

H N P D I S C U S S I O N P A P E R

# Environmental Management for Malaria Control in the East Asia and Pacific (EAP) Region

Steve Lindsay, Matthew Kirby, Enis Baris and Robert Bos

April 2004





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CONTROL IN THE EAST ASIA AND  
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## Health, Nutrition and Population (HNP) Discussion Paper

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## Environmental Management for Malaria Control in the East Asia and Pacific (EAP) Region

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**Abstract:** Malaria attacks millions in the East Asia and Pacific (EAP) region, and greatly impedes economic development, particularly affecting the rural poor. In the early 1900s malaria was controlled in many parts of the region using environmental management (EM) for vector control. EM is where the environment is modified or manipulated to reduce malaria transmission by attacking local vector mosquitoes and requires an understanding of the ecology of these species. Today malaria control is based on drugs and insecticides, but their sustainability has been undermined by the development of resistance and growing concerns about the long-term environmental impact of some insecticides. EM would strengthen malaria control activities and be cost-effective. To be successful EM requires co-ordination and collaboration between different public sectors. This document presents the options that exist to minimize malaria risks associated with infrastructure development projects. It also aims to raise awareness of the wide array of opportunities that exist to design, construct and operate infrastructure as a sustainable means of reducing malaria transmission risks in specific settings. We make three major recommendations. Firstly, health impact assessments should be part of the planning process of all infrastructure projects, in order to identify, qualify and possibly quantify adverse health effects at the earliest possible stage and suggest remedies. Secondly, design and installation of infrastructure works that modify the environment or support environmental manipulation activities should become a significant part of malaria interventions in the EAP Region. The utility and cost-effectiveness of such interventions need to be researched and confirmed. Thirdly, in order to build an enhanced capacity for multidisciplinary research, there is a need to invest in training at a variety of levels.

Environmental management offers exciting new opportunities for sustainable malaria control throughout the EAP, not on its own, but as part of an integrated approach to malaria management.

**Keywords:** Environmental management, malaria, vector control, East Asia and Pacific Region

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## FOREWORD

The Global Strategy for Malaria Control, adopted in 1992 at the Amsterdam Ministerial Conference, outlines four strategic technical elements, including prevention and vector control. As efforts intensified following the 1999 launch of the Roll Back Malaria initiative by WHO, The World Bank, UNICEF and UNDP, the outside observer may have come to the conclusion that the global campaign against this killer disease relied exclusively on stepped-up case detection and treatment, and on the scaling up of the use of insecticide-treated nets (ITNs). Nothing is further from the truth. First of all, rolling back malaria is an all-inclusive endeavour and relies on the comparative advantages of a broad range of partners. Recent publications on the links between malaria and agriculture, and on the application of agricultural practices to reduce malaria transmission risks bear witness to this. And then, of course, there is the issue of sustainability, strongly embedded in the mission and vision of WHO's Department of Protection of the Human Environment.

If there is one lesson to be learned from the history of malaria control, it is that considering and ensuring the sustainability of control efforts and their results at the early planning stages is of the essence. Just like it is essential to consider the impacts on malaria that may result from major (or, cumulatively, from a number of minor) infrastructure projects. Failing to do so undermines investments in health and transfers hidden costs to the health sector. The present publication of The World Bank and the World Health Organization underpins all the above principles: partnership, acting upstream, integrated vector management approaches and the economic dimensions of malaria control.

We look forward to the continued collaboration with our World Bank colleagues towards a true and effective integration of malaria safeguards into the design and operations of infrastructure projects and to contributing jointly to sustaining achievements in malaria control.

*Margaret Chan*

Director

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## PREFACE

Despite its successful elimination from most of Europe and North America, malaria remains a major public health problem in much of the developing world. WHO estimates that 300 to 500 million cases of malaria occur each year, resulting in more than one million deaths. Although the overwhelming burden of morbidity and mortality rests on the people of sub-Saharan Africa, in the East Asia and Pacific Region, despite some progress during the last decade, malaria remains a major burden and a leading cause of mortality and morbidity for the poor and children in most countries. Goal 5 of the Millennium Development Goals is a direct response to this threat, to “Combat HIV/AIDS, malaria and other diseases” by halting and reversing the incidence of malaria by 2015.

Several countries in the EAP region such as China, Vietnam, Thailand, and Cambodia have renewed their efforts and made good progress in combating malaria. Malaria transmission has been interrupted in all but the most southernmost provinces of China. With these successes, though, come additional challenges. While most of the more traditional approaches have been successful in reducing mortality and morbidity, malaria still remains endemic in many mountainous and coastal areas with large populations at risk, especially those with high mobility such as seasonal workers. As overall burden decreases, cases become concentrated in certain socio-cultural groups or in limited geographic areas. In other circumstances, though, it is the local ecology and vector dynamics that put certain sub-populations at-risk.

This study goes beyond the boundaries of more traditional malaria control measures and advocates for integrated environmental management of malaria to minimize the risks posed by rural and infrastructure development whose impact to environment may also include increased vulnerabilities to malaria outbreaks. Environmental management can play an important adjunctive role to effective case management and personal protection measures in reducing the risk of malaria. The following report reviews the diversity of ecologic environments and vector dynamics found in the East Asia and Pacific Region and assesses the potential role for environmental management in the control of malaria. As the success of malaria control efforts in the region continue to accrue, environmental management will likely take on increasing importance in areas where standard control measures have had limited impact and in helping to prevent resurgence of malaria in areas where control measures have been successful.

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**Professor Lindsay** is a disease ecologist with a passion for studying some of the world's most important vector-borne diseases; chiefly malaria, lymphatic filariasis and trachoma. He has considerable experience in medical entomology, parasitology, ecology and clinical epidemiology and solves pure and applied problems in the laboratory and field using a wide range of techniques from DNA finger-printing and mathematical modelling, to methods used by social scientists, epidemiologists and biologists. His particular interest is in the design of simple tools for malaria control and he has carried out field research in The Gambia, Ethiopia, Tanzania, Thailand and Uganda over the last 17 years. He has published over 80 peer-reviewed papers, many in major international journals. He was in one of the leading group of researchers to demonstrate that insecticide-treated bednets protected children against malaria.

**Matt Kirby** is a post-graduate student in parasitology and medical entomology working on the physiological adaptations of the main African malaria vectors to different climates.

**Enis Baris** is a medical doctor with post-graduate training in epidemiology. Currently, he is Senior Public Health Specialist in the Europe and Central Asia Region of the World Bank where he works as Team Leader for health projects in Azerbaijan, Bulgaria and Turkey. He has worked extensively on health and development issues, including HIV/AIDS, tuberculosis and tobacco control, in East Asia with the World Bank and, previously, in Canada and with the World Health Organization. His interest in malaria stems from his earlier involvement in malaria eradication in Turkey where he first realized the importance of environmental management as an effective, sustainable and socially acceptable control measure.

**Robert Bos** is a public health biologist responsible for the human health aspects of water resources development and management in the WHO programme on Water, Sanitation and Health. In the 1980s and 1990s he coordinated the activities of the joint WHO/FAO/UNEP Panel of Experts on Environmental Management for Vector Control (PEEM). His current portfolio includes Health Impact Assessment of water resources development, promotion of intersectoral collaboration for health in irrigation and dam projects, both at policy and operational levels, and the pursuit of synergies between nature conservation (wetlands, biodiversity) and community health goals.



## ABBREVIATIONS

ADB	Asian Development Bank
DALYs	Disability Adjusted Life Years
DDT	Dichloro-diphenyl trichloroethane
EAP	East Asia and Pacific
EHP	Environmental Health Project of USAID
GDP	Gross Domestic Product
GIS	Geographic Information Systems
GMS	Greater Mekong Subregion
HIA	Health Impact Assessments
IDRC	International Development Research Centre of Canada
IEC	Information, education and communication
IRS	Indoor Residual Spraying
ITN	Insecticide-Treated Nets
IVM	Integrated Vector Management
IWMI	International Water Management Institute
MDG	Millennium Development Goals
MIM	Multilateral Initiative on Malaria
NGOs	Non-Governmental Organisations
PEEM	Panel of Experts for Environmental Management
POPs	Persistent Organic Pollutants
P.f.	Plasmodium falciparum
PNG	Papua New Guinea
RBM	Roll Back Malaria
SEA	South East Asian Region
SIMA	Systemwide Initiative on Malaria and Agriculture
SP	Sulfadoxine-pyrimethamine
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNICEF	United Nations Children's Fund
USAID	United States Agency for International Development
VBD	Vector Borne Diseases
WB	World Bank
WHO	World Health Organization



## EXECUTIVE SUMMARY

### Box 1

#### What is Environmental Management for Vector Control?

Environmental management for vector control aims to induce changes in ecosystems that help reduce their receptivity to the propagation of disease vectors. Disease vectors are organisms that play a key role in the transmission of certain diseases. Such vector-borne diseases (VBD) include malaria, yellow fever, schistosomiasis (bilharziasis), filariasis and plague. The vast majority of vectors are blood-sucking insects, of which mosquitoes are the best-known group because they transmit malaria. These diseases place a heavy burden on local populations and have dire consequences for the economies of endemic countries.

The distribution of VBD depends directly on the ecological requirements of the local vector species. Very often, the aquatic environment is of critical importance to their life cycle. Environmental management for vector control therefore frequently aims at introducing changes in the local hydrology or in water-use practices. Conversely, development projects of an infrastructural nature (and water resources development projects stand out in this connection) may inadvertently lead to changes in the environment that result in a deterioration of the VBD situation.

A distinction is made between environmental modification and environmental manipulation. Modification implies permanent changes such as landscaping, drainage, land reclamation and filling. It will often entail minor or major infrastructural works and requires significant capital investment. Manipulation is a recurrent activity, requiring proper planning and operation, such as removing aquatic weeds from irrigation and drainage canals. In agro-ecosystems, environmental manipulation can often be incorporated into conventional agricultural practice. Its costs are usually modest but recurrent. Many environmental manipulation operations require infrastructural development.

Environmental management for vector control is not intended to replace other control strategies. Rather, it provides a basis for other methods, such as chemical control, to build on in a complementary fashion, while reducing the environmental costs and resistance risks incurred by excessive use of insecticides. It also adds resilience to the results of control programmes, important at times of economic instability or social unrest. Clear decision-making criteria and procedures in an Integrated Vector Management (IVM) framework will ensure the most cost-effective combination of measures for each local situation. Environmental management for vector control is a particularly powerful approach in the context of development projects, especially those of an infrastructural nature (dams, irrigation schemes, roads and railroads, airports, flood control projects and urban development). These usually offer important opportunities to minimise adverse effects for the health of local and resettled populations and, indeed, to promote their health status in an efficient and sustainable manner.

For detailed descriptions of environmental management the reader is advised to refer to the 'Manual on Environmental Management for Mosquito Control' produced by WHO <sup>3</sup>.

## BACKGROUND

### ***Malaria***

Malaria is a major impediment to economic development in the East Asia and Pacific (EAP) Region affecting the lives of millions of people. This debilitating infection is spread by anopheline mosquitoes and is caused by two species of protozoans, *Plasmodium falciparum* and *P. vivax*. Falciparum malaria is potentially lethal, whilst vivax malaria is more benign. Today malaria control in this region is based on the sensible strategy of rapid treatment of cases with effective antimalarials and the protection of individuals from infective mosquitoes using insecticide-treated bednets (ITN) or indoor spraying. Alongside this approach, the development of a cheap and effective vaccine is seen as a major strategic goal in the fight against this deadly disease (<http://www.mosquito.who.int>). New drugs, insecticides and vaccines are all welcome additions to the armamentarium against malaria, but little attention has been given to alternative strategies to reduce the burden of disease. This is surprising considering major reductions in mortality from infectious diseases, including malaria, in Europe and North America occurred well before the introduction of effective drugs and vaccines<sup>4</sup>. The principal aim of this report is to review the scientific literature, project reports and other relevant sources to show that from today's perspective environmental management has an important role in malaria prevention and control now and in the future.

### ***Environmental management***

In the early 1900s the control of both falciparum and vivax malaria in parts of the EAP Region was highly successful largely as result of environmental measures for the control of mosquito larvae (for descriptions of environmental management see Box 1). This concept was based on the pioneering work of Watson in Malaysia who demonstrated the importance of environmental modification by showing that selective clearing of the forest around settlements could control the mosquito *Anopheles umbrosus*, a forest vector, resulting in the elimination of malaria<sup>5,6</sup>. Thereafter, environmental management was used widely in South-East Asia, with the advantage that it could be applied with relatively few skills and local technology (see Annex II for a brief review of the history of environmental management in the EAP).

Environmental management fell off the malaria control agenda when DDT became the main tool for the World Health Organization's (WHO) malaria eradication programme from 1956-67. Here was a relatively cheap and highly effective product for residual house-spraying against malaria vectors<sup>7</sup> that promised an end to malaria. This period also coincided with a shift from health protection and promotion in an integrated rural development context, based on sound ecological principles, to a vertical control programme, lodged solely in the health sector, where the research assessment focused largely on the resting habits of vectors and their susceptibility to insecticides. Such was the faith in DDT that all other control measures were sidelined and forgotten. Since the failure of this campaign to sustainably eliminate malaria from the tropics, the effectiveness of environmental management has remained tragically under-exploited.

