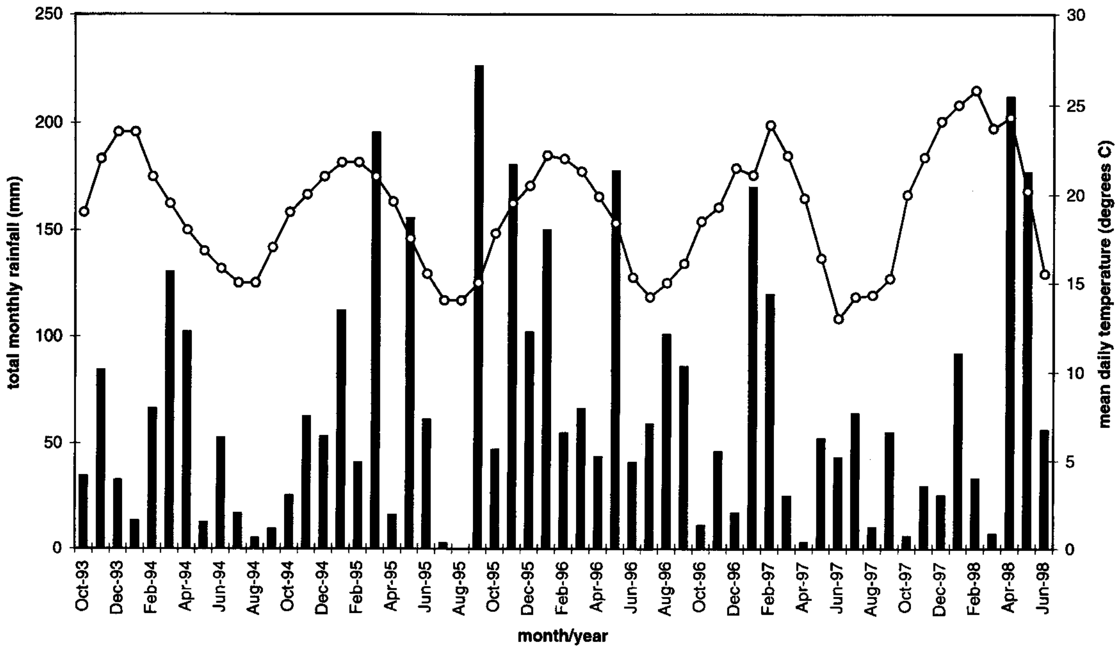

Fig. 2. The seasonal total monthly rainfall (bars) and mean monthly temperature (open circles) for Homebush Bay.

ed from tides and rainfall. The effectiveness of these applications of control agents were assessed by quantitative larval surveys and deployment of sentinel larvae as well as monitoring of adult populations.

RESULTS AND DISCUSSION

Environmental factors

The temperature and rainfall data for the study period are presented in Fig. 2. The populations of mosquitoes were maintained by inadequate drainage in the wetlands, and retention of water in pools within the mangroves and in depressions on the salt-marsh.

The wetlands were well above the mean high water mark (1.4 m) and generally only tides higher than 1.8 m could penetrate the wetlands. High tides able to inundate the wetlands usually occurred over a series of 3–5 days each month. This often resulted in a compound effect whereby successive tides pushed the water remaining from the previous days further into the wetlands. However, the extent of tidal penetration into the wetlands was unreliable and erratic. Differences in actual tide heights (influenced by wind, storm water in the river, inadequate drainage, and rainfall–runoff in the wetlands) and the compound effect of successive tides, made correlations between the predicted or measured tide height and the area actually flooded very difficult.

Mosquito fauna

The adult sampling recorded 21 species, and each species was collected in both Bicentennial Park and Newington (Table 1). The sampling of wetlands for larvae resulted in the collection of 4 species: *Ae. alternans, Ae. camptorhynchus, Ae. vigilax,* and *Cx. sitiens.* The range of adults reflected the presence of the saline wetlands, and also the freshwater habitats in the overall development area. The variation in presence and abundance of different species between each wetland over the 5 years is shown in Table 1.

Of the 4 salt-marsh species, *Ae. vigilax* and *Cx. sitiens* were more common than *Ae. alternans* and *Ae. camptorhynchus* at both wetlands and in all years. The seasonal distribution of these 4 species was similar to that observed on the coast south of Sydney (Russell 1986, Russell et al. 1992). For *Ae. vigilax* and *Cx. sitiens,* seasonal activity and relative abundance between sites and between years are illustrated in Figs. 3 and 4.

