Chapter 8
Adaptation of Mosquito Vectors to Salinity and Its Impact on Mosquito-Borne Disease Transmission in the South and Southeast Asian Tropics

Ranjan Ramasamy, Sinnathamby N. Surendran, Pavilupillai J. Jude, Sangaralingam Dharshini, and Muthuladchumy Vinobaba

Abstract Mosquito vector-borne diseases are a significant health problem in South and Southeast Asia. Some mosquito vectors in the region are well known to lay eggs and undergo pre-imaginal development in brackish water. However, a number of other important vectors, e.g. *Anopheles culicifacies* (malaria) and *Aedes aegypti* and *Aedes albopictus* (dengue and chikungunya), have previously been widely held to do so exclusively in freshwater. But recent evidence shows that these species can also lay eggs and undergo pre-imaginal development in brackish water collections in coastal areas of the region. This property produces a reservoir of vectors that are not targeted in larval control programmes. It can contribute to disease transmission in a previously unrecognised manner that can be compounded by environmental changes caused by expanding populations in coastal zones, climate change and rising sea levels due to global warming. Increased disease transmission in coastal areas will also lead to higher disease incidence in inland areas. Many countries in South and Southeast Asia have long coastlines, a high proportion of coastal zone relative to total land area and a large proportion of the population living in coastal areas. Hence, the region is particularly vulnerable to disease transmission by brackish water vectors. Appropriate policies and strategies need to be developed in a local, national and international context to counter this threat to human health in South and Southeast Asia.

R. Ramasamy (✉)
Department of Life Sciences, Faculty of Science and Technology,
Anglia Ruskin University, Cambridge, UK
e-mail: ranjan.ramasamy@anglia.ac.uk

S.N. Surendran • P.J. Jude
Department of Zoology, University of Jaffna, Jaffna, Sri Lanka
e-mail: noble@jfn.ac.lk; pjustinjude@gmail.com

S. Dharshini • M. Vinobaba
Department of Zoology, Eastern University, Chenkaladi, Sri Lanka
e-mail: dharshini1982@yahoo.com; laxmi@esn.ac.lk

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8.1 Overview of Mosquito-Borne Human Diseases in Tropical South and Southeast Asia

Mosquito-borne human diseases are a cause of considerable mortality and morbidity worldwide. Diseases such as chikungunya, dengue and West Nile viral encephalitis are of great international concern because of their increasing incidence and global spread (Weaver and Reisen 2010). Mosquito vectors transmit many important human parasitic and arboviral diseases in tropical South and Southeast Asia. The World Health Organization (WHO) reported that there were approximately 130.6 million suspected cases of malaria caused by protozoan parasites of the genus *Plasmodium*, predominantly *P. falciparum* and *P. vivax*, in its Southeast Asian region in 2012 (WHO 2013a). This caused an estimated 1,226 deaths. The WHO Southeast Asian region includes countries with extensive coastal zones such as Bangladesh, India, Indonesia, Maldives, Myanmar, Sri Lanka, Thailand and Timor-Leste. In its Western Pacific region, which also contains many coastal countries regarded as part of Southeast Asia (Brunei, Cambodia, Malaysia, Papua New Guinea, the Philippines, Singapore and Vietnam), the WHO reported 10.8 million suspected cases and an estimated 458 malaria deaths in 2012 (WHO 2013a). The malaria situation in the greater South and Southeast Asian region is highly dynamic due to the increasing resistance of parasites to common antimalarial drugs and mosquito vectors to common insecticides, movement of human populations and changes in land use patterns, forest cover, health services and other pertinent factors. Several species of *Anopheles* mosquitoes are responsible for transmitting malaria in the region with some identified as dominant vectors (Sinka et al. 2011).

Lymphatic filariasis caused by the nematode parasites *Wuchereria bancrofti*, *Brugia malayi* and *Brugia timori* is widely prevalent in the region. It is responsible for considerable morbidity and disfigurement in infected persons. Recent WHO data suggest that approximately 60–65 million people in the two regions have lymphatic filariasis (WHO 2012). *Culex quinquefasciatus* in the Asian mainland and various species of *Anopheles* and *Mansonia* in the Southeast Asian archipelago are chiefly responsible for transmitting filariasis in the region (Walter Reed Biosystematics Unit 2013).