### ***Macro-economic perspective of malaria***

Malaria costs lives and money. And where the disease thrives economies suffer<sup>8</sup>. There is a striking correlation between a country's per-capita gross domestic product (GDP) and malaria that demonstrates that malaria endemic countries suffer from lower rates of economic growth. Thus the average per capita GDP in malarious countries in 1995 was more than five fold lower than countries with little or no malaria (US\$ 1,526 vs 8,268). Moreover, economic growth was

considerably lower in malaria-endemic countries from 1965-1990 than other countries (average annual GDP growth US\$ 0.4% vs 2.3%). In addition to the impact on GDP there is also the significant cost to the health sector that in itself will impact on the macro-economics of individual countries. Malaria impedes the development of a country's population in a complex manner, restricting population growth, reducing savings, economic investment and the productivity of the workforce, as well as causing premature death – thus it has many direct and indirect health costs. Future prospects for the control of malaria are not encouraging, as it has been estimated that without effective interventions the number of malaria cases is likely to double in the next 20 years<sup>9</sup>

Drugs and insecticides are needed to attack malaria today and in the near future, but they are unlikely on their own to be long-term solutions to the growing problem of malaria. Environmental management needs to be considered a central pillar of malaria control that all other activities are linked to in an integrated fashion, informed by accurate ecosystem analyses.

## **MALARIA SITUATION IN THE EAST ASIA AND PACIFIC REGION**

The EAP Region is a classification of countries used by the World Bank (see footnote 1) which extends from the Mongolian plateau in the north, south across China and the Malay Peninsula, sweeping across the Indonesian archipelago and other islands in the South China Sea to Fiji, Samoa and Tonga in the south-east (Figure 1).<sup>1</sup>

**Figure 1. East Asia and Pacific (EAP) Region**



<sup>1</sup> The WHO uses a different classification to the World Bank EAP Region: the South-East Asia Region including Bangladesh, Bhutan, Democratic People's Republic of Korea, India, Indonesia, Maldives, Myanmar, Nepal, Sri Lanka & Thailand and the Western Pacific Region including Australia, Brunei Darussalam, Cambodia, China, Cook Islands, Fiji, Japan, Kiribati, Lao People's Democratic Republic, Malaysia, Marshall Islands, Federated States of Micronesia, Mongolia, Nauru, New Zealand, Niue, Palau, Papua New Guinea, Philippines, Republic of Korea, Samoa, Singapore, Solomon Islands, Tonga, Tuvalu, Vanuatu & Viet Nam.

## **MALARIA ECOTYPES IN THE EAP REGION**

Malaria transmission is highly variable across the region depending on the local ecology and social environment. Despite this variability, malaria can be broadly classified into a number of distinct epidemiological types, which are modified from a classification made by WHO (WHO; Table 1)<sup>10</sup>. It should be appreciated that these are broad generalisations intended to give the reader an overview of the principal characteristics of malaria in the EAP region. In reality the picture is more complex and depends on the local setting.

## **LOCAL VECTORS AND THEIR ECOLOGICAL REQUIREMENTS**

Knowledge of the composition (see Table 2) and biting habits of anopheline mosquitoes associated with malarious areas is crucial to the establishment of effective vector control programmes. This is especially important in the EAP Region since it has a large number of potential vector species. Readers should consult Annex III for details of the local vectors in individual countries in the EAP Region and their ecological requirements. These can be broadly summarized into four main ecological zones (Table 2) and illustrates the complexity of malaria transmission in this region, with each mosquito species adapted to specific environmental conditions. A country by country list is also provided for further clarification (Table 3).

**Table 1. Major epidemiological types of malaria in the EAP Region<sup>10</sup>.**

Malaria type (main occurrence)	Characteristics	
	Epidemiological	Operational
Malaria of plain & valleys (Indian subcontinent, China)	<ul style="list-style-type: none"> <li>• Variable, mainly moderate transmission.</li> <li>• <i>P. vivax</i> may predominate.</li> <li>• Strong seasonal variation.</li> <li>• Risks of epidemics.</li> <li>• Drug resistance generally well established.</li> </ul>	<ul style="list-style-type: none"> <li>• Large-scale insecticide spraying programmes often ineffective.</li> <li>• Inadequate disease management.</li> <li>• Insufficient general health services and private services in some areas.</li> </ul>
Savannah malaria (Papua New Guinea)	<ul style="list-style-type: none"> <li>• Perennial transmission, with seasonal variations away from equator. <i>Plasmodium falciparum</i> predominates.</li> <li>• Morbidity &amp; mortality mainly in young children &amp; pregnant women.</li> <li>• Expansion of drug resistance.</li> </ul>	<ul style="list-style-type: none"> <li>• Insufficient coverage by health services.</li> <li>• Malaria control programmes most often rudimentary.</li> </ul>
Coastal malaria (Malaysia, Indonesia)	<ul style="list-style-type: none"> <li>• Variable rates of transmission.</li> </ul>	<ul style="list-style-type: none"> <li>• Insufficient general health services and private services in some areas.</li> <li>• Malaria control programmes most often rudimentary.</li> </ul>
Forest malaria (Thailand)	<ul style="list-style-type: none"> <li>• Variable, mainly moderate transmission.</li> <li>• <i>P. vivax</i> may be common.</li> </ul>	<ul style="list-style-type: none"> <li>• Large-scale insecticide spraying programmes often ineffective.</li> <li>• Inadequate disease management.</li> <li>• Insufficient general health services and private services in some areas.</li> </ul>
Highland malaria (South-East Asian highlands, South-West Pacific)	<ul style="list-style-type: none"> <li>• Risk of epidemics due to climatic extremes, changing agricultural practices or migration to malarious areas.</li> </ul>	<ul style="list-style-type: none"> <li>• Presence of health services variable.</li> <li>• Preparedness for management of malaria cases may be poor in habitually malaria-free areas.</li> <li>• Terrain, distances and precipitation present obstacles to malaria control.</li> </ul>
Agricultural development projects	<ul style="list-style-type: none"> <li>• Increased transmission due to irrigation, in certain circumstances e.g. rice cultivation.</li> <li>• Risk of seasonal malaria outbreaks due to attraction of non-immune labourers.</li> </ul>	<ul style="list-style-type: none"> <li>• Insecticide-resistance frequent in cotton-growing areas.</li> <li>• Some financial resources are available for malaria control.</li> </ul>
Urban & periurban malaria	<ul style="list-style-type: none"> <li>• Transmission &amp; population immunity highly variable over short distances.</li> <li>• Epidemics caused by specially adapted vectors.</li> </ul>	<ul style="list-style-type: none"> <li>• Relatively good coverage by health services.</li> <li>• Variety of antimalarial drugs available from different sources.</li> <li>• High human population density.</li> <li>• Breeding sites readily identifiable.</li> </ul>

**Table 2. Major zones of malaria and their vectors, after Service<sup>11</sup>**

Zone	Area covered	Vectors
Indo-Chinese Hills	A triangular area including the Indo-Chinese peninsula, the north western fringe beyond the Tropic of Cancer	<i>An. nigerrimus</i> <i>An. annularis</i> <i>An. culicifacies</i> <b><i>An. dirus</i></b> <b><i>An. fluviatilis</i></b> <i>An. jeyporiensis</i> <i>An. maculatus</i> <b><i>An. minimus</i></b>
Malaysian	Most of Indonesia, Malaysian peninsula, Philippines & Timor	<b><i>An. campestris</i></b> <b><i>An. donaldi</i></b> <b><i>An. letifer</i></b> <b><i>An. nigerrimus</i></b> <i>An. whartoni</i> <b><i>An. aconitus</i></b> <b><i>An. balabacensis</i></b> <b><i>An. dirus</i></b> <b><i>An. flavirostris</i></b> <i>An. jeyporiensis</i> <b><i>An. leucosphyrus</i></b> <b><i>An. ludlowae</i></b> <b><i>An. maculatus</i></b> <i>An. mangyanus</i> <b><i>An. minimus</i></b> <i>An. philippinensis</i> <b><i>An. subpictus</i></b> <b><i>An. sundaicus</i></b>
Chinese	Largely the coast of China, Republic of Korea, Taiwan and Japan	<b><i>An. anthropophagus</i></b> <b><i>An. sinensis</i></b> <i>An. balabacensis</i> <i>An. jeyporiensis</i> <i>An. pattoni</i>
Australasian	Northern Australia, Papua New Guinea and the islands east of it to about 175° east of Greenwich, except for the malaria-free zone of the south-central Pacific	<i>An. bancrofti</i> <b><i>An. farauti</i></b> <i>An. hilli</i> <i>An. karwari</i> <b><i>An. koliensis</i></b> <b><i>An. punctulatus</i></b> <i>An. subpictus</i>

Species shown in bold are primary vectors, the rest are secondary vectors.

**Table 3. Malaria vectors in the EAP Region**

Country	Anopheles vector																												
	An. aconitus	An. annularis	An. anthropophagus	An. b. balabacensis	An. barbrositis	An. campestris	An. culicifacies	An. dirus	An. donaldi	An. farauti	An. flavirostris	An. jeyporiensis	An. koliensis	An. leifer	An. leucosphyrus	An. litoralis	An. maculatus	An. mangyanus	An. nitinus	An. nimpe	An. niviipes	An. philippinensis	An. punctulatus	An. sinensis	An. subpictus	An. sundalcicus	An. umbrosus	An. vagus	An. varuna
Cambodia				♂											♂		♂			♂						♂			
China			♂																	♂				♂					
East Timor	♂	♂		♂	♂						♂						♂								♂	♂			
Indonesia	♂	♂		♂	♂					♂	♂		♂		♂		♂		♂				♂	♂	♂	♂	♂		
Korea																								♂					
Lao PDR	♂							♂									♂		♂		♂								
Malaysia	♂			♂		♂			♂	♂				♂	♂		♂								♂	♂			
Myanmar	♂	♂					♂	♂															♂			♂			
Papua N. G.										♂			♂											♂					
Philippines				♂							♂					♂	♂	♂											
Solomon Is.										♂			♂											♂					
Thailand	♂							♂									♂		♂		♂	♂				♂			♂
Vanuatu										♂																			
Viet Nam	♂						♂	♂				♂					♂		♂	♂					♂	♂		♂	♂

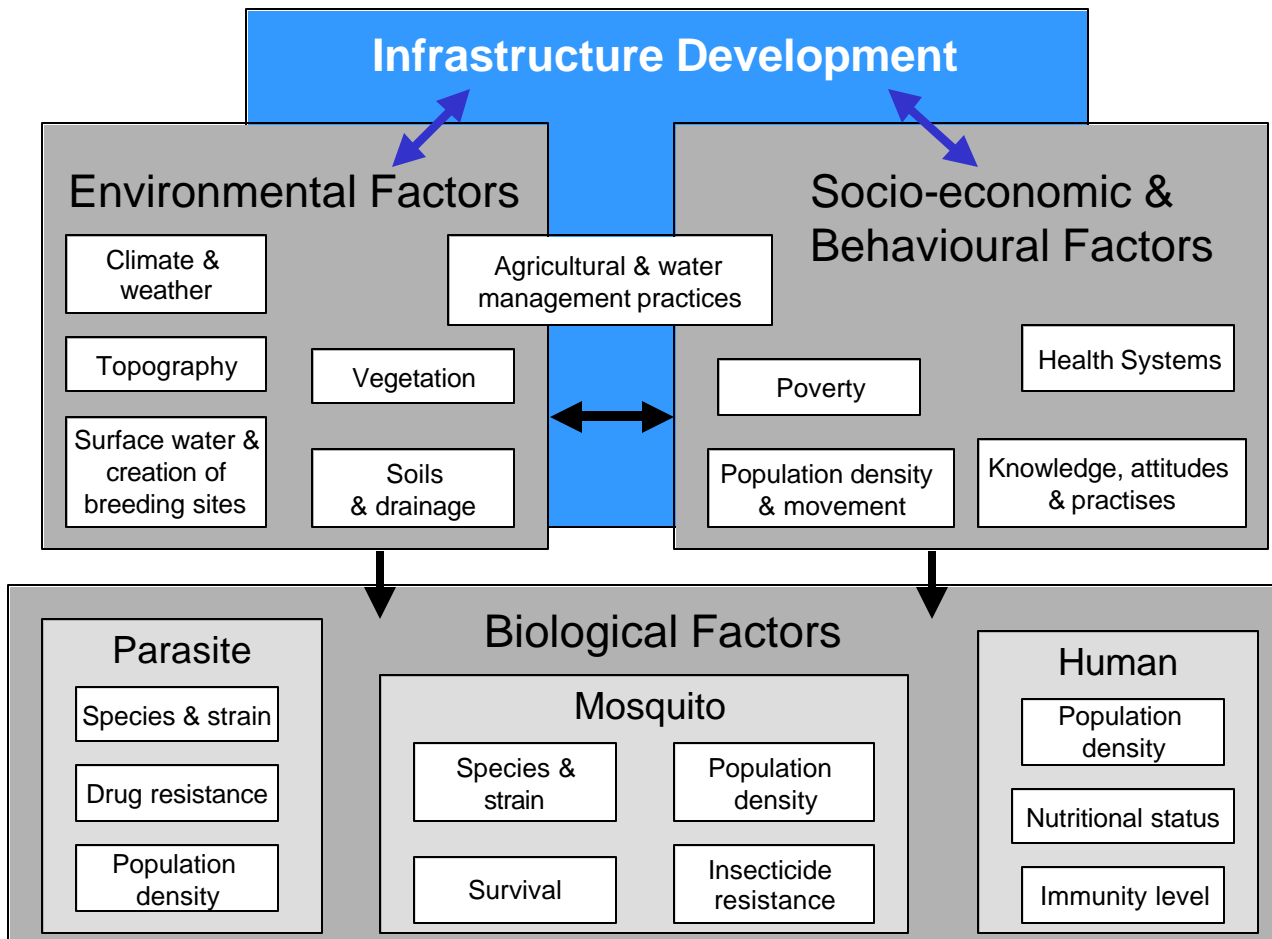
Where ♂ is a minor vector and ♂ is a major vector of malaria.