Aedes vigilax: *Aedes vigilax,* although towards the southern extent of its range on the east coast, was extremely abundant on occasion. Adults became active in October and numbers increased from November, usually in conjunction with the 1st series of tides greater than 1.8 m. Abundance generally peaked in February, when up to 8,268 females were collected per trap, and decreased toward May and June when only a few individuals were collected (Fig. 3).

This species overwinters as eggs and commences

Table 1. The abundance (mean number mosquitoes per trap) of all mosquito species collected from the 4 trap sites in each of Newington (N) and Bicentennial Park (BP) wetlands over 5 consecutive seasons in Homebush Bay.

	1993–94		1994–95		1995–96		1996–97		1997–98	
Species[1]	N	BP	N	BP	N	BP	N	BP	N	BP
Ad. venustipes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	<0.01	<0.01
Ae. alboannulatus	0.62	0.05	0.32	0.45	0.40	0.21	0.26	0.18	0.07	0.01
Ae. alternans	0.44	0.62	1.02	5.00	2.01	2.90	0.58	0.64	0.49	0.01
Ae. camptorhynchus	0.04	0.00	0.05	0.15	0.20	0.19	1.13	0.55	0.29	0.01
Ae. flavifrons	0.00	0.00	0.01	0.02	0.02	0.00	0.00	0.01	0.00	0.0
Ae. multiplex	0.00	0.00	0.00	<0.01	0.00	0.01	0.00	0.00	<0.01	0.0
Ae. notoscriptus	1.17	1.25	1.28	1.69	5.22	2.58	1.39	1.40	0.49	0.48
Ae. procax	0.03	0.00	0.08	0.22	0.23	0.02	0.05	0.01	0.03	0.00
Ae. rubrithorax	<0.01	0.00	0.00	<0.01	0.00	0.04	0.00	0.00	0.00	0.00
Ae. vigilax	193.73	78.30	127.81	279.63	27.72	43.68	70.18	66.86	316.75	75.45
Ae. vittiger	0.00	0.00	0.00	0.00	0.02	<0.01	0.01	0.00	<0.01	0.00
An. annulipes	1.14	0.19	0.44	1.25	4.42	1.72	1.60	0.43	0.72	0.14
Cq. linealis	3.93	0.48	2.41	3.94	3.38	0.83	1.62	0.67	0.27	0.26
Cx. annulirostris	1.03	0.75	2.39	8.19	9.31	7.34	11.84	4.24	7.83	1.95
Cx. australicus	—[2]	—[2]	—[2]	—[2]	5.20	2.12	4.37	1.75	0.81	0.32
Cx. halifaxii	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	<0.01	0.00
Cx. molestus	8.80	0.94	4.79	3.07	5.43	0.70	0.91	0.25	1.36	0.27
Cx. orbostiensis	0.12	0.03	<0.01	<0.01	0.06	0.05	0.00	0.00	0.08	0.00
Cx. quinquefasciatus	8.43[2]	3.54[2]	6.79[2]	11.19[2]	5.34	2.16	7.69	6.01	5.90	1.81
Cx. sitiens	179.56	31.30	9.04	12.3	18.18	2.92	21.28	11.66	31.87	11.01
Ma. uniformis	<0.01	0.01	<0.01	0.01	0.01	0.05	<0.01	0.01	<0.01	0.41

[1] *Ad., Aedeomyia; Ae., Aedes; An., Anopheles; Cq., Coquillettidia; Cx., Culex; Ma., Mansonia.*

[2] *Culex australicus* were not differentiated from *Cx. quinquefasciatus* during 1993–94 and 1994–95.

activity annually in October (Russell, unpublished data). Thereafter, the primary factors influencing the abundance of *Ae. vigilax* were tidal or rainfall inundation and the application of control agents. This species lays its eggs on soil at the base of salt-marsh vegetation (*S. quinqueflora* and *S. virginicus*) or on the vegetation itself, associated with pools and depressions on the marsh or beneath the mangrove canopy (Kay and Jorgensen 1986, Gislason and Russell 1997).