Dengue, the most common human arboviral disease, is widespread in South and Southeast Asia with 176,719 cases and 887 deaths reported in the WHO Southeast Asian region in 2010 and 242,424 cases with 784 deaths in the WHO Western Pacific region in 2009 (WHO 2012). *Aedes aegypti* and *Aedes albopictus* mosquitoes that are common throughout the region are predominantly responsible for transmitting dengue (Weaver and Reisen 2010; Walter Reed Biosystematics Unit 2013). Other mosquito-borne diseases that are endemic to the region include Japanese encephalitis and chikungunya. Yellow fever transmitted by *Ae. aegypti* and *Ae. albopictus* is endemic in parts of Africa and South America (WHO 2013b). An effective vaccine is available against yellow fever. The reasons for the absence of yellow fever from the South and Southeast Asian region, notwithstanding the presence of competent vectors, are not well understood. Increasing international travel and trade however poses the risk of its introduction to the region.

8.2 Vector Control Is Important for Reducing the Prevalence of Many Mosquito-Borne Diseases

A licensed vaccine is presently available against only Japanese encephalitis among all the major mosquito-borne diseases of the region. Vaccines for malaria, dengue and chikungunya are currently under development. The presence of four serotypes of the dengue virus hampers the production of a vaccine against dengue. In addition, a suboptimal immune response to any one of the serotypes can exacerbate disease caused by a subsequent infection with that serotype (Halstead 2003; Chun et al. 2007). Drugs for specific treatment of dengue are not presently available, and only symptomatic treatment is possible for the disease. On the other hand, specific and effective drugs are available to treat malaria and lymphatic filariasis. However, the Greater Mekong subregion in Southeast Asia is the origin of many strains of malaria parasites that have developed resistance to several antimalarial drugs and then spread worldwide. The recent emergence in this area of *P. falciparum* that is resistant to artemisinin combination therapies that are the first-line treatment for uncomplicated *falciparum* malaria is therefore of considerable international concern (Dondorp et al. 2010).

Minimising human-mosquito contact and reducing vector populations by the application of insecticides and through managing and eliminating pre-imaginal development sites therefore remain important components of mosquito-borne disease control programmes. The use of insecticide-impregnated bed nets and indoor residual spraying of insecticides is the mainstay of malaria vector control programmes throughout the world. These methods, together with early case detection and treatment as well as the management of larval habitats, have succeeded in reducing the incidence of malaria in many countries of the region over the past decade (WHO 2013b). However, the *Aedes* vectors of dengue can bite outdoors and during daytime making bed nets less effective against acquiring infections. Mosquito proofing houses, which has proved helpful in eliminating dengue from the southern United States, is not popular or widely affordable in the humid and densely populated countries of South and Southeast Asia. Therefore, reducing the *Aedes* vector populations through eliminating, minimising and larviciding pre-imaginal development habitats and the application of insecticide through fogging and residual spraying at infection foci are the principal methods used for controlling dengue in the region (WHO 2009). Such measures are additionally effective against chikungunya because *Ae. aegypti* and *Ae. albopictus* are also the principal vectors of chikungunya. *Aedes aegypti* is additionally capable of transmitting other Australasian arboviruses, such as Ross River and Murray Valley encephalitis viruses, as demonstrated in laboratory experiments (Ramasamy et al. 1990). It is also a potential vector of the filarial parasite *Brugia malayi* in Asia (Erickson et al. 2009).

8.3 Global Warming, Rising Sea Levels and Changes in Coastal Salinity

The United Nations Framework Convention on Climate Change described global climate change as long-term changes in commonly measured meteorological parameters, over and above natural variations, that are directly or indirectly attributable to human activity altering the composition of the atmosphere. Such parameters include temperature, rainfall and humidity. Global warming is the rise in average global temperatures due to the increasing emission of gases, principally carbon dioxide, causing a greenhouse effect in the atmosphere. Global warming leads to a rise in sea levels caused by the melting of polar ice and glaciers and the thermal expansion of seawater (Intergovernmental Panel on Climate Change 2013). The rise in sea levels, depending on the extent of the warming that is principally governed by the rate of burning of fossil fuels, is predicted to be about 82 cm by the end of the twenty-first century (Intergovernmental Panel on Climate Change 2013). Rising sea levels are anticipated to increase the extent of saline (>30 parts per thousand or ppt salt) or brackish (0.5–30 ppt salt) water bodies in coastal areas. These include coastal estuaries, lagoons, marshes and mangroves (Nicholls et al. 2007). The salinity of estuarine systems is projected to increase, and their boundaries move further inland with more pronounced tidal water flows into rivers (Nicholls et al. 2007). A proportion of coastal wetlands such as salt marshes and mangroves are expected to become inundated, but additional saline wetlands are anticipated to form further inland (Nicholls et al. 2007). Rising sea levels and higher water withdrawal rates from freshwater aquifers near the coast by expanding populations are also envisaged to increase saltwater intrusion into the aquifers (FAO 2007).