## CONTEXTUAL DETERMINANTS OF MALARIA

The factors that govern the ecology of malaria are many and varied and depend on local conditions. These factors are known as the contextual determinants of malaria and fall into three broad categories (Figure 2): environmental, socio-economic and biological. These broad areas operate at a range of spatial and temporal scales, further increasing the complexity of the local ecology of malaria. What is fundamental here is the overwhelming importance of economic factors that drive malaria. Much of malaria is man-made, where the breeding habitats of vector mosquitoes are created by human activity, such as road building and the construction of irrigation networks. Those at greatest risk of malaria are the poor and vulnerable that live in poorly-

constructed housing that often increases their risk of infection, and which have poor nutrition and poor access to effective health care.

**Figure 2. Contextual determinants of malaria, modified from<sup>12</sup>**



## STATUS OF MALARIA AND FUTURE TRENDS

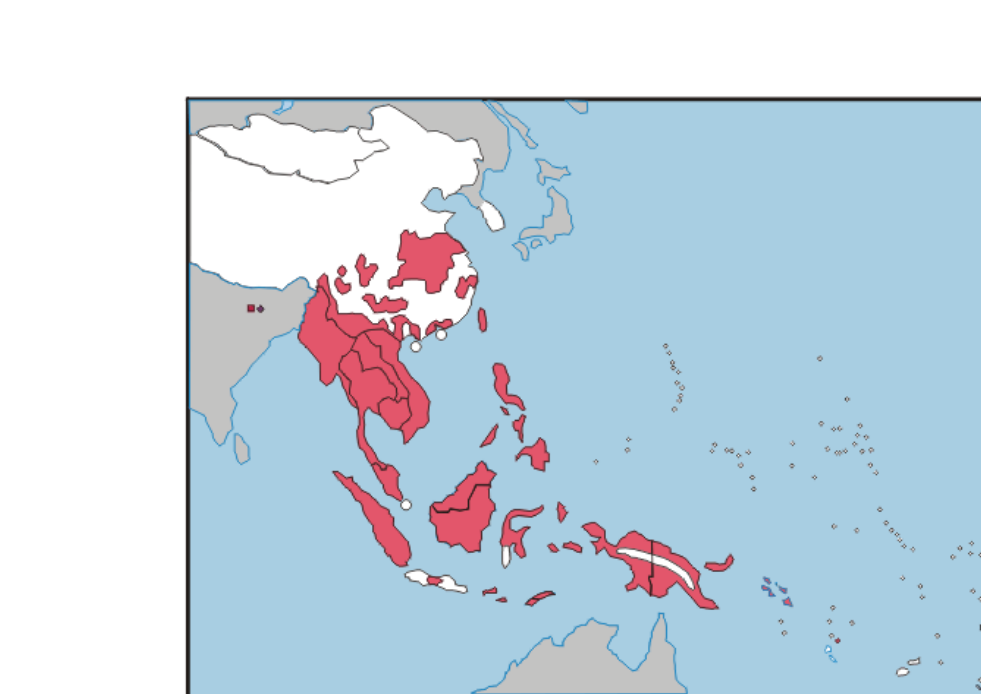
Data collated by WHO suggest that there were 2.8 to 3.7 million malaria cases in the South-East Asia (SEA) region in the last five years (<http://mosquito.who.int>, 24.11.02), whilst our analysis for EAP (SEA, excluding countries on the Indian sub-continent) indicates that this may be substantially higher (Table 4). In practice the quality of data across this region is highly variable, and often reliant on educated guesswork, so these figures should be treated with a degree of caution. Nonetheless it is clear that malaria represents a substantial threat to many communities across the region (Figure 3) and is **getting worse**<sup>10</sup>.

## Box 2

### Disability adjusted life years (DALYs)

The DALY is a summary measure of population health<sup>13,14</sup>. DALYs capture the number of years lost through dying early, after adjusting for the severity of the disability. It is a useful measurement since it can be used for comparing the cost-effectiveness of different interventions and for making broad comparisons between the seriousness of different diseases or other disabilities. Statistics from WHO show that in 2001 malaria accounted for 3,327,000 DALYs in those South-East Asian countries with high child and adult mortality (i.e. Bangladesh, Bhutan, Democratic People's Republic of Korea, India, Maldives, Myanmar & Nepal), 353,000 DALYs in those with low child and adult mortalities (i.e. Indonesia, Sri Lanka & Thailand) and 409,000 DALYs in countries in the Western Pacific with high child and adult mortality (i.e. Cambodia, China, Cook Islands, Fiji, Kiribati, Lao People's Democratic Republic, Malaysia, Marshall Islands, Federated States of Micronesia, Mongolia, Nauru, Niue, Palau, Papua New Guinea, Philippines, Republic of Korea, Samoa, Tonga, Tuvalu, Vanuatu & Viet Nam). Information on the cost-effectiveness of different malaria control interventions is sparse, but is urgently needed in order to make evidence-based decisions about the most cost-effective methods of control<sup>15</sup>.

**Figure 3. Malaria in the EAP Region.** Malaria endemic areas shown in red.



Since most malaria vectors require relatively clean water in which to develop, malaria is predominantly a disease of rural and peri-urban areas, largely affecting the poor. Moreover, many infrastructure projects introduced into the countryside have frequently been blamed for increasing the risk of malaria to local communities, since they can create aquatic habitats suitable for anopheline mosquitoes, the vectors of malaria<sup>16-19</sup>. This is particularly important since most

malaria in the EAP Region is due to infection with *Plasmodium falciparum*, the potentially life-threatening parasite, rather than the more benign *P. vivax*.

Today the main focus of national malaria control programmes in much of the EAP Region is indoor-spraying with residual insecticides, including DDT, although insecticide-treated nets (ITNs) are increasingly popular. Environmental management may be mentioned as an activity included in a country's malaria control strategy, such as in Lao P.D.R.<sup>20</sup>, Malaysia<sup>21</sup>, Thailand<sup>22,23</sup>, but in practice little is carried out. For certain there is no question of true integration, based on a sound ecosystem analysis, with clear criteria and decision-making procedures, which considers the composition of the package of vector control measures at a given place and on a given time. The reason for this is that malaria control organizations lack the flexibility and training for effective adaptive management; which requires making frequent changes and establishing institutional arrangements to overcome intersectoral barriers.

Despite the general recognition that malaria is a big problem, it is considered to be the sole responsibility of the health sector to control the disease. There is an almost complete lack of any development towards integrated approaches that involve other sectors in prevention and control. This is an opportunity lost.

**Table 4. Burden of malaria in EAP**

Country in the EAP Region	Population (mill.) <sup>#</sup>	Population at risk (mill.)	<i>P.f.</i> (%)	Clinical malaria cases	Confirmed malaria cases	Reported deaths/year	\$US GNI/capita <sup>+</sup>	Healthy Life expectancy (yrs) <sup>-</sup>
Cambodia	13.1	3.5	88	140,800	62,400	608	260	47.1
China	1,282.4	3.7	10	18,600	18,600	39	840	62.1
East Timor	0.7	0.7	85	-	-	-	-	-
Fiji	0.8	0		-	-	-	1,820	59.6
Indonesia	212.1	150	46	6,000,000		700	570	57.4
Kiribati	0.08	0		-		-	950	53.6
Korea, Rep.	46.7	1.9	0	4,142	-	1	8,910	66.0
Lao PDR	5.3	4.2	80	40,000	40,000	350	290	44.7
Malaysia	22.3	-	49	12,700	12,700	35	3,380	61.6
Marshall Islands	0.05	0		-	-	-	1,970	56.1
FS Micronesia	0.2	0		-	-	-	2,110	56.6
Mongolia	2.5	0		-	-	-	390	52.4
Myanmar	47.7	36.8	85	480,000	-	2,943	-	49.1
Palau	0.02	0		-	-	-	-	57.7
Papua New Guinea	4.8	3.96	75	1,585,000	81,200	617	700	46.8
Philippines	75.7	10.8	70	334,400	36,600	536	1,040	59.0
Samoa	0.2	0		-	-	-	1,450	59.9
Solomon Islands	0.4	0.4	70	68,000	68,000	38	620	59.0
Thailand	62.8	30	50	92,000	-	-	2,000	59.7
Tonga	0.09	0		-	-	-	1,660	60.7
Vanuatu	0.2	0.19	50	31,200	6,400	0	1,150	56.7
Viet Nam	78.1	41.9	70	293,000	74,000	148	390	58.9
<b>Total</b>	<b>1856.24</b>	<b>108.05</b>		<b>9,099,842</b>				

<sup>-</sup> 2000 figures total population at birth (WHO Statistical Information System)

<sup>+</sup> 2000 figures (World Bank national accounts data & OECD national accounts data figures)

<sup>#</sup> Source: FAO statistical data

<sup>\*24</sup> \*\*Estimated. (*P.f.* is *Plasmodium falciparum*)

## THE INTERNATIONAL POLICY FRAMEWORK

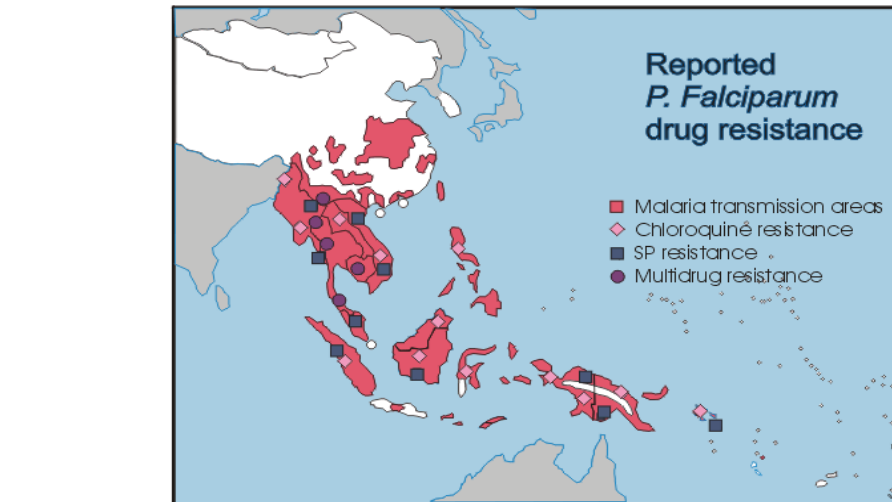
The international community is committed to reducing malaria in the EAP Region and other parts of the tropics. Roll Back Malaria (RBM) is a partnership founded by WHO, the United Nations Children's Fund (UNICEF), United Nations Development Programme (UNDP) and the World Bank (WB). It operates as a broad network of many partners who all subscribe to the same principles and objectives. Each partner has maximum opportunities to contribute its comparative advantages to the partnership's endeavours. The strategic goals of RBM date back to the 1992 Amsterdam malaria declaration. The main aim of RBM is to halve the global malaria burden by 2010 ([www.rbm.who.int](http://www.rbm.who.int)). It is hoped that this ambitious goal can be achieved by promptly and effectively treating clinical cases of malaria, preventing malaria infections and improving treatment of the disease during pregnancy, promoting the use of ITNs to reduce exposure to malaria parasites and improving the control of malaria in emergency and epidemic situations. This is an **excellent** short-term strategy for reducing the burden of malaria rapidly throughout the world, although there are serious obstacles to its long-term sustainability partly because the programme does not allow for the effects of natural selection. Malaria parasites and the anopheline vectors that transmit them have extremely high rates of reproduction with a considerable capacity to generate diversity through sexual reproduction. When challenged by an aggressive molecule some individual parasites or mosquitoes will be innately resistant and survive. Since these genes are more likely to survive they will spread through the parasite or vector population, providing the challenge from the anti-parasite or anti-mosquito molecules are maintained. Considering the wide spread use of antimalarials in the EAP Region it is not surprising that the biggest problem facing the control of malaria is the rise of multiple drug-resistant malaria (Figure 4).

In further support of these efforts, specific reference to malaria has been included in the Millennium Development Goals (MDG), which were agreed by 170 Heads of State at a special session of the UN General Assembly in 2000 ([www.undp.org](http://www.undp.org)). Three of the eight MDGs deal with health. MDG 6, Combat HIV/AIDS, malaria and other diseases, has as its target: by 2015, halt and begin to reverse [...] the incidence of malaria and other major diseases. At the same time, MDG 7 aims to ensure environmental sustainability and even though its 2015 targets address environmental integrity and safe drinking water supply and sanitation, it implicitly covers the need for environmental management approaches in health. The significance of the MDGs lies in the agreement of Heads of State, setting the framework for a collective responsibility of all public sectors to comply with them and make substantial contributions. Agriculture, energy, mining, industry and others are therefore compelled, under this agreement, to join forces with the health sector in the fight against malaria.