On the salt-marsh in both Newington and Bicentennial Park, larvae of *Ae. vigilax* were abundant in

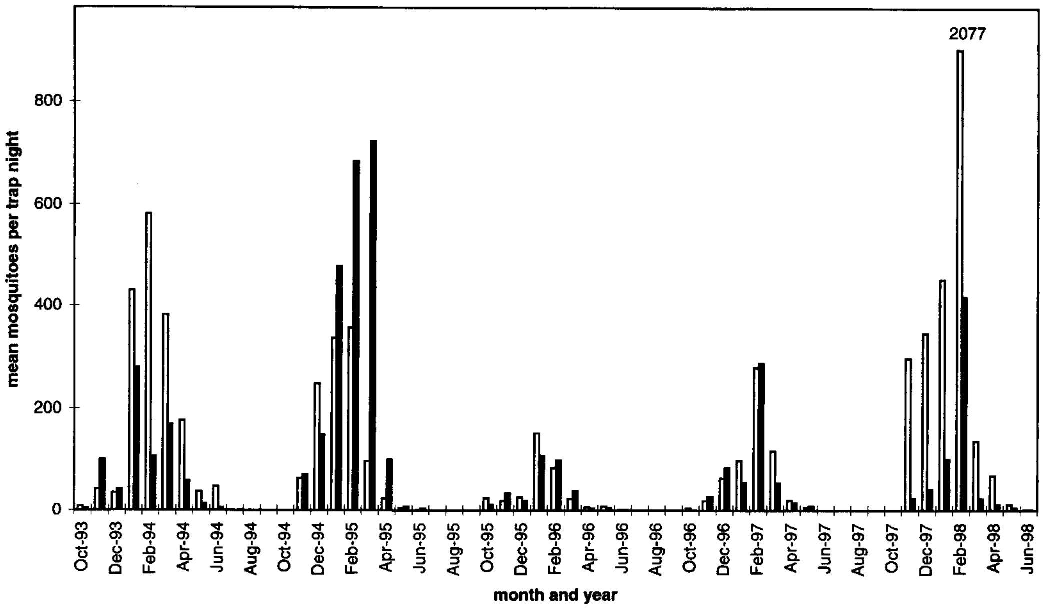

Fig. 3. The seasonal abundance distribution of *Aedes vigilax* from the wetlands of Newington (□) and Bicentennial Park (■), Homebush Bay.

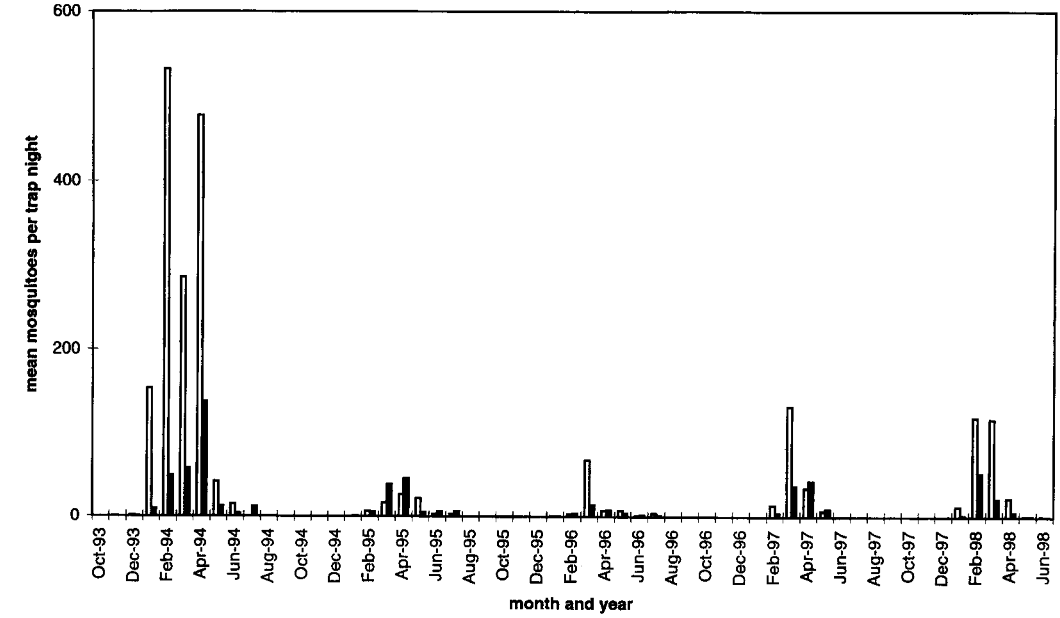

Fig. 4. The seasonal abundance distribution of *Culex sitiens* from the wetlands of Newington (□) and Bicentennial Park(■), Homebush Bay.

pools remaining after tidal or rainfall inundation. The most productive habitats were those vegetated by *S. quinqueflora,* and particularly those that dried completely approximately 2 weeks after inundation, thus precluding the maintenance of predators.