The tropical areas of South and Southeast Asia have extensive coastlines bordering the Indian and Pacific Oceans and various seas. Southeast Asia also has the largest archipelago in the tropics. Indonesia and the Philippines with 248 and 104 million persons, respectively, are the two most populous countries in this archipelago (CIA 2012). Table 8.1 presents data on the length of the coastline in relation to the land area for Indonesia and the Philippines and selected other countries in the region. A comparison is made with the Federated States of Micronesia, a collection of about 600 small islands in the Western Pacific tropics. India on the other hand has a long coastline but a low coast to land area ratio compared to countries composed of many islands.

Countries in South and Southeast Asia with extensive coastlines and high coast to land area ratios are particularly vulnerable to the consequences of rising sea levels on their biosphere and geosphere. One in ten persons worldwide lives in coastal areas that are less than 10 m above sea level (McGranahan et al. 2007). Such areas are prone to increasing salinisation caused by rising sea levels. The densely populated tropical South and Southeast Asian countries have a large proportion of their

Table 8.1 Coastline related to land area in selected South and Southeast Asian countries and Micronesia

	Land area	Coastline	Coast/area ratio
Country/statistic	Km^2	Km	m/Km^2
Bangladesh	130,168	580	4.5
India	2,973,193	7,000	2
Sri Lanka	64,630	1,340	20.7
Malaysia	328,657	4,675	14.2
Indonesia	1,811,569	54,716	30.2
Philippines	298,170	36,289	121.7
Micronesia (Western Pacific)	702	6,112	8,710

Data from Central Intelligence Agency (2012)

populations living in such vulnerable areas. For example, Vietnam, Bangladesh, Thailand and Indonesia, respectively, have 55, 46, 26 and 20 % of their population living on land that is less than 10 m above sea level (McGranahan et al. 2007).

8.4 Mosquito Vector Development in Brackish and Saline Waters

Global warming can alter the transmission of mosquito-borne diseases. This is due to the effects of changing temperature on mosquito survival and pre-imaginal development and the more rapid development of ingested pathogens in mosquitoes and shorter intervals between blood meals at moderately higher ambient temperatures (Ramasamy and Surendran 2012). However, global warming will also raise sea levels, leading to an increase in saline and brackish water bodies in coastal areas. We recently drew attention for the first time to the possible impacts of rising sea levels on the transmission of vector-borne diseases (Ramasamy and Surendran 2011).

There are about 3,500 species of mosquitoes that are present throughout the world, but only a few hundreds of them feed on humans. The pre-imaginal stages of several mosquito vectors of human disease are able to develop in brackish or saline water habitats. Larvae of such salinity-tolerant mosquitoes possess specific physiological mechanisms to overcome high osmolarity in their surrounding (Bradley 1987). A relatively thick cuticle that is impermeable to water and ions helps pupae to survive salinity (Bradley 1987). Details of the more important vector mosquitoes that possess salinity-tolerant pre-imaginal stages in South and Southeast Asia are summarised in Table 8.2.

We have postulated that an expansion of brackish/saline water bodies in coastal areas associated with rising sea levels can increase densities of salinity-tolerant vectors and lead to the adaptation of freshwater vectors to breed in brackish and saline waters (Ramasamy and Surendran 2011). Higher vector densities can increase transmission of diseases in coastal localities, which can then spread to inland areas through bridging vectors (Ramasamy and Surendran 2011, 2012). Because the tropical countries in South and Southeast Asia possess many lagoons, coastal

Table 8.2 Common salinity-tolerant mosquito vectors of human disease in South and Southeast Asia

Species	Distribution	Transmitted pathogens
Aedes togoi	SE Asia	Japanese encephalitis virus and filarial parasites
Ae. (Ochlerotatus) vigilax	Australasia, SE Asia	Barmah forest and Ross River viruses and filarial parasites
Anopheles farauti and An. annulipes	Australasia, SE Asia	Malaria parasites
An. subpictus	S and SE Asia	Malaria and filarial parasites
An. sundaicus	S and SE Asia	Malaria parasites
Culex sitiens	S and SE Asia, Australasia	Japanese encephalitis and Ross River viruses and filarial parasites
Cx. tritaeniorhynchus	S Asia	Japanese encephalitis virus

Adapted from Walter Reed Biosystematics Unit (2013), Ramasamy and Surendran (2011)

marshes, mangroves and estuaries and many have extensive coastlines or a high ratio of coastline to land area, they are particularly susceptible to an increase in disease transmission caused by salinity-tolerant mosquito vectors.