### CONCEPTS OF RESISTANCE

Over the last 30 years, strains of malaria parasites resistant to a number of different antimalarials have spread around the world<sup>25</sup>, paralleled by the development of insecticide-resistance in mosquitoes<sup>26</sup>. The rapid development and spread of resistant organisms demonstrates that evolution cannot be halted and that chemical methods of malaria control are difficult or impossible to sustain in the long term. It is therefore timely to reconsider the role of environmental management as part of an integrated programme against malaria vectors. Importantly environmental management should help reduce our dependence on antimalarials and insecticides, hence delaying the emergence of resistant parasites and insects. Such a strategy will be effective, sustainable and economic. It is also appropriate to test environmental management in the EAP Region where transmission is generally low and therefore more amenable to control.

**Figure 4. Antimalarial drug resistance in the EAP Region**



#### **DRUG RESISTANCE**

There is an urgent need to restrict the spread of multiple-drug resistant strains and develop new drug combinations and therapies for the treatment of this disease. Whilst effective drugs are available, they are expensive and may not be used routinely throughout the region. But even if they become more affordable, resistance is likely to emerge because of the large number of people infected with parasites, the treatment of many cases of fever unrelated to malaria with antimalarials and the failure of patients to complete a full course of drugs. The problem of drug-resistant malaria is exacerbated by the extensive availability of counterfeit drugs (a multi-million market in South East Asia) and by the scale of the movement of people in the region. For example, between 10-20 million people cross the 4,000 km border in Yunnan Province, China into Myanmar, Lao P.D.R. and Viet Nam every year<sup>27</sup>. This is a rich environment for the mixing and spread of parasites resistant to antimalarials. It therefore seems likely that in the future we may well encounter strains of malaria that are untreatable with our present arsenal of drugs.

#### **INSECTICIDE RESISTANCE**

Insecticide resistance is a threat to the effective control of malaria vectors throughout the region. Worldwide resistance to a wide range of different classes of insecticide has been reported<sup>28</sup> and it is increasingly unpopular for countries to use DDT for indoor residual spraying (IRS) because of environmental and human safety concerns<sup>1</sup>. It would seem that (1) increased pyrethroid resistance stems from the indiscriminate use of these insecticides in agricultural and in urban areas<sup>29</sup>, and that (2) the increased use of nets causes a multiplier effect on the number of cases reported<sup>26</sup>. It is also important to appreciate that the construction of large-scale infrastructure development projects, in particular for agricultural production systems, that have increased reliance on large quantities of insecticide for crop protection may inadvertently lead to the spread of resistance in local vector populations.

## ECONOMICS OF RESISTANCE

Resistance of parasites to antimalarials and mosquitoes to insecticides has very serious economic consequences since when resistance to drugs or insecticides prevents effective disease control, health services must switch to another chemical, which is invariably more expensive. The rate at which resistance develops can be reduced by adopting a rational approach to the use of drugs and insecticides in malaria control in order to minimise their use and reduce costs. Thus antimalarials should be restricted to treating patients with diagnosed malaria, not any patient presenting at a health centre with fever. And it is important that patients take a complete course of antimalarials to prevent the application of sub-lethal doses of antimalarials that favour the spread of parasites partially resistant to the drug of treatment. Insecticides should be targeted at areas at greatest risk from malaria and options for rotating different insecticides or using combinations of different insecticides should be considered. Environmental management has an important role to play here since it can reduce the use of both drugs and insecticides in endemic communities. Thus environmental management should be considered as an opportunity to reduce the costs associated with resistance. However, such an integrated approach is rarely considered, let alone implemented, and the present emphasis is to do as much as possible with the available tools. Consequently, short-term gains are unlikely to be sustainable.

### Box 3

#### POPs and DDT

Persistent Organic Pollutants (POPs) are long-lasting chemicals that can accumulate through the food web and may cause adverse effects to human health and the environment. Since many of these chemicals can be transported around the globe to regions where they have never been used or produced they pose a threat to the environment of the whole world. Because of this threat the international community has called for urgent global action to reduce and eliminate releases of these chemicals.

DDT is perhaps the most infamous POP and is a remarkably persistent and cheap molecule that has excellent insecticidal properties. Although its use in agriculture was banned in most countries in the 1970s, it is still used for malaria control in a number of tropical countries. When applied correctly, DDT sprayed on indoor walls against malaria mosquitoes is considered to have little impact on the external environment and makes a valuable contribution to saving lives and reducing malaria in the poorest tropical countries. Often, however, application procedures are not correctly followed, and there is also an illegal flow of DDT to the agriculture sector, as a result of which the compound ends up in the environment after all. Many DDT-using countries do not have the capacity to enforce procedures and regulations.

WHO has been working with the United Nations Environment Programme (UNEP)<sup>1</sup> to provide information on the health and environmental concerns associated with DDT as well as the current use of DDT in malaria control. Any country can embark on an indoor residual spray campaign with DDT if they deem it necessary but they are required to report this use to WHO and UNEP. It is also impressed on these countries to apply WHO criteria and guidelines and that precautions must be taken to avoid DDT from being used for agriculture.

Although malaria control agencies are advised to use DDT only as a last resort<sup>2</sup>, countries may revert to using DDT as the need arises, as in South Africa. It is important that countries where DDT is used for

As resistance to old and new drugs and insecticides continues to develop (because evolution cannot be halted), industry and academia find themselves in a race against the clock to develop new drugs and insecticides to replace those, which become ineffective. The cost of drug and insecticide development is extremely high and pharmaceutical and insecticide companies can be reluctant to invest in the development of new antimalarials and insecticides for public health purposes, since the financial return for their investment is low, simply because most countries with malaria cannot afford expensive drugs or insecticides. The development of cheap and effective antimalarials or insecticides is not inexhaustible and there is the distinct possibility that the spectre of untreatable malaria may emerge soon in parts of the tropics. This further emphasises the need to develop parallel interventions that minimise the application of these chemicals.

Our present health-systems help propagate chemical treatments. There is a belief system firmly entrenched within the health sector that views chemicals as the principal and acceptable way of controlling disease. Indeed in most cases, this is what the public demands. This appetite is fuelled by considerable commercial and academic interest in the development of new drugs, insecticides and vaccines. Whilst the use of most drugs or insecticides is not sustainable in the long term, the current belief system seems immovable. In contrast, with environmental management there is little commercial support and health professionals and the public tend to be ignorant of the overwhelming success of public health interventions for the control of diseases. There is a very important role for advocacy and education to play here in clearing the mists of ignorance.

#### OPTIONS FOR CHANGE WITH ENVIRONMENTAL MANAGEMENT

Environmental management for malaria control consists of options for reducing the number of mosquito habitats or reducing biting by adult mosquitoes. Control of the aquatic stages is largely about removing suitable water bodies for mosquitoes to lay their eggs and to prevent the maturation of the aquatic stages. This does not of course mean that this type of intervention is limited solely to water resources development; it is also appropriate to almost all other kinds of infrastructure development, from road building to industrial development, particularly during the construction phases of such operations.

Any plan to use environmental management for the control of malaria in a particular locality needs to be tuned to local conditions and targeted at interrupting the habits and life cycle of local vectors. Anywhere that water collects for longer than one week represents an opportunity for mosquitoes to produce their offspring. Malaria (anopheline) mosquitoes breed largely in clean water, while culicine mosquitoes, which are extremely common in urban areas, will breed in polluted water. This distinction is particularly important for malaria control in urban settings. Few people know the difference between the two types of mosquito. Where control programmes target only anophelines they may lose community support if people continue to be attacked by large numbers of culicines. In such cases the local community may assume, wrongly, that malaria control has been ineffective.

Essentially environmental management can be divided into two compatible approaches:

- ***Environmental modification***, that means infrastructure development, and
- ***Environmental manipulation***, that requires individuals/communities to make changes to the environment as a periodic routine.

Some of the major options for control are outlined in Annex I, giving examples of where they have been used successfully.

## OPTIONS FOR INCLUDING ENVIRONMENTAL MANAGEMENT IN INTEGRATED VECTOR MANAGEMENT

Environmental management should be considered as the bedrock on which to base all other malaria control activities in the EAP Region. The basis for suppression of malaria can be best established and maintained through a number of approaches directed at disease vectors. This should be a truly Integrated Vector Management (IVM) approach to malaria control. Environmental management is about good housekeeping of the environment, ensuring that opportunities for vectors to exploit are reduced to a minimum. Clean and healthy environments and good quality housing are part of the basic health infrastructure required for development to take place and environmental management should be considered part of that process.

In the early part of the 20<sup>th</sup> century environmental control was centrally operated requiring large capital investments and significant inputs of labour. In some areas under colonial rule, such as Indonesia and Palestine, measures to reduce larval habitats were often forcibly imposed on communities<sup>30,31</sup>. We are not advocating that the EAP Region returns to the environmental management approach of the past. It is clear that today control can be best achieved through community participation<sup>32-34</sup>, often working in partnership with local municipal and governmental agencies, and with non-governmental organizations. This approach tends to be more cost-effective and fosters community pride and solidarity.

Environmental management for vector control requires good communication and co-ordination between professionals of different disciplinary backgrounds, not just those who work in the health sector. Here we face a major obstacle since there is a dichotomy between **vested sectoral interests** and **intersectoral co-operation**. It also requires mechanisms of co-ordination and collaboration to be developed between different public sectors, which have their roots in vested societal interests. Trade-offs between power-sharing and increased effectiveness through synergies will need to be made. At another level there are the obstacles and biases of the commercial interests linked to some, for example to chemical interventions, but not to environmental management. In systems where social inequity breeds significant levels of corruption, options to deploy environmental management for vector control are at a clear disadvantage.

IVM is a process of evidence-based decision-making procedures aimed to plan, deliver, monitor and evaluate targeted, cost-effective and sustainable combinations of regulatory and operational vector control measures, with a measurable impact on transmission risks, adhering to the principles of subsidiarity, intersectorality and partnership. Parallel to its counterpart in agriculture, Integrated Pest Management, IVM bases itself on the sound knowledge of local ecosystems, and the position of vector species in each ecosystem (e.g. Table 5). Automatically, therefore, the first line of action is Environmental Management, in an effort to reduce the environmental receptivity to vector breeding and disease transmission. Clear criteria, related to effectiveness, efficiency and sustainability, determine when and to what extent biological and chemical interventions are deployed to achieve the desired goal of transmission reduction. Decision-making is delegated to the lowest possible level in a given system of governance.

#### **Box 4. Subsidiarity**

In the definition of IVM shown above, the concept of subsidiarity may be unknown or misunderstood. It refers to the quality of being subsidiary, i.e. the principle that a central authority should have a subsidiary function, performing only those tasks which cannot be performed effectively at a more immediate or local level. For malaria vector control, the principle of subsidiarity becomes particularly relevant in settings where an administrative decentralisation of government is taking place or has taken place. In a decentralised structure, different essential vector management functions will be performed at different levels. It is in the spirit of subsidiarity that the lowest possible level of decision-making responsibility has to be defined. Below is an example of the distribution of essential functions at different levels of organization, without reference to any specific country:

Level	Essential functions
District (administrative)	Epidemiological surveillance, problem analysis, intervention design & intersectoral action.
Provincial (administrative)	Quality control, performance appraisal & data checks.
Central (administrative)	Technical support, procurement co-ordination, early warning task force, international links.
Region (ecosystem)	Research and development, capacity building, data compilation, sophisticated support services (i.e. PCR, resistance testing, etc).

## THE POTENTIAL OF ENVIRONMENTAL MANAGEMENT IN DIFFERENT SETTINGS

Although it is possible to estimate the burden of disease due to malaria in the EAP Region (Table 4), the fraction attributable to infrastructure development and the percentage by which infrastructure can improve this is extremely difficult to estimate. A recent workshop held by the World Bank produced a risk table for

**Table 5. Types of environmental management for controlling major vectors of malaria in the EAP Region.**

Major vector	Type of breeding habitat	Potential EM intervention
<i>An. aconitus</i>	Ricefields, particularly if tall & partially shaded, irrigation ditches, large grassy pools.	Flushing, intermittent irrigation, crop drying, dry belting.
<i>An. balabacensis</i>	Forest breeder found in temporary ponds & pools. Artificial containers & tree holes, open brooks & seepage.	Exposure to sun, filling.
<i>An. dirus</i>	Forest mosquito breeding in small ground pools or slow moving streams in forests.	Exposure to sun, filling.
<i>An. farauti</i>	Semi-permanent ground pools, but sometimes containers, brackish-water tolerant.	Flushing with salt water, filling & draining.
<i>An. koliensis</i>	Sunlit temporary pools in grassland & along forest edge, marshy sunlit pools at edge of stream, brackish lagoons.	Flushing, filling & drainage.
<i>An. maculatus</i>	Hill streams & ponds open to sunlight.	Flushing, shading.
<i>An. minimus</i>	Stream margins, gravel pits & small puddles in the shade.	Flushing, exposure to the sun.
<i>An. punctulatus</i>	Sunny & muddy water, open brooks & seepage.	Drainage.
<i>An. sondaicus</i>	Partially cleared mangroves & coastal wetlands. Stagnant brackish water.	Shading breeding places, weed clearing, drainage, highly salt water.

malaria transmission risk associated with different types of infrastructure projects (Table 6). The lack of precision seen here illustrates the difficulty of the task.