Beneath the mangrove canopy, larvae of *Ae. vigilax* were most abundant in tidal pools or in shallow impoundments containing *S. quinqueflora,* but the situation in Newington differed from that in Bicentennial Park. In Newington extensive semipermanent inundation occurred and larval activity was mostly limited to the margins of the impoundments and the small pools created by silted channels. Despite the near permanent status of the impounded water, fish were rarely detected outside the deeper channels. In Bicentennial Park, the majority of mangrove habitats drained freely, the persisting pools contained established fish populations, and larvae were not common. However, a relatively small, highly disturbed area was present where tidal exchange was restricted, drainage channels were blocked to form a series of small shallow pools containing *S. quinqueflora,* and larval activity was intensive.

The seasonal abundance distribution of *Ae. vigilax* was erratic over the 5 years (Fig. 3). During 1993–94, the abundance of *Ae. vigilax* in Newington was greater than that in Bicentennial Park, but during 1994–95 the situation was reversed. An increase in available habitat in both areas resulted from high rainfall in January and March of 1995 (Fig. 2) but although an increase occurred in the populations of *Ae. vigilax* at Bicentennial Park, populations at Newington decreased with the introduction of the larvicide program. The next 2 seasons, 1995–96 and 1996–97 produced similar abundances of *Ae. vigilax* in both areas, but at relatively low levels. Paradoxically, the low abundance of *Ae. vigilax* during the 1995–96 season was likely to have resulted from above-average rainfall (Fig. 2). A total of 1,047 mm of rain was recorded, greater than the long-term average of 910 mm. The quantity and consistency of rainfall resulted in extensive areas of habitat remaining inundated for long periods, allowing the establishment of fish and invertebrate predators while also restricting access to preferred oviposition sites for *Ae. vigilax* at the base of salt-marsh vegetation.

Ae. vigilax were exceptionally abundant in Newington during 1997–98. Although the abundance of *Ae. vigilax* in Bicentennial Park remained similar to that for 1995–96 (Fig. 3) and 1996–97, the abundance in Newington increased dramatically, particularly in February when the monthly abundance substantially exceeded that previously recorded during the study period. Highlighting the erratic nature of habitat inundation between sites was the lack of tidal penetration at Bicentennial Park at this time. Although habitats beneath the mangrove canopy were inundated, the salt-marsh was only partly flooded.

The combination of heavy rainfall and high tides in February 1997–98, which inundated the majority of habitats in the Newington wetland, provided ideal conditions for the development of larvae. Preceding this combination of events were very low rainfall and relatively high temperatures (Fig. 2), and these resulted in almost complete drying of the wetland approximately 2–3 weeks after tidal inundation. The high drying frequency of the wetlands at this time prohibited the establishment of predator populations and was conducive to full maturation of egg reserves. The removal of control treatments in the early months also contributed to population growth.

Culex sitiens: *Culex sitiens* is typically associated with warmer climates, is rare south of Sydney, and its occasional relatively high abundance was unexpected. The seasonal activity of this species differed from that of *Ae. vigilax* in that *Cx. sitiens* often did not appear until January. Its peak abundance varied between seasons but generally occurred between February and in April (Fig. 4), when up to 3,195 females were collected per trap.

The seasonal abundance of *Cx. sitiens* was generally associated with the wetter months, which are more suitable to the ecology of this species, which lays rafts of eggs in pools in the salt-marsh and beneath the mangrove canopy (Lee et al. 1989), and generally in water of a slightly lower salinity than that preferred by *Ae. vigilax* (Mottram et al. 1994).

The most noticeable feature of the seasonal activity of *Cx. sitiens* during the study was the considerably higher adult populations in both sites during the 1993–94 season. In the following years the larviciding program is likely to have impacted on the populations in Newington, but other factors in the Newington area also may have reduced the availability of favorable habitats for *Cx. sitiens.*

With the exception of the 1994–1995 season, greater numbers of *Cx. sitiens* were collected from Newington than from Bicentennial Park in each year, reflecting the greater area of potential habitat. The extensive permanently to semipermanently inundated areas beneath the mangrove canopy seem to be suitable areas for larval development, but differences between seasons may have affected the production of adults. The habitats exploited by *Cx. sitiens* in Bicentennial Park are less extensive but tend to be more stable, and this is reflected in the lower but relatively more consistent populations.