Evidence that has been discussed in detail elsewhere (Ramasamy and Surendran 2011, 2012) supports this new perspective on coastal transmission of mosquito-borne diseases. In particular, the inland incursion of seawater caused by the 2004 Asian tsunami and the effect of draining coastal marshland in Western Europe provide specific supportive evidence (Ramasamy and Surendran 2011, 2012). *Anopheles culicifacies*, the predominant freshwater vector of malaria in South Asia, was recently shown to undergo pre-imaginal development in brackish waters in Sri Lanka (Jude et al. 2010). *Anopheles sundaicus*, a well-known salinity-tolerant malaria vector in Southeast Asia, is now reported to be widespread in coastal areas of Sri Lanka (Surendran et al. 2010, 2011). Many mosquitoes identified through morphology as *Anopheles subpictus* sibling species B, which is reported to be salinity tolerant in Sri Lanka and elsewhere in the region, have been shown to be members of the *An. sundaicus* complex by DNA sequencing (Surendran et al. 2010). *An. sundaicus* is able to develop in nearly saline water, but the physiological mechanisms responsible for this ability have not been determined. It is possible that a capacity to differentially localise Na^+/K^+ ATPase in rectal cells that permits osmoregulation through ion excretion as reported for *Anopheles albimanus* (Smith et al. 2008), a salinity-tolerant malaria vector in the Americas, may also be a feature of *An. sundaicus*. This requires experimental verification. Genetic selection for salinity tolerance over a period is possible in anopheline vectors because sibling species that differ in salinity tolerance are reportedly present in the *Subpictus*, *Sundaicus* and *Farauti* vector complexes of the region (Sinka et al. 2011). Maps of the recent distributions of the three vector complexes and the *Culicifacies* complex, whose members may also adapt to salinity, in South and Southeast Asia, are shown in Fig. 8.1. Mosquitoes of the *Subpictus, Sundaicus* and *Farauti* complexes are widely distributed in the region. A future expansion of brackish water habitats with rising