**Table 6. Risk of malaria transmission in infrastructure projects**  
(Rough guide only). Source. World Bank

Type of project	Risk of increasing anopheline mosquito breeding sites	Malaria transmission risk	Ease of implementing effective environmental interventions
Roads	High	High	Easier
Logging	High	High	Difficult
Urbanization	Initially high, then low (as breeding sites and contacts with vectors are reduced due to improved infrastructure)	Initially high, then low	Easier
Irrigation: Rice/sugar	High	High to low	Easy to difficult
Irrigation: Canals/rehab	Low to high	Low to high	Easy to difficult
Energy (dams, pipelines)	High	High	Easy to difficult
Water supply	Moderate	Low to moderate	Easier

#### **ECONOMICS OF ENVIRONMENTAL MANAGEMENT**

Resources for malaria control have been contracting for the last 50 years, and have been made worse by the economic crisis in the region that has resulted in failures in malaria control activities and outbreaks of malaria in Thailand and Indonesia. Military conflict, civil unrest and the large-scale movement of people have made matters worse. In much of the EAP Region there are few effective health services, and this situation is particularly severe in remote border regions where there is often a serious problem with multiple-drug resistant malaria. The process of decentralization of health services will, in the long run, create conditions favouring a 'local solution to local problems' with environmental management at its core. However, in the short term, in countries like Indonesia, the process of decentralization has weakened health services, including those related to malaria control. Thus, structural adjustment in this region is to a certain extent responsible for the spread of this disease.

RBM has obtained wide support from the international community and has promises of US\$1 billion per year to finance malaria control around the world<sup>35</sup>. The present strategy is sensibly targeted at immediate improvements in control using ITNs and treatment of clinical malaria, whilst the long-term strategy is lacking. This is where environmental management can play a part in securing long-term malaria control and sustaining the results of efforts of an intermediate nature.

An important issue is that despite the considerable research into this disease, there have been relatively few economic assessments of malaria interventions. For example, in a recent economic evaluation of malaria interventions in Sub-Saharan Africa<sup>15,36</sup> the reviewers identified only 14 studies aimed at the prevention and treatment of malaria and measured cost-effectiveness using a modeling approach. These interventions included ITNs, residual spraying, chemoprophylaxis in childhood or pregnancy and improvement of case management. In low-income countries and where malaria is endemic these strategies are cost effective (Table 7), at least in the short term.

**Table 7. Cost-effectiveness of malaria control in very low income countries in Africa**

Intervention	Cost-effectiveness range (US\$/DALY averted)
Insecticide-treated bednets	4-10
Residual spraying (2 rounds/year)	32-58
Chemoprophylaxis for children (assuming existing delivery system)	3-12
Intermittent treatment of pregnant women	4-29
Improvement in case management	1-8

Data from <sup>15</sup>.

Few studies have looked at the cost-effectiveness of malaria control activities in the EAP region. In Laos, Cambodia and Viet Nam about 60% of the malaria control budget is spent on implementing vector control activities, largely by indoor spraying with insecticide<sup>37</sup>. A cost-effectiveness study in Thailand<sup>38</sup> found that lambda-cyhalothrin impregnated nets were the most cost-effective intervention (US\$ 1.54/ case prevented), whilst spraying with DDT (US\$ 1.87) was cheaper than malaria surveillance by passive case detection alone (US\$ 2.50). However, in Viet Nam the use of permethrin-impregnated bednets (US\$ 0.90/person) was more expensive than residual spraying with lambda-cyhalothrin (US\$ 0.47/person)<sup>39</sup> because of the expense of purchasing the nets.

Despite the prospect that environmental management could provide a cost-effective intervention when viewed over the long term<sup>15,40</sup>, few cost-effective analyses has been carried out to date<sup>41</sup>. One excellent example of the cost-effectiveness of environmental management comes from the control of malaria in copper mines in Zambia (formerly northern Rhodesia) between 1929 and 1949. This programme included vegetation clearance, straightening of rivers and removing obstructions in the waterway, swamp drainage, oiling and house screening, although some employees were also given quinine prophylaxis and treatment, with a few sleeping under untreated bednets<sup>42</sup>. Within three to five years, malaria deaths and clinical episodes of malaria were reduced by 70-95%. The estimated cost of environmental management of US\$ 858 per death averted falls within the range described for ITNs of US\$ 219-2958<sup>15,43</sup>. However, it should be made clear that resistance to insecticides may reduce the efficacy of ITNs in the future, which is not the case for environmental management. Although environmental management is expensive in the short term a recent cost-effective analysis of these data suggest that such a strategy today would be cost-effective in the long term, at US\$ 22-92/DALY averted.

Many environmental management schemes, such as major drainage schemes, will provide long-term solutions to malaria control. Although initial infrastructure costs may be substantial they can provide protection against malaria to thousands for decades, bringing the annual costs of protecting an individual down to extremely low levels. In many cases the costs of environmental management may be negligible as they may occur outside the health sector. For example, a major drainage scheme initiated in a city may be designed primarily to reduce surface water, but correctly designed, could also help control malaria.

Properly managed infrastructure development projects can also lead to better quality housing, improved nutrition, cash to buy insecticide treated nets (ITNs) and a full course of effective antimalarials that will all contribute to a decline in malaria. Economic investment in the poorer

parts of the region, will therefore lead to both a decline in malaria and poverty. Thus health gains are likely to outweigh investment.

## MALARIA AND INFRASTRUCTURE DEVELOPMENT

### Recent serious impacts of infrastructure projects on malaria

Many infrastructure projects such as road construction, irrigation systems, agricultural drainage, flood control or impoundments may inadvertently lead to increased mosquito breeding, and hence more malaria. Here are a few recent examples.

#### *Dams*

The water used for irrigation from dams will often provide suitable breeding sites for malaria vectors. For example, in Tigray, in northern Ethiopia, thousands of small dams are being introduced in this drought-prone area to provide water for irrigation, people and domestic animals. In villages close to these dams malaria incidence is seven fold higher than in villages remote from a dam<sup>44</sup>. Here the increase in transmission occurs due to the breeding of mosquitoes in small water bodies in the fields and where the dams leak. Similar increases in the disease have also been recorded with irrigation projects in other areas of fringe transmission in Burundi<sup>19,45</sup>, India<sup>46</sup>, Kenya<sup>19</sup> and Madagascar<sup>47</sup>.

#### *Reforestation*

*An. dirus* is one of the most efficient vectors of malaria in Thailand. It is a forest mosquito and thrives in small pools shaded by the thick forest canopy. The logging of extensive areas of forest in Thailand over recent decades has resulted in a decline in the numbers of *An. dirus* and has contributed to a reduction in malaria<sup>48</sup>. However, there is evidence that recent plantations provide conditions even better for *An. dirus* than the original rainforest and malaria is on the increase in such areas. This increased incidence is particularly worrisome because of the high number of parasite strains resistant to a multitude of antimalarials drugs in Thailand.

#### *Shrimp farming*

Malaria has declined in the Mekong delta since major control efforts started in 1992<sup>49</sup>. However there are substantial areas where malaria control has been less successful and malaria is endemic. Most of these areas are where salt-water intrusion occurs. Here, the important vector, *An. sundaicus*, a mosquito that breeds in brackish water, has established itself in the extensive ditches and ponds used for shrimp cultivation. The larvae of this mosquito are found in close association with algal mats that lie just under the water surface. These island nurseries provide warm water for the young stages to mature rapidly and safe sanctuary from hungry fishes below. There is an interest in common between public health and nature conservation in this connection: the rapid turnover of shrimp farms leads to an excessive destruction of mangroves, and the abandoned shrimp ponds become key breeding places for malaria vectors. Environmental Management can have dual benefits in this setting.

### Lack of health impact assessments (HIA) with infrastructure developments

Despite major investments in the EAP Region by the Asian Development Bank (ADB) and World Bank there is often a complete absence of any (HIA) assessment on major infrastructure development projects and few that consider environmental management as a worthwhile control strategy (for further information on HIA the reader should consult these references<sup>50-52</sup>). Here are a few examples of projects where malaria is a major concern. In all cases little has been done to monitor any change in disease status in these areas making it difficult to assess the impact of

these projects on malaria in local communities. It would be imprudent to assume there was no effect, and the real costs of malaria on local communities remain hidden.

### *Cambodia*

An irrigation project, situated in the Chinit River Basin in Kompong Thom Province and costing US\$ 23.8m, has been set-up to repair damaged or neglected irrigation systems and to extend irrigation coverage in rural Cambodia<sup>53</sup>. Currently only 6% of rice-growing areas are irrigated, and the project is expected to provide 2,000 ha of dry season irrigation and 7,000 ha of supplemental wet season irrigation. Improved water access could also permit greatly expanded dry season cropping in the future, and this will provide an increased income to small, poor rural farmers. An upstream dam and storage reservoir will be built once improvements to canal works have been made. However, though the impacts of enforced relocation of households and the environmental effects on migrating fish have been considered, there is little evidence of any HIA and no prediction of the impact of irrigated agriculture on mosquito-borne disease risk. Though the effects of construction on deforestation, endangered species and major surface waters in the area (Lake Tonle Sap, West Baray reservoir irrigation channels and rivers) have been evaluated by the Ministry of the Environment, the health risk assessment only considers increased air and noise pollution, leaching of construction products and sanitary waste in local waters. There appears to be little involvement of the Ministry of Health in these projects, which is a pity since the health sector is capable and supportive of technical assistance, so there is an opportunity for disease control involvement in infrastructure planning.

### *Mekong Delta*

The Agricultural Development Programme proposed to run until 2006 is focused on the repair of irrigation systems and improving water supply in rural communities of the Mekong River and tributary floodplain regions. The health impacts of the major weir and pump irrigation schemes in the Attapeu, Champassak, Khammouanae and Saravane Provinces include changes to household nutrition, sanitation and disease incidence<sup>54</sup>. Advantageously, increased agricultural production will produce a surplus sellable for necessary medicines and childhood education. However, increasing water availability especially during the dry season might create new habitats for malaria vectors. The approach of the National Malaria Control Programme to reduce malaria incidence focused on early detection and treatment has been found to be less effective in irrigated areas. Nevertheless improvements to drainage and canal maintenance implemented by the projects could actually reduce overall breeding site availability and thus vector numbers.

The UNICEF/WHO joint Mekong RBM initiative<sup>55</sup> was developed to target poor, isolated and vulnerable communities living in border regions within the Greater Mekong Subregion (GMS), which consists of Cambodia, Lao PDR, Myanmar, Thailand, Viet Nam and Yunnan Province of the People's Republic of China. These people have poor knowledge of malaria risk, self-treatment and protective measures against malaria. Vector control measures are rarely a feature of their community organisations. A lack of political commitment and awareness of cultural constraints combined with the high cross-border mobility of these populations has resulted in their neglect in national malaria control programmes. Malaria epidemics with high morbidity and mortality are likely to follow.

The RBM initiative has established partnerships with a range of organisations in order to implement the plans at regional, country and district levels. In 2000 the Government of Japan, through the umbrella of the ADB, contributed US\$ 600,000 to provide technical assistance to RBM. The TA was designed to co-ordinate and support the efforts of UNICEF and WHO in the subregion, with emphasis on the restructuring of existing information, education and communication (IEC) and the development of new material to target ethnic minorities and migrants. Community motivation and involvement was highlighted as essential to the

improvement of response to epidemics. As such, community (location, density, organisation) and environmental (geography, vegetation, ecology) characteristics were targeted for review in order to improve IEC information. Translation of material into local dialects, the establishment of training workshops to enhance GMS integration and the training of provincial health staff were all seen as necessary regional strategies. In fact 6% of the budget was allocated for training workshops alone. A common theme of the ADB technical assistance proposal was the regional improvement of malaria control programmes. The adoption of a regional approach develops the potential for collaboration between GMS governments, provides opportunities for comparative assessment and should be more effective in targeting culturally similar transborder groups. Other regional and international organisations involved with vector control, service delivery and surveillance should be encouraged to adopt this approach.

### *Xiaolangdi Project, Yellow River*

The Xiaolangdi multipurpose dam project<sup>56</sup>, a strategic Chinese national project and the largest of its kind on the Yellow River, was designed with the intention of improving flood control, protecting against ice formation, supplying water for irrigation, reducing sedimentation, generating hydro-electric power and encouraging tourism. The dam when on completion will result in the inundation of 278km<sup>2</sup> of land and the creation of a reservoir with a storage capacity of 12,650 million m<sup>3</sup>.

An Environmental Impact Assessment in 1997 identified that changes in the hydrology of the region could increase malaria in the area. Disease control measures for malaria were proposed that did not consider environmental management as a possible intervention, with control focused on medical screening and periodic insecticide spraying<sup>57</sup>. The influx of construction workers and the relocation of people affected by inundation was a major concern. As a result all workers were physically examined and their health certification checked before employment. The construction contractors that have established their own health clinics also carry out annual medical screening. Once a year residual insecticides were applied to inner walls and rubbish heaps in construction work areas, while quick-acting compound insecticides were used in overgrown outdoor areas, sewage and drainage ditches.

The environmental assessment of 1993<sup>58</sup> recommended periodic monitoring of potential anopheline breeding sites followed by the application of *Bacillus thuringiensis* var. *israeliensis* and/or habitat modification where cost effective. Local anti-epidemic stations were given the responsibility for larval monitoring. There is evidence that reduction of larval density was achieved in the construction zones through use of larvicides but there are neither data for any indication of environmental management, nor the effect of this intervention on controlling malaria in local communities.

## **ENSURING MAXIMUM HEALTH SAFEGUARDS**

Whenever new infrastructure projects are being constructed, the environment is modified deliberately by a development sector such as agriculture or mining using a project budget. Almost all infrastructure projects will make changes to the local environment that could impact on malaria transmission, increasing the risk of malaria in local communities. In order to prevent this it is essential that safeguards are introduced in the planning, design and operation of all major infrastructure projects in the EAP Region.