Aedes alternans: *Aedes alternans* was active generally from November until April, and reached maximum abundance during March 1995 when up to 135 females were collected per trap. With the exceptions of 1994–95 and 1995–96, this species had relatively low mean yearly abundances at less than one mosquito per trap (Table 1). *Aedes alternans* larvae are predatory on other larvae, and are associated commonly with *Ae. vigilax.* Their presence and abundance seemed to be linked intrinsically to generational hatchings of *Ae. vigilax.*

Aedes camptorhynchus: *Aedes camptorhynchus* was primarily active during earlier (September–October) and later (May–June) months of the season. The abundance of this species was greatest in 1996–97, when individuals were collected throughout the season and up to 21 females were recorded per trap. The population sizes were low overall, with mean yearly abundances generally below 0.5 females per trap night (Table 1), but as this is a cool-climate species at the northern extent of its range, this mosquito was not expected to be particularly abundant.

Dispersal

Dispersal of the 2 major salt-marsh species, within and between the 2 wetlands, will influence the respective sampling results. *Aedes vigilax* is known to be able to move tens of kilometers (Lee et al. 1989) from its larval habitats, and adults collected in Newington may well have emerged from habitats in Bicentennial Park (and vice versa). *Culex sitiens* seems to have a shorter flight range in the region but readily travels beyond the 2 km that separates the 2 wetlands (Russell, unpublished data). Investigations of local dispersal patterns of both species, and how this behavior influences their abundance in each wetland, are being undertaken.

Control efforts

The sampling of adults indicated that the temephos larviciding program in Newington during 1994–95 through 1996–97 had not been effective in completely suppressing adults over those years, and surveys detected substantial larval populations to discount the possibility that the adults had migrated from Bicentennial Park. Although the larvicide was responsible for reducing the inherently greater Newington populations, the activity patterns of *Ae. vigilax* in Newington remained comparable with those in Bicentennial Park (Fig. 3) where temephos was not used.

The ground-based applications had various limitations. The agent was dispersed by hand casting, with irregular and inconsistent applications to pools observed to contain larvae, but some pools on the salt-marsh were more visible and accessible than others, and more so than many of those within the mangroves. Thus, overall, the treatments were not comprehensive, and had limited success because of the inappropriate methodology and inadequate coverage. However, the reverse pattern of 1994–95, where the populations of both *Ae. vigilax* (Fig. 3) and *Cx. sitiens* (Fig. 4) were higher in Bicentennial Park, were due (at least in part) to the introduction of the larviciding program in Newington in that year. However, the Bicentennial Park populations were increased by more extensive habitat at that site, at that time, as mentioned above. Likewise, the extraordinary abundance of *Ae. vigilax* in Newington at the beginning of the 1997–98 season was due (at least in part) to the removal of the temephos program, whereas the populations at Bicentennial Park were comparable to the previous year.

The change to the aerial applications of *B.t.i.* larvicide in 1997–98 brought a dramatic decline in *Ae. vigilax.* A substantial suppression of populations of adults of both species occurred in both Newington and Bicentennial Park and the larval monitoring confirmed the impact of the pesticide at both sites. Given the prevailing conditions and the experience of 1993–94, high adult populations otherwise would have been expected to be sustained through April and possibly May.

CONCLUSIONS

This investigation has increased our understanding of the local pest mosquito populations and their associations with the wetland habitats, and will assist the development of an effective management strategy to suppress pest mosquito populations in Homebush Bay after the Olympic Games in the year 2000. The production of mosquitoes from the wetlands resulted from the provision of habitat through inadequate drainage and lack of access for predatory fish. Management of the mangrove communities, by reestablishing natural tidal exchange with the Parramatta River, will provide for drainage of impounded areas and improve the access of predatory fish. Management of the salt-marsh communities, by providing networks of runnels and recirculation ditches (Hulsman et al. 1989, Dale et al. 1993), will provide for water movement from and fish access to the depressions. Such a combination of environmental management techniques, together with strategic use and effective application of biorational control agents, such as *B.t.i.* and methoprene, should significantly reduce the mosquito habitats and mosquito populations, and relieve the pest nuisance in this environmentally sensitive area.

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