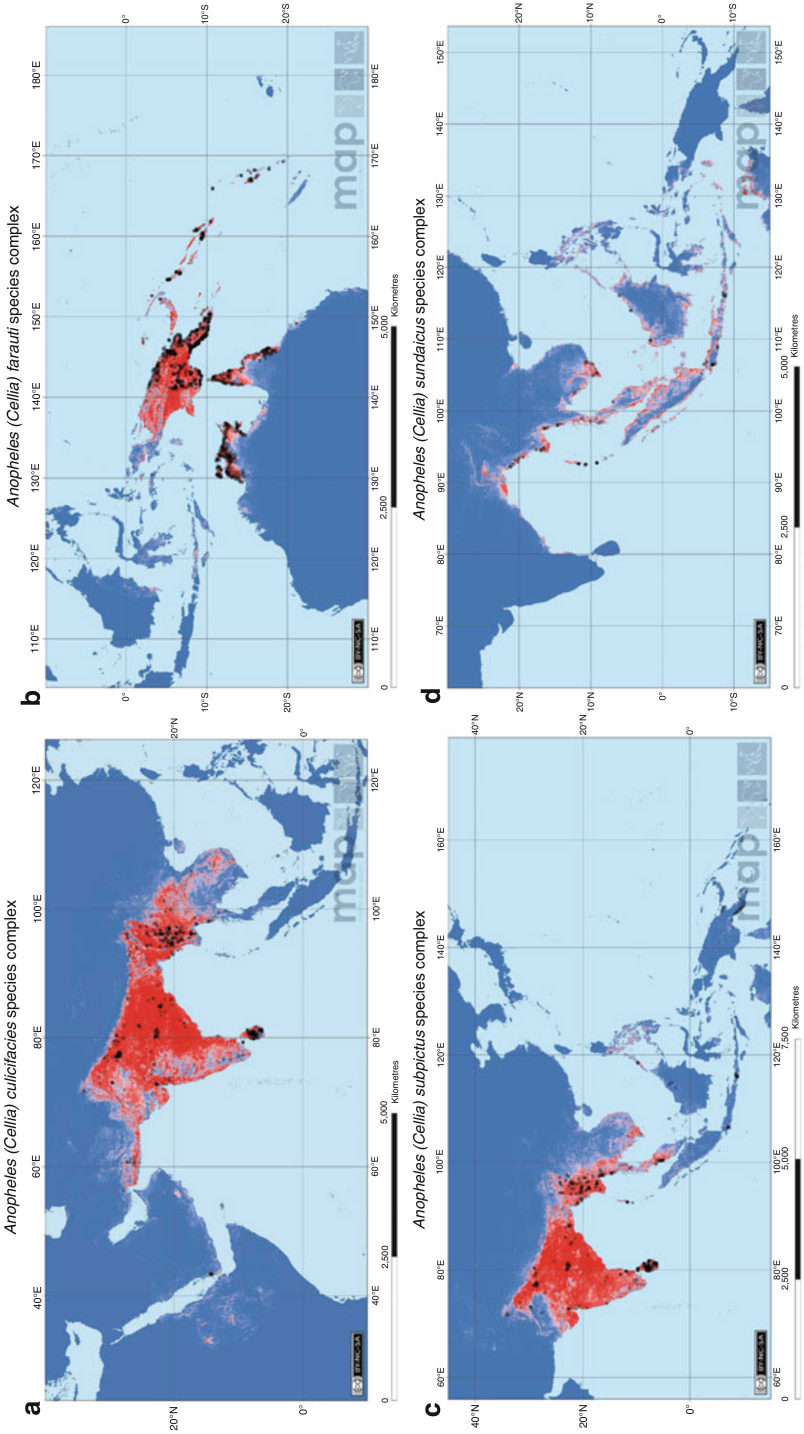

Fig. 8.1 The distributions of (**a**) *Anopheles (Cellia) culicifacies* species complex, (**b**) *Anopheles (Cellia) farauti species* complex, (**c**) *Anopheles (Cellia) subpictus* species complex in South and Southeast Asia (Reproduced with permission from Sinka et al. 2011, under the Creative Commons licence)

sea levels has the potential to increase malaria transmission by the salinity-tolerant members of the three complexes as well as brackish water-adapted freshwater species like *An. culicifacies*. This can increase the incidence and geographical spread of malaria in coastal areas that can subsequently be extended by bridging vectors to inland areas of the region.

We also recently showed that *Aedes aegypti* and *Aedes albopictus*, well known to be the vectors of dengue and chikungunya in the region, undergo pre-imaginal development in brackish water collections in coastal urban and peri-urban environments in the island of Sri Lanka (Ramasamy et al. 2011). Larvae and pupae were found in brackish water in discarded plastic and glass containers and disused boats and wells in beach areas. Figure 8.2 illustrates examples of such brackish water larval habitats. In the field surveys carried out in the northern and eastern provinces of Sri Lanka (Fig. 8.3), 17 % of brackish water containers in coastal beaches of Thannamunai in the eastern Batticaloa district were found to have *Ae. aegypti* and *Ae. albopictus* larvae, while 6 % of brackish water containers along the coast of Jaffna City in the north had *Ae. aegypti* larvae (Ramasamy et al. 2011). In Kurunagar, a coastal division of the city of Jaffna, 25 % of brackish water wells were found to have *Ae. aegypti* larvae in a salinity range of 2–9 ppt (Surendran et al. 2012). Such *Aedes* larval positivity rates in brackish water of up to 15 ppt salt in Jaffna (Ramasamy et al. 2011) are higher than the House Index (percentage of houses positive for *Aedes* larvae) or Breteau Index (number of containers with larvae per 100 houses) for freshwater habitats that have been typically associated with dengue epidemics in other countries (Sanchez et al. 2006). Pre-imaginal development in brackish water can play an unappreciated role in the transmission of dengue as

Fig. 8.2 Brackish water development habitats of *Aedes aegypti* and *Aedes albopictus* larvae in Sri Lanka. The photographs show the brackish water collections containing larvae in (**a**) and (**b**), disused boats; (**c**) and (**e**), abandoned wells; (**d**) and (**f**), discarded food and beverage containers (Reproduced with permission from Surendran et al. 2012)