The impact of these major environmental changes on human health is rarely evaluated or followed-up, as seen from the examples described in the previous section. In 1999 the World

Bank recognised this gap and recommended that HIAs should be carried out with the existing Environmental Assessments, and that this provided a cost-effective opportunity for malaria control through infrastructure projects (<http://wbIn0018.worldbank.org/>). In this way it may be possible to ensure that the project related modifications reduce vector density, vector contact, and increase the capacity of the community to protect themselves against malaria. Such improvements are also likely to increase productivity since fewer days will be lost due to ill health.

Thus from the outset it is vital that a full HIA is made of any new project as early as possible in order to help steer the planning process. These discussions should be made in partnership with interested parties: local communities, health agencies and other relevant sectors. Simple changes in project design at an early stage may prevent increases in malaria at no extra cost. In cases where there is a high risk of exacerbating malaria simple surveillance systems need to be established in order to monitor changes in disease patterns and contingency plans developed in cases of epidemics.

## **PROMOTION OF ENVIRONMENTAL MANAGEMENT – THE FUTURE**

The main malaria research and control programmes such as RBM, Multilateral Initiative on Malaria (MIM), the Global Fund to Fight AIDS, Tuberculosis and Malaria and the Bill and Melinda Gates Foundation are notable for their lack of attention to the environment and development. They do not mention the use of environmental methods for vector control, or the effect of development policies and projects on malaria. These policies must change to provide a more conducive policy framework for environmental management in order to improve the effectiveness and sustainability of malaria control. Within the RBM partnership it is the World Bank (WB) that has a comparative advantage in this connection as its daily business is to negotiate loans for infrastructure projects with client governments.

### **CAPACITY BUILDING**

There is also an urgent need for capacity building at all levels. The DDT era failed to eradicate malaria, but has almost eradicated public health scientists with an interest in environmental management at all levels; including policy makers, academics and, most importantly, malaria control programme managers. However, there is a resurgence of interest in a small but growing section of programme managers, such as those in the WHO/FAO/UNEP PEEM, USAID/Environmental Health Project (EHP), Canadian IDRC, IWMI/SIMA and the academic community that recognises that attacking the aquatic stages of mosquito larvae is an under-developed area of research and one likely to yield new opportunities and tools for malaria control. This rising wave of interest needs to be encouraged and fostered, particularly as it should provide opportunities for the training of malaria control staff in hands-on environmental management. Such initiatives need financial backing if they are to flower. It should be appreciated that there are few international centres of tertiary education with environmental management as a focus and these need to be developed, particularly in the EAP Region.

There is ample evidence from the historical records and a variety of recent case studies that environmental management protects against malaria. However, at present, there is an insufficiently solid evidence-base needed for informing policy makers about optimal strategies for environmental management in specific ecological settings. Whilst the health sector is informed about the success or failure of new drugs, vaccines and insecticides using clinical trials (i.e. randomised-control trials) this is rarely, if ever, done with environmental interventions. This

needs to change before the health community can be convinced of the effectiveness of environmental management. Thus environmental control strategies need to be developed and assessed by intervention trials where success is measured by a reduction in clinical malaria. Such interventions should be considered as part of the long-term strategy to reduce transmission intensity in order to place less reliance on the heavy use of antimalarials and insecticides. Control strategies that are shown to be effective can then be integrated into established control programmes.

Most importantly the continual erosion of the number of professionals with practical experience with environmental management for malaria control needs to be halted and reversed. Without such champions there is little hope for any changes in current practises. There is thus an urgent need to train malaria control managers and related staff in methods of environmental management. This should be through tertiary level education from PhD and MSc studentships, as well as short training courses and workshops for relevant personnel. An important part of this education is that training is not confined to individuals from the health sector, but is truly interdisciplinary. There also needs to be a strong vein of social science that runs through the education since all environmental management programmes need to work closely with local communities in order to make the interventions effective. Another fundamental issue is that economists should be encouraged to make cost-effectiveness evaluations of action programmes since there is a paucity of information in this area, which restrains moves to encourage the development of environmental management techniques.

Education should not stop with the professional trainers. People, from the young to the old, need to understand what malaria is caused by and what they can do to prevent and treat the disease. This is not just the responsibility of the local Health department, it must be the role of all educators, from teachers to religious leaders to the media - anyone.

### **INTERSECTORAL PLANNING AND DECISION MAKING**

For environmental management to be successful barriers between different planning sectors need to be breached. Because of the complexity of environmental management there is a clear need for effective dialogue between the health sector, settlement planning sectors, environmental concerns (such as wetland conservation), academic institutions (for providing research support) and local communities. The structure of these groupings will vary from country to country depending on the different models of governance; but essentially there needs to be effective dialogue between experts at the Government level, facilitating planning of control operations managed at the local District or Municipal levels with the support of local communities. A conducive policy framework is essential: the development policies of the different sectors involved in infrastructure development should include clear references to the need to assess health impacts and to design and implement health safeguards in accordance with these. Strengthening of the health sector, both the vector control and the environmental health programmes, in their essential functions will permit an improved responsiveness to the needs of other sectors in this connection.

### **PROPER VECTOR CONTROL PROCEDURES**

Malaria control programmes need to look at what can be achieved by environmental management in their own areas and work with other sectors to develop plans for making these improvements. This is particularly important with any new infrastructure projects where slight modifications may contribute to a decline in malaria, rather than an increase. Such strategies are essential for making villages, towns and cities healthy places in which to live. Healthy workforces are also more productive, helping countries to develop. An effective system of environmental management

should also reduce the countries' dependency on drugs and insecticides reducing both direct costs and indirect costs associated with the rapid evolution of drug and insecticide resistance.

It is important to stress that environmental management cannot operate alone; it must work alongside other control strategies in an integrated fashion. To give it its proper place in IVM there need to be managerial improvements, clear decision-making criteria and procedures in order to optimise the raft of measures to be delivered.

#### **DEVELOPMENT OF AN ENVIRONMENTAL MANAGEMENT TOOLKIT**

Technical guidance for environmental management for vector control requires urgent updating. The most recent WHO guidelines in this field date back to 1982 (Manual for Environmental Management for Mosquito Control, WHO Offset publication 66) and were mainly a compilation of the pre World War II knowledge and experience, that had been forgotten during the DDT era. The three UN agencies that established the joint Panel of Experts on Environmental Management for Vector Control in 1981 focused their efforts in the 1980s and 1990s on a range of valid intersectoral aspects. It is now timely to review the state of the art, consider the significant progress that has been made in engineering and management, and take on board our current knowledge base on vector ecology, vector-borne disease epidemiology, water management, social science in a process that will result in the production of an environmental management toolkit that respond to the needs of our times. In other words, it should present environmental management as a component of IVM, and back up the technical guidance with information on economic, institutional and managerial issues that can be conducive to the successful promotion of EM efforts.

#### **OBSTACLES WITH ENVIRONMENTAL MANAGEMENT**

The ability of environmental management techniques to control malaria depends critically on how well it is matched to the ecological requirements and behaviour of the primary malaria vectors in an area. It is essential that before any water management strategies are initiated the location of all major anopheline breeding sites be identified. In parts of the EAP where significant levels of malaria can be maintained by extremely low levels of vectors of a variety of different species, this is not always an easy task. Moreover, the public health scientist needs to take into consideration the timing of the interventions in respect to the seasonality of malaria transmission, as well as other environmental factors that operate at a local level, such as geology, topology and local climate.

Although the public health scientist will generally argue that water control is often necessary for effective malaria management, there is a potential conflict here with conservationists. Around 50% of the world's wetlands have been lost in the past century (<http://iucn.org/themes/wetlands/wetlands.html>) and 800 freshwater species are threatened with extinction. These habitats are not only of importance for animals and plants; they also provide drinking water, food and wood for local communities. In such cases the malariologist needs to work closely with local communities and conservationists to demonstrate that interventions against mosquitoes will not harm the environment. In many cases, a detailed ecosystem analysis is likely to reveal common interests between nature conservation and the reduction of environmental health risks to local communities. Pointing out the health advantages may also boost community mobilisation for conservation efforts. Joint efforts between conservation and health agencies can achieve important synergies. Health authorities will, however, have to adapt their services to communities in such areas to meet their very specific needs, including those related to the residual environmental health risks following the implementation of an environmental management plan.

**Box 5**  
**Bio-environmental management was cheaper than  
DDT spraying in India<sup>59,60</sup>**

Malaria resurged in India in the 1960s due to insecticide and drug resistance, economic problems and a reluctance of householders to have their homes sprayed with insecticides. In Kheda District in Gujarat an Integrated Disease Management programme was established with the active participation of local communities. It involved intensified case detection and treatment to reduce the number carrying malaria parasites coupled with an attack on the vectors by eliminating vector-breeding habitats. Most breeding sites were close to people's homes and in irrigation canals. Breeding sites were removed or fish (Guppies) added to water to eat the mosquito larvae. Ponds flourished to grow fish for sale and for mosquito control. At the end of the six year study the levels of malaria was similar to that achieved before with indoor residual spraying (IRS) with DDT, however bio-environmental vector control was 18% cheaper than IRS and considerably more environmentally-friendly.

Environmental control strategies need to be developed and incorporated within infrastructure developments and assessed by intervention trials where success is measured by a reduction in clinical malaria. Such interventions should be considered as part of the long-term strategy to reduce transmission intensity in order to place less reliance on the heavy use of antimalarials and insecticides.

## CONCLUSIONS

Our views concur with a recent workshop report held by the WB on June 9-10, 1999. These are reiterated, expanded and added to below:

- Health impact assessments should be made at the same time as the existing Environmental Assessments, and they offer the most cost-effective method to control malaria in infrastructure projects.
- Infrastructure projects are an essential element of development and can contribute to the long-term health and well being of beneficiaries. Many of these projects offer great opportunities to contribute to a lasting reduction in malaria transmission, provided a number of issues are taken into account.
- These risks should be reduced by careful changes in the design of infrastructure projects. The efficacy and cost-effectiveness of these environmental management procedures need to be assessed by large-scale (randomised-control) field trials.
- Interventions that are most likely to be initiated include: improved drainage systems, filling and levelling sites with standing water, improved water management systems, better housing and improved access to health facilities. Education of local communities about health issues should also be encouraged to help facilitate community participation with these projects. This is an excellent opportunity to link development projects with health system improvement.
- The choice of intervention depends on the local ecology of the vectors, community and environment. This is a complex problem and requires well-trained researchers with a wide breadth of knowledge. Entomological research in the region has tended to focus on specific problems, such as basic taxonomy, local descriptions of transmission intensity and levels of insecticide resistance. This has to change and entomologists need to think much more broadly in order to develop and assess new intervention tools. There is a real

need to break down traditional barriers between scientific disciplines and get entomologists, epidemiologists, social scientists, engineers, and clinical scientists working together. There is thus a great need for developing training and capacity building in this region. Links with northern partners should also be encouraged to help develop the research capacity of EAP researchers.

- The production of an Environmental Management toolkit will help accelerate best practice in infrastructure development and will lead to a renewed interest, inside and outside the health sector, to put resources in environmental management activities.
- Infrastructure staff should collaborate with health staff from the early stages of planning for the infrastructure project, and cost-benefit analyses of the project must consider long-term health impacts.
- Today the control of malaria is dominated by the use of antimalarials and ITNs. Resistance to these drugs and insecticides will develop rapidly. It is important to establish long term sustainable strategies for malaria control, such as environmental management. The World Bank should demonstrate its leadership by supporting the development of environmental management strategies for malaria control.
- Investment in environmental management today, will lead to reduced health spending tomorrow.

## ANNEX I: ENVIRONMENTAL MODIFICATION AND MANIPULATION

### ***Environmental modification***

#### *Impoundments*

Impoundments are reservoirs of water stored behind dams for hydro-electric power, irrigation or water for people and livestock. Those interested in the subject are advised to read WHO's submission to the World Commission on Dams<sup>61</sup> and the International Institute for Land Reclamation and Improvement's publications on Health and Irrigation<sup>62,63</sup>. When dams are constructed mosquito numbers generally fall, if large numbers of small water bodies are combined into one large area of water as the reservoir fills. If mosquito larvae occur within dams they are usually confined to the shoreline, not the main body of water since many fishes are rapacious predators of mosquito larvae. Only when there is floating vegetation shielding the aquatic stages of mosquitoes will vector populations expand.

There are a number of ways for reducing the threat of malaria from dams that relate to their design and operation<sup>61</sup>. Reservoirs should avoid being sited in areas that have extensive areas of shallow water. Not only will this lead to increased water loss through evapotranspiration, but it may also provide ideal breeding sites for mosquitoes. During the construction of impoundments vegetation should be cleared around the water edges, particularly between high and low water marks. Consideration also needs to be given to fluctuating water levels in the reservoir exposing or creating new breeding sites. Drainage of pools along the margins of the impoundment should be carried out, where possible, and the integrity of the shoreline needs to be maintained to prevent erosion, vegetation growth and driftwood creating breeding sites. Low flow zones in water channels need to be reduced to prevent water stagnating and providing breeding habitats for mosquitoes. Seepage from the base of a dam can also be a problem, wasting water and providing persistent pools of water for the propagation of mosquitoes. Off-takes, of greater diameter than normal, will allow the water level in the reservoir to drop rapidly allowing many mosquito larvae around the edge of the reservoir to be stranded and killed, providing there is no pooling. Moreover, the rapid run off can be used for flushing mosquitoes out of irrigation channels.

#### *Canal lining*

Lining irrigation canals with concrete makes good sense, not just to reduce seepage and thus save water, but also to reduce the risk of creating mosquito-breeding sites. Lining will increase water flow, washing the aquatic stages of mosquitoes out from canal networks. If they are well maintained, plants will not become established to offer shelter for some species of mosquitoes. Since there is less seepage with lined canals this results in less need for drainage, which may also reduce mosquito breeding. In cases where vector mosquitoes become established in the canals it makes it easier to control mosquitoes either by water management or by targeted use of insecticides. People and domestic cattle should be prevented from crossing canals or drainage channels in order to prevent the formation of hoof or foot prints that can make ideal breeding habitats for some mosquitoes. Construction of bridges or placing large stones or rocks in such areas may also help alleviate the problem.

#### *Filling*

Abandoned ditches, borrow pits and ponds should be filled to remove potential mosquito breeding sites. These are particularly important if situated close to human habitation, although it should be recognised that heavily polluted water is often inimical to anophelines. Refuse can be used for filling such sites provided it is compacted and covered in earth to reduce fly problems. A

simple example of this is the control of malaria in Bharat Heavy Electricals in Hardwar, India, where the number of malaria cases was reduced from 3,049 in 1985 to just 190 in 1995 by filling pits, low-lying areas, ditches and other depressions with ash from a coal-fired power<sup>64,65</sup>. Although malaria was reduced at this site it is difficult to know the precise contribution made by environmental management.

### *Drainage*

A well-constructed drainage system can prevent the formation of small water bodies suitable for the aquatic stages of mosquitoes. The straightening of streams and the removal of vegetation from banks can reduce mosquitoes by washing the aquatic stages away and allowing larvivorous fish access to the mosquitoes<sup>66</sup>. Surface-drainage requires improving water courses and the construction of ditches. In all cases these need to be built following the path of waterflow that exists in the area to prevent pooling of water along the drainage channels. Lining drains with concrete, stone or brick will allow faster water flow, reduce silting and weed growth, but will add substantially to the costs of implementation. Integrated control of breeding sites by improving drainage, filling and levelling and planting eucalyptus has been used to convert a once prolific area of mosquito breeding in a peri-urban area into a public park in Zambia<sup>67</sup>. Tree planting to drain boggy ground has also been used as part of an integrated programme to reduce malaria transmission and help reforestation for the provision of wood and improvement of water management in Gujarat, India<sup>33,68</sup>. In many instances the lack of proper drainage reflects the economic realities of irrigation development, which often is only marginally profitable. Including a drainage component often pulls the internal rate of return of a project in 'the red' and renders the proposed development economically unfeasible. This was, for example, the root cause for the malaria epidemic linked to irrigation development of the Cukurova Plain in southern Turkey in the 1970s<sup>69</sup>.

### *The 'Lido system'*

In areas of extensive water covered with vegetation where drainage is impractical, the area can be deepened to the extent that plants cannot grow. If the banks of the impoundment are also steepened and stabilised, the introduction of larvivorous fish can reduce mosquito production dramatically.

### *Subsoil drainage*

Subsurface drainage is used in wet areas for preventing water logging, improving aeration and reducing salinisation. Such drains are constructed of channels filled with rock, rubble or gravel and covered with vegetation ('French' drain), stones alone or pipes.

### *Design of drainage schemes*

The design of drainage systems can be relative simple in small areas, but can be extremely complex over large areas. Generally a system of grid-iron drainage, with few junctions, is preferred to the herring-bone arrangement with many junctions since blockages tend to occur at junctions thus increasing mosquito breeding.

### *Coastal swamp drainage*

Constructing embankments to prevent the inundation of seawater at high tides can assist drainage of some coastal swamps. Pipes fitted into the embankments with an automatic outflow gate will allow water from the lagoon to be drained at low tide. A saltwater marsh drainage project, combined with larviciding and antimalarials for case treatment was used to control a malaria epidemic in Haiti<sup>32</sup>.

### *Vertical drainage*

In flooded areas lined with silt or clay over permeable bedrock, shafts can be sunk through the impermeable layer to allow water to leak into the permeable strata below.

### *Drinking water provision*

Provision of safe drinking water and ensuring the related infrastructure is not causing seepage, leakage or standing water is an important environmental management measure in itself. This is particularly so since it allows people to move their settlements away from water bodies on which they would otherwise rely for their drinking water.

### *Reduction of man-mosquito contact*

#### a) Site selection

Mosquitoes tend not to fly far from their breeding habitats, about 2-4km. Thus positioning houses 1.5 to 2 km from large breeding sites will result in a substantial reduction in transmission. Similarly villages at higher elevations and exposed to the wind will also have fewer mosquitoes than sites situated in the lowlands where it is less windy and small water bodies abound. Where the land within the mosquito flight range is sparsely populated or in areas flooded during dam construction, it may be possible to persuade people to move away from mosquito-breeding habitats. In rice-growing areas, where prodigious numbers of adult mosquitoes are often produced, it has also been suggested that areas immediately next to the ricefields should not be inhabited in order to reduce exposure to malaria parasites. This practise of dry belting villages in rice-cultivation areas is theoretically sound, but in reality, as with the previous examples, encouraging people to move away from water is extremely difficult to achieve and is not widely applicable as an intervention measure.

#### b) Raising buildings off the ground

Since most mosquitoes searching for blood are flying close to the ground<sup>70,71</sup>, one of the simplest ways of avoiding mosquito bites is to build homes off the ground. In the early 1900s it was recommended that around Rome the floor of a house should be raised off the ground and be built at least two storeys high to provide bedrooms for the occupants on the top floor and reduce biting by mosquitoes<sup>72</sup>. Even today people can reduce biting by sitting in the evening on raised platforms in rural Gambia. Field studies in Papua New Guinea<sup>73</sup> and The Gambia<sup>74</sup> have even demonstrated that simply keeping the feet off the ground protects from biting mosquitoes.

#### c) Mosquito-proofing of dwellings

In the early 20<sup>th</sup> Century housing screening were regarded as one of the main methods to control malaria<sup>75</sup>. Mosquito-proofing houses was used by Patrick Manson to demonstrate the role of mosquitoes in malaria transmission<sup>76</sup> and modifying house structure was used to protect people from malaria in Italy<sup>77</sup>, Greece<sup>78</sup>, Panama<sup>79</sup> and the USA<sup>80</sup>. There is ample evidence that house screening contributed to the elimination of malaria from many parts of the world<sup>75</sup>. More recently, risk factor surveys for malaria have shown that well-built homes and those with ceilings or closed eaves are protected from mosquitoes and malaria. A recent study using experimental huts in The Gambia demonstrated that installing a ceiling made of netting reduced transmission by 80%<sup>81</sup>. This reduction compares favourably with that seen with ITNs in the same huts and need not be expensive.

## **Environmental manipulation**

### *Controlling water levels*

An example of this technique is intermittent irrigation used for controlling mosquitoes in rice-growing areas. Here paddies are cyclically drained and flooded during the planting and growing seasons. Whilst this may act to depress mosquito breeding in the ricefields, temporary removal of water should not reduce rice yields and may actually increase yields by restricting weed growth. This method has proven successful in India, China and other parts of South-East Asia<sup>82</sup>. In China the practise of allowing ricefields to naturally dry out has also led to major successes in malaria control<sup>83</sup>. One recent example of this comes from the Sichuan Province of China where malaria has almost been eliminated by a simple change in agricultural practises (G. Gibson personal communication). Over the past four years rice paddies, which provided ideal habitats for the two principal malaria vectors, were replaced by a system where standing water in the fields was restricted to about 100 days during the rice growing season in the summer, followed by the cultivation of 'dry crops', such as wheat or cash crops in the winter. This shift in agricultural practises has led to a decline in vectors to levels that can no longer support malaria transmission.

In India intermittent irrigation combined with the use of extracts from the neem tree (*Azadirachta indica*) lead to a reduction in anophelines<sup>84</sup>. However, intermittent irrigation is less successful with mosquito species that rapidly colonise paddies shortly after flooding, such as the African mosquito, *An. gambiae* s.l. In this case, puddling of paddies after drainage can still lead to large numbers of mosquitoes being produced<sup>85,86</sup>. In contrast to this, by maintaining a continuous water depth the formation of small rainfall pools in streambeds can be prevented. In Sri Lanka, where *An. culicifacies* frequently breeds in small pools formed along dried stream beds, 85% of larvae were found when stream water depth dropped below 20cm. By maintaining a continuous flow of water at greater depth effective control was achieved<sup>87</sup>. Avoidance of water pooling proved cost-effective by eliminating the need for larviciding. However continuous release has a restricted application because in some regions slow continuous flow will encourage slow-water breeders.

### *Stream sluicing or flushing*

A regular discharge of a large volume of water into a stream, by releasing water held behind a dam across the stream, can flush out mosquito larvae from the stream bed. Existing irrigation infrastructures have been manipulated in tea and rubber plantations in South-East Asia, where *An. minimus* and *An. maculatus* prefer the relatively still water at the edges of streams. Automated siphon sluices were favoured in Malaya, Ceylon (now Sri Lanka) and northern Bengal in the 1930s and 1940s, though the system required regular maintenance after heavy floods to remove silt. In Sri Lanka, flushing reduced *An. culicifacies* larvae in streams and reduced the risk of malaria in surrounding areas<sup>87</sup>. Flushing has also been used successfully to control *An. pseudopunctipennis* larvae in ricefields in Mexico<sup>24</sup>. Such an approach is likely to be successful against *An. fluviatilis*, *An. maculatus*, *An. superpictus* and other vectors that prefer streams, though flushing of streams may present hazards due to drowning so human safety needs should also be considered. It is also important to assess how much water is available for larval control e.g. the storage capacity of tanks upstream minus the water consumed for dry season cultivation. Periodic release requires a schedule to be agreed between irrigation officials and health managers. It is also necessary to convince farmers of the benefits of such water usage.

### *Changes of water salinity*

In certain situations raising the salinity of coastal marshes or lagoons through the introduction of saltwater may lead to a reduction in anophelines. This is only feasible where the local vector cannot breed in salt water and where rainfall is not heavy. In the last 10 years, flushing coastal areas with seawater near Honiara, the capital of Solomon Islands, has greatly reduced breeding of

*An. farauti*<sup>24</sup>. In Indonesia where highly saline lagoons are used for the growth of fish and prawns, the breeding of *An. sundaicus* is restricted (<http://w3.whosea.org/malaria/success.htm>).

#### *Shading of stream banks*

This method of control was used to control *An. maculatus* in Assam, India<sup>88</sup>, where it prefers open areas of water. Such approaches have also been used against *An. fluviatilis* and *An. sundaicus*. Under dense shade, no vegetation grows near the edges of the stream so that the current takes away mosquito larvae and renders them more susceptible to predation by fish.

#### *Vegetation clearing*

Clearing of vegetation has been used to control *An. balabacensis* in Sabah<sup>88</sup> and may have an effect on *An. minimus* that prefers larval habitats along the edges of streams in the shade<sup>23</sup>. Alternatively large-scale clearance of forest may result in increases of *An. minimus*. In general clearing of vegetation removes resting places for outdoor sheltering mosquitoes and increases water evaporation contributing to a reduction in breeding sites. On the other hand such exposed sites may favour other vector species. Planting trees with high water requirements, such as *Eucalyptus robustus*, can also help reduce surface water<sup>3,33,68</sup>.

#### *Water pollution*

Pollution of water has been used as a deliberate method for the control of *An. fluviatilis* and *An. maculatus* in India and Malaysia<sup>88</sup>. Here vegetation such as grass clippings and other vegetable compost is added to water sites to increase anaerobic decomposition that can deter some mosquitoes from laying eggs. This procedure though may favour some culicine mosquitoes, increasing biting locally. Pollution with industrial waste is clearly not an option because of the damage to the environment and human health.

#### *Larvivorous fish*

Fish are exceptionally good predators of mosquito larvae. In Guangzhou county, China, common and grass carp fry are released into paddies soon after rice seedlings are planted, and receive no supplementary feed. Here an increase in fish stocking has been correlated with a decrease in malaria incidence over the same time period. Using edible fish can turn environmental management into a profitable method of malaria control; the net return from a concurrent rice-fish crop system was 52% above that of the rice crop alone. A ditch-ridge system in the paddies will facilitate water drainage required to speed up rice development and allow fish to be kept in the ditches before the blooming stages. The economic benefits of fish may also encourage community participation in mosquito control. *Gambusia spp* have been effective for the control of anopheline larvae in the Solomon Islands in the past. However, the effective control of the aquatic stages of mosquitoes using larvivorous fish at a local scale has been difficult to extend to large-scale programmes. When this is tried it is important that indigenous species are used so as not to disturb local ecosystems. Indiscriminate use of *Gambusia* may not only offer little biological control advantage but it can endanger both rare and economically desirable species. For example, its omnivorous nature can significantly reduce the number of eggs and fry of fish with similar ecological requirements.



## ANNEX II: HISTORY OF ENVIRONMENTAL MANAGEMENT

Today around 90% of malaria cases are found in sub-Saharan Africa, but at the beginning of the 1900s the number of cases in Asia must have been significantly greater. For example in Yun county of Yunnan Province in China more than 30,000 deaths were recorded during an epidemic in 1933<sup>27</sup> and in 1944 about 40% of all deaths in peninsular Malaya were attributed to malaria<sup>89</sup>. The extensive deltas in the region, such as those formed by the Red, Mekong, Chao Phraya, Salween, Irrawaddy and Ganga rivers are all prone to flooding and have a long history of malaria epidemics<sup>27</sup>.

Environmental management was the most effective method for reducing malaria in the EAP Region during the early 1900s. Sir Malcolm Watson in Malaysia<sup>90</sup> demonstrated that draining and filling the swamps surrounding Klang and Port Swettenham, Selangor, led to a sharp reduction in malaria<sup>91</sup>. In one year he had reduced the deaths from malaria from 368 to 59.<sup>6</sup> There were also substantial reductions in malaria associated first with coffee growing and, later with rubber plantations. With both crops, good drainage and weeding are essential, requirements that also lead to a decline in suitable mosquito habitats. In Malaysia it was also shown that the selective clearance of tropical forest around settlements, good drainage and the restriction of housing to at least 1km from the edge of the nearest undrained rainforest led to malaria eradication.

Watson had shown that understanding the ecology of the local malaria vectors was the key to their control. Thus near the coast, *An. sundaicus* was controlled by building bunds and installing tidal gates to keep out the saline water favoured by this mosquito. Inland *An. umbrosus* and its related species were reduced by drainage and clearing vegetation to restrict breeding sites and to make any open water unfavourable as mosquito-breeding habitats. Whilst *An. maculatus* was managed by constructing sub-soil drainage of ravines or regular larviciding. This more cost-effective method of control became known as species sanitation. This approach restricted the use of control strategies to only the most dangerous malaria vectors and led public health workers to distinguish particular malaria-ecological zones, such as mangroves, coastal plains, coastal hills, inland plains and inland hills. Most importantly, specific intervention types were targeted at specific zones.

Species sanitation was so successful that it was practised widely across South-East Asia<sup>92</sup>. In Indonesia, synchronised cropping and intermittent irrigation in ricefields was shown to control malaria in local communities<sup>93</sup>. In synchronised cropping rice paddies were left dry for two months each year and this led to a significant slump in adult mosquitoes. Alternatively, intermittent irrigation where fields were flooded for nine days and then left to dry out for three days led to a 75% reduction in larval density and encouraged local governments to make this compulsory in Bali and Lombok. In coastal areas, control was achieved in saltwater lagoons by removing floating algae, the preferred breeding habitat of *An. sundaicus*. Clearing the algae led to high larval mortality as a result of predation by larvivorous fishes. In other places engineering works were undertaken to flood the lagoons with saltwater, where the raised salinity was inimical for larvae. These works were carried out on a grand scale, with over 46 engineering works successfully demonstrating a reduction in malaria in coastal settlements<sup>94</sup>. This included the construction of flood dikes, drainage, filling and levelling, removal of fish ponds, banning cutting mangrove, improving irrigation systems, planting shade trees on the edges of lagoons and rivers, preventing weed growth, restoring tidal action by cutting bunds, larviciding and screening houses. In each site the choice of intervention was tailored to local needs.

Large-scale environmental management programmes helped reduce malaria in Italy<sup>95</sup>, Panama<sup>96</sup> and the Tennessee Valley in the United States<sup>30</sup>. In Italy considerable sums were spent on major engineering activities to drain 100,000 ha of the Pontine Marshes, through a system of ditches and canals, and included diversion of major rivers. Such studies, which fill the historical literature, illustrate the wide-scale practise and success of environmental management in different parts of the world.

## ANNEX III: LOCAL VECTORS AND THEIR ECOLOGICAL REQUIREMENTS

Past changes in the world's climate and movement of tectonic plates have helped shape the ecology of the EAP region, including the present distribution of malaria vectors<sup>97</sup>. Mainland South-East Asia has a distinct floral and faunal composition, representing an 'Oriental' zone that differs markedly from the 'Australian' zoogeography of Papua New Guinea, Irian Jaya, East Timor, Solomon Islands and Vanuatu to the south<sup>98</sup>. The intermediate Indomalaysian archipelago and the Philippines are much similar to the Oriental zone with which they share a high percentage of flora and fauna. Thus a distinct discontinuity exists between the Oriental and Australian zones, that is referred to as Wallace's line<sup>99</sup> after the naturalist who first described this sharp transition. This divergence is echoed in the distribution of malaria vectors in the region. Many of the vectors found on mainland South-East Asia also occur on the adjacent islands, whilst those in the Australian zone are distinct. Further north, China and the Republic of Korea have a zoogeography representative of the Palaearctic zone and their mosquito fauna is different again.

The dominant vectors in the EAP Region are:

- *An. dirus* that thrives in forested regions in the mainland Mekong countries;
- *An. balabacensis* transmits the disease in east Malaysia and the southern Philippines;
- *An. aconitus*, *An. sundaicus* and *An. maculatus* in Indonesia;
- *An. minimus* is important in Lao PDR, Cambodia and Viet Nam;
- *An. sinensis* in China and the Republic of Korea;
- *An. maculatus* in Peninsular Malaysia, and;
- *An. farauti*, *An. koliensis*, and *An. punctulatus* in the Southwest Pacific.

### Cambodia

*An. balabacensis* is the major vector in Cambodia, although *An. sundaicus* is important in coastal areas<sup>100</sup>. *An. minimus*, *An. leucophyrus* and *An. maculatus* are also present.

### China

*An. sinensis* is the main malaria vector in the plains-dominated districts of the northern region between 25 and 32°N where it is found breeding predominantly in ricefields. In the south on the borders with Myanmar, Viet Nam and Lao PDR *An. minimus* is widespread in hilly areas, and regarded as the important vector species, with 7.0% of the mosquitoes infective with malaria sporozoites in Yunnan Province<sup>101</sup>. In central China *An. anthropophagus* is more prevalent than the other two species<sup>102</sup>; in Anhui Province 1.6% of *An. anthropophagus* had infective parasites (sporozoite rates)<sup>24</sup>.

### Indonesia

In Irian Jaya *An. farauti*, is considered the most important vector and is found widely in artificial containers and tree trunk hollows. *An. punctulatus* is also an important vector that prefers sunny and often muddy waters, and occurs sympatrically with *An. farauti* in open brooks and small collections of seepage water that are common in the wet season. *An. koliensis* is a secondary vector preferring grassland and marshy sunlit pools at the edges of forest streams but it extends its distribution to brackish lagoons where it may be a locally important vector.

In Java, *An. aconitus*, is the main malaria vector. It feeds largely on animals outdoors where it lays its eggs in rice fields in central Java and rests along stream banks and irrigation ditches<sup>103</sup>. *An. sundaicus* is a problem in saltwater lagoons on the coast and *An. maculatus* is an important vector in the hilly forests.

In Sumatra, *An. barbirostris* and *An. kochi* are widely distributed, where they breed in small and shallow pools, hoof marks and fish ponds. *An. leucosphyrus* is also common in areas of deep jungle where it selects well-shaded water with vegetation in order to lay its eggs. Similar conditions are favoured by *An. balabacensis*.

In Borneo, there is a large number of potential vector species, including: *An. aconitus*, *An. sundaicus*, *An. subpictus*, *An. annularis*, *An. maculatus*, and *An. umbrosus*.

In the Celebes, *An. minimus*, *An. flavirostris*, *An. sundaicus* and *An. subpictus* are the malaria vectors.

#### *Lao PDR*

A total of 19 Anopheline species have been recorded in Lao PDR. *An. dirus*, *An. minimus* and *An. maculatus* are the principal vectors and have all been found infected with malaria parasites (oocysts)<sup>104</sup>. These three are present in most provinces where they bite humans both outdoors and indoors, though *An. minimus* bites later in the night than the other two species, with peak activity after 22.00 hours. These species are forest dwellers; *An. dirus* breeds in small ground pools while *An. minimus* and *An. maculatus* prefer slow-running streams<sup>105</sup>.

The lowland plains and floodplains are largely malaria-free, though endemic areas of malaria do exist distant from the forest and foothill regions. *An. nivipes* and *An. aconitus* are also widespread in Laos and the latter dominates dry season collections<sup>104</sup>. Although they have a tendency to feed on animals outdoors unlike the three major vector species, both have been found biting humans indoors throughout the night, and both have been incriminated as vectors in neighbouring Thailand. This suggests these species may be important local vectors in Lao PDR. Both species breed in areas not favoured by *An. dirus*, *An. minimus* or *An. maculatus*, namely lowland cultivation sites, ricefields and irrigation channels containing slow moving water with much vegetation<sup>105</sup>.

#### *Malaysia*

##### Peninsular Malaysia

Of the 68 species of *Anopheles* that have been recorded in Malaysia, only nine have been shown to be vectors of malaria<sup>106</sup>. *An. maculatus* is incriminated as the main vector of malaria in the interior hilly regions near the Thai border<sup>107</sup>. It has been captured while biting humans both indoors and outdoors over a prolonged period (18.30-06.30 hrs) during which biting activity is sustained at a similar level. The highest peak of indoor biting was observed at 21.30 hrs. *An. maculatus* is a prolific breeder in clear slow-moving streams exposed to sunlight<sup>106</sup>. Most malaria cases on the peninsular are found in remote regions or are associated with forest clearance for agriculture or new roads, which opens up streams and ponds favoured by *An. maculatus*<sup>108</sup>. The outdoor feeding *An. aconitus* is considered a secondary vector to *An. maculatus* in the dry season in foothills near the Thailand-Malaysia border<sup>109</sup>.

*An. campestris* prefers to feed on people indoors and is an important vector in the plains<sup>24</sup> where it breeds in paddy fields, and a secondary vector in coastal regions where it breeds in brackish waters<sup>110</sup>. *An. letifer* is the most important coastal vector. The larvae are found in cold, calm

acidic brackish waters at the forest fringes and in swamps. Though it prefers feeding on animals such as cattle and chickens, it has been found biting humans outdoors.

#### East Malaysia – Sabah and Sarawak

*An. balabacensis* is the most important interior forest vector in Sabah. It is highly anthropophilic with up to 90% of bloodmeals taken from humans<sup>106</sup>. *An. balabacensis* and *An. flavirostris*, have both been found with high proportions of human blood meals, and represented 90% of light-trap catches on Banggi Island<sup>111</sup>. Of the *An. balabacensis* collected 5.0% were infective with sporozoites - an extremely high percentage. Both species breed in temporary ponds and pools.

*An. leucosphyrus* frequently feeds indoors and then leaves and rests outdoors. It is the most important inland vector in hilly areas of Sarawak, whilst *An. donaldi* is a secondary vector. Both species are more likely to feed on animals than *An. balabacensis* but nevertheless significant numbers are found in indoor catches. *An. leucosphyrus* breeds in shaded swampy regions in Sarawak and *An. donaldi* breeds in open marshlands. Both species dominate farm hut collections in mountainous regions and both have tested positive for the presence of malaria parasites<sup>112</sup>. In the coastal areas of both Sabah and Sarawak *An. sundaicus* has been incriminated as a vector species, but the proportion of cases transmitted by this mosquito is very low except amongst people living close to its breeding sites<sup>89</sup>. The propensity of the three most important vectors in Malaysia, *An. maculatus*, *An. balabacensis* and *An. leucosphyrus*, to rest and bite outdoors has limited the effectiveness of residual spraying control measures<sup>113</sup>.

#### Papua New Guinea

Members of the *An. punctulatus* complex are the important vectors of malaria in Papua New Guinea (PNG). In the north-western interior Attenborough *et al.*<sup>114</sup> found *An. punctulatus sensu stricto* to be the predominant vector in the highlands above 650m. Below 240m more than 93% of the anopheline mosquitoes captured were *An. koliensis*. Both species tested positive for sporozoites; positivity rates ranged from 0.6-2.3%, depending on altitude. Both species have been shown to feed exclusively on humans in the absence of domestic pigs<sup>115,116</sup>. The only other important vector species of PNG is *An. farauti*, a competent vector of *P. vivax* and *P. falciparum*<sup>117</sup>. It is distributed widely across PNG with marked behavioural variation depending on location. Larvae have been found in both fresh and brackish water<sup>118</sup>. This discovery ultimately led Foley *et al.*<sup>118</sup> to recognise more than one species within the taxon *An. farauti sensu lato*. These species are frequently found together in PNG but may be more important in coastal regions where *An. punctulatus* and *An. koliensis* do not occur in great numbers. The different species comprising *An. farauti s.l.* have all been caught feeding on people and it is therefore important to establish the vectorial importance of each species at specific locations before recommendations for control are made.

#### Philippines

Here several islands are vector-free, although *An. flavirostris* is the primary vector in Mindanao and Palawan. In Palawan it averages 22 bites/man/night with 1.6% of mosquitoes having sporozoites<sup>119</sup> and represents almost 60% of the Anophelines caught in outdoor catches and 79% of indoor catches. *An. annularis* represented 37% of the outdoor catch and 19% of the indoor catch, though its role as a vector in the Philippines is uncertain. *An. littoralis* is an important saltwater vector in the Sulu archipelago<sup>24</sup>.

#### Thailand

*An. dirus* is the major vector throughout much of the country. Of four anopheline species collected from human bait in eastern Thailand, only *An. dirus* was found infected with *P.*

*falciparum*<sup>120</sup>. However the dominance of this species is confused by the presence of at least five species that look almost identical but each with distinct biting activity, seasonal abundance and geographic distribution<sup>121</sup>. Some members of the *An. dirus* complex feed predominantly on people outdoors, transmitting malaria at forest fringes