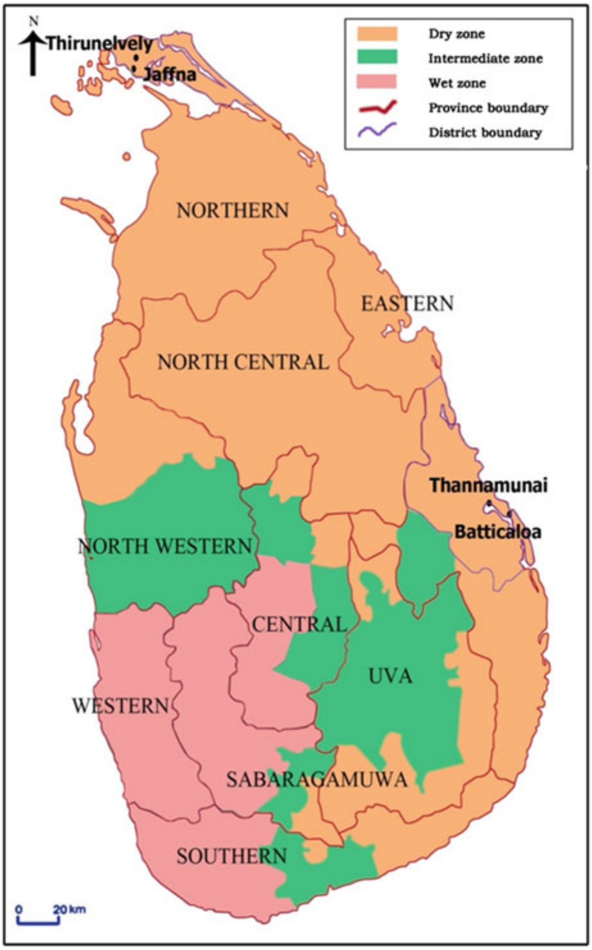

Fig. 8.3 Map of Sri Lanka showing the different provinces and the *Aedes* larvae collection sites in the Jaffna and Batticaloa districts. Sri Lanka is an island in the Indian Ocean with an area of 65,525 km^2 located between latitudes 5′55 and 9′50 North of the equator. The central hills of the island divide the surrounding plains into two distinct rainfall zones: the wet and dry zones. The wet zone receives an annual rainfall exceeding 2,500 mm in two main rainy seasons: the north-east monsoon in October–December and the south-west monsoon in May–July. Inter-monsoonal rains also occur in the wet zone. The dry zone, with an annual rainfall below 2,000 mm, receives maximal rainfall during the north-east monsoon and little or no rain during the rest of the year. An intermediate zone, with mixed characteristics, lies between the dry and wet zone. The *beige*, *green* and *pink* shaded areas show the dry, intermediate and wet rainfall zones, respectively (Reproduced with permission from Surendran et al. 2012)

dengue control efforts worldwide are presently directed only towards freshwater habitats of the two *Aedes* vectors because of the long and widely held view that they only develop naturally in freshwater (Barraud 1934; Chan et al. 1971; Kulatilaka and Jayakuru 1998; Ooi et al. 2006; WHO 2009, 2013c). The adaptation of

Ae. aegypti and *Ae. albopictus* to coastal brackish water habitats could have major consequences to human health since vaccines are presently not available against dengue and chikungunya that are increasing in incidence globally (Weaver and Reisen 2010). Small island countries like Singapore and Sri Lanka within the region have not been able to eliminate dengue despite well-resourced and long-established control programmes (Chan et al. 1971; Kulatilaka and Jayakuru 1998; Ooi et al. 2006). We hypothesise that the exclusive targeting of freshwater pre-imaginal habitats for vector source reduction and management until now has contributed to this failure. Our observations in Sri Lanka also suggest that *Ae. aegypti* and *Ae. albopictus* from different locations in the country may vary in their ability to tolerate salinity (Ramasamy et al. 2011). We observed that *Ae. albopictus* and *Ae. aegypti* first and third instar larvae from the Jaffna peninsula, where there is more extensive groundwater salinisation (Rajasooriyar et al. 2002), had significantly higher LC_{50} for salinity in developing into adults (11.9 and 13.0 ppt for first instar larvae of *Ae. aegypti* and *Ae. albopictus*, respectively) than the corresponding larvae from Batticaloa in mainland Sri Lanka (9.8 and 10.2 ppt for first instar larvae of *Ae. aegypti* and *Ae. albopictus*, respectively) (Ramasamy et al. 2011).

In Brunei Darussalam, which is 3,775 km away from Sri Lanka, we observed larvae of *Ae. albopictus* in discarded plastic food and beverage containers in beach areas in water with salinity of up to 8 ppt (Idris et al. 2013). The laboratory determined LC_{50} for the development of first instar *Ae. albopictus* larvae to adults in Brunei Darussalam in brackish water was approximately 9 ppt salinity (Idris et al. 2013). *Aedes aegypti* was however found in brackish water in a house from a water village on the Brunei river estuary (Ramasamy and Surendran 2013). The failure to detect *Ae. aegypti* pre-imaginal stages in brackish water containers along beaches in Brunei Darussalam may be due to the peri-urban nature of the beaches and the greater endophilicity of *Ae. aegypti* in Brunei Darussalam, a country that is less densely populated than the surveyed coastal areas of Sri Lanka. The observations in Brunei Darussalam and Sri Lanka suggest that the development of *Ae. aegypti* and *Ae. albopictus* in brackish water may be a widespread phenomenon in tropical countries that can contribute to dengue transmission.

We speculate that *Ae. aegypti* and *Ae. albopictus* may be evolving strains that are adapting to brackish water habitats in the urban or peri-urban environment by a process that may be driven by anthropogenic changes that increase such habitats, the exclusive application of larval control methods to freshwater habitats and the use of insecticides in mainly inland locations for agriculture and vector control. *Aedes albopictus* has spread from Asia to Africa, America and Europe since the 1980s (Rezza 2012). It recently caused a chikungunya epidemic in northern Italy and dengue transmission in southern France (Rezza et al. 2007; Cavrini et al. 2009; La Ruche et al. 2010). We hypothesise that salinity-tolerant and diapausing *Ae. albopictus* will further increase the potential for arboviral disease transmission in coastal areas of the temperate zone in Asia and elsewhere.

The physiological mechanisms that permit *Ae. aegypti* and *Ae. albopictus* to oviposit and for the eggs to hatch into larvae that then develop into adults are not known. Larvae of the American brackish water mosquito *Aedes taeniorhynchus*, a vector of Eastern equine encephalitis virus, osmoregulate by drinking the surrounding fluid and excreting Na+and Cl− from the posterior rectum to produce a hyperosmotic urine (Bradley 1987). Early laboratory studies show that *Ae. aegypti* larvae are able to tolerate a limited increase in salinity in their surroundings by increasing the concentrations of free amino acids and ions in their haemolymph in order to osmoconform to their environment (Edwards 1982). Recent evidence suggests that the pre-imaginal development of *Ae. aegypti* in brackish water of up to 15 ppt salinity in Sri Lanka is accomplished by a combination of reversible and irreversible physiological changes (Ramasamy et al. 2014).

Many tropical South and Southeast Asian countries are experiencing a rapid growth of populations living in coastal areas (McGranahan et al. 2007; UNEP 2007). Discarded containers along coasts that can accumulate brackish water and serve as habitats for the pre-imaginal development of mosquito vectors will become more common if refuse collection becomes increasingly inadequate because the relevant government authorities fail to cope with the rising need. Such a scenario, coupled with the application of mosquito control methods only to inland, urban and freshwater habitats, can favour the adaptation of vector mosquitoes to undergo pre-imaginal development in coastal brackish water habitats. This can additionally increase the prevalence of mosquito-borne diseases in the region.

The Jaffna peninsula is located at the apex of northern Sri Lanka (Fig. 8.3). Jaffna is traditionally an agricultural area with an extensive coastline. It is largely composed of sedimentary limestone of the Miocene period (Rajasooriyar et al. 2002), has a maximum altitude of 10.4 m and contains many lagoons and other seawater inlets. Almost all locations in the peninsula are <10 km from the sea, lagoon or other seawater inlets. Therefore, the entire peninsula may be considered to be a coastal zone. Dengue is endemic (Ramasamy and Surendran 2012, 2013), and there have been recent epidemics of malaria (Ramasamy and Surendran 2012, 2013) and chikungunya (Surendran et al. 2007) in the Jaffna peninsula. There are no reports of the local transmission of Japanese encephalitis and filariasis in the Jaffna peninsula in recent times although their respective primary vectors *Culex tritaeniorhynchus* and *Culex quinquefasciatus* are present in the peninsula (Rajendram and Antony 1991; Jude et al. 2012). Furthermore, the larvae of *Culex sitiens*, a known vector of arboviruses including the Japanese encephalitis virus, are present in domestic wells with salinity ranging from 10 to 20 ppt in the islands off the peninsula (Jude et al. 2012). We propose that the Jaffna peninsula is therefore a model location for studying the future impact of global climate change and rising sea levels on mosquito vector populations and disease transmission in tropical coastal zones of Asia. The availability of relevant expertise and resources in the University of Jaffna makes a systems-based approach for studying the primary and secondary effects of different climate change parameters, changing salinity and other ecological and socio-economic factors, on mosquito populations and disease transmission possible in the Jaffna peninsula.

In summary, several mosquito vector species that have traditionally been regarded as developing exclusively in freshwater habitats are now known to be able to undergo pre-imaginal development in brackish water in the peri-urban and urban

Table 8.3 Examples of freshwater mosquito vectors of human disease that are able to undergo pre-imaginal development in brackish water

Species	Location	Maximum salinity tolerance (ppt)	Reference
Aedes aegypti	Brunei Darussalam, Sri Lanka	10	Ramasamy and Surendran (2013)
		15	Ramasamy et al. (2011, 2014), Surendran et al. (2012)
Aedes albopictus	Brunei Darussalam	8	Idris et al. (2013)
	Sri Lanka	14	Ramasamy et al. (2011)
Anopheles culicifacies	India	7	Gunasekaran et al. (2005)
	Sri Lanka	4	Jude et al. (2010)
Anopheles stephensi	India	17	Gunasekaran et al. (2005)

environments. The data are summarised in Table 8.3. The relative contribution of brackish water-developing vectors, compared to vectors developing in freshwater habitats, towards disease transmission in coastal areas remains to be elucidated in detailed epidemiological studies. An analysis of dengue incidence in relation to rainfall in Jaffna and the rest of Sri Lanka is compatible with the hypothesis that brackish water vectors are a perennial source of dengue transmission and act as a virus source to help generate the increase in dengue transmission that follows soon after the onset of monsoonal rains (Ramasamy and Surendran 2013).

8.5 Impact of Increased Disease Transmission on Coastal Communities in South and Southeast Asia

Rising sea levels can therefore act synergistically with climate change and then interact in a complex manner with other environmental and socio-economic factors near coasts to generate a greater potential for the transmission of malaria, dengue and other mosquito-borne diseases. More than half the world's population lives within 60 km of a shoreline, and population densities in coastal areas will increase markedly in disease-endemic countries of the region (McGranahan et al. 2007; UNEP 2007). Growing numbers of people will therefore be at risk of acquiring infections from increasing vector populations in coastal areas. Greater host density, by increasing vector-host contact, will also contribute to an increase in disease transmission rates.

Factors such as climate, agricultural practice, forest cover, animal reservoirs of disease, efficiency of garbage collection in coastal locations and human population changes can influence the greater mosquito-borne disease transmission risk in coastal areas (Ramasamy and Surendran 2012). Higher incidence of such disease in coastal areas can serve as a focus to spread the disease inland through efficient freshwater vectors. The resulting health impacts may be particularly significant in the more resource-poor countries of the South and Southeast Asian region.

8.6 Mitigating Measures

Controlling the transmission of malaria, dengue and other mosquito-borne diseases and providing medical care to the corresponding patients consume a significant part of the health and national budgets of several South and Southeast Asian countries. This diverts scarce resources from improving medical services in other areas. Illness due to mosquito-borne diseases also reduces economic productivity. Therefore, improved control of dengue and other mosquito-borne diseases, through targeting brackish water larval habitats, is an important consideration for health authorities and governments in the region.

There is a clear need for supporting more research at local, national and international levels into the impact of rising sea levels and climate change on mosquito vector populations in coastal areas of the region. The impact of rising sea levels on the expansion of brackish and saline water bodies along coasts is subject to local geosphere factors, occurs over a timescale of decades and is therefore best studied at local levels. The bionomics of salinity-tolerant mosquito vector populations needs to be investigated in more detail. Present methods of identifying sibling species in malaria vector species complexes based on morphology or karyotyping have proved unreliable and unsuitable for field studies (Surendran et al. 2010). Robust and readily usable methods for differentiating sibling species that differ in salinity tolerance in the field need to be developed for different localities of the region. Mathematical models of disease transmission that take into consideration vector development in brackish water habitats have to be developed. The physiological mechanisms employed by mosquitoes such as *An. culicifacies* and *Ae. aegypti* that were considered to be freshwater species in adapting to brackish water need to be elucidated. Besides furthering knowledge on mosquito biology, this research can lead to the development of specific larvicides that can be used in brackish water habitats.

Therefore, greater attention needs to be devoted to monitoring disease incidence and mosquito vector development in coastal brackish and saline water habitats. Countermeasures to prevent an expansion of such habitats and reduce vector development therein are required. The extension of vector source reduction and management programmes to the brackish water habitats of the *Aedes* vectors of dengue and chikungunya is likely to immediately improve disease control in coastal areas. Pilot studies are needed in dengue-endemic areas to confirm this. Similarly, greater attention to brackish and saline water development of malaria vectors may also be helpful in further reducing malaria transmission in the region. Larval source reduction in defined habitats is effective in controlling dengue (WHO 2009) and malaria in many situations (Fillinger and Lindsay 2011). Managing and eliminating brackish water mosquito vector habitats may assume even greater importance in a future context of global warming, as sea levels rise and increase the extent of such habitats (Ramasamy and Surendran 2011, 2012). In this context, the stability and effectiveness of larvicides that are developed for freshwater use need to be examined in brackish and saline waters (Jude et al. 2012).

Community understanding and action have contributed to minimising freshwater larval development sites of dengue vectors in many disease-endemic countries. It is expected that this can be usefully extended to the brackish water habitats of the vectors. Governments can publicise the importance of brackish water mosquito vectors for transmitting disease through newspapers, radio, television and appropriate websites. This can include, for example, highlighting the additional importance of brackish water habitats of dengue vectors in national dengue awareness campaigns.

It is also important that the many local and national authorities responsible for different concerned sectors, e.g. health, agriculture, coastal planning, environment, irrigation, livestock development, etc., are made aware of the increased risk of mosquito-borne diseases in coastal areas due to rising sea levels, in order to incorporate it into their strategic development plans. Application of appropriate countermeasures can greatly reduce the potential for increased transmission of mosquito-borne diseases in coastal areas of South and Southeast Asia in the context of climate change and a rise in sea levels.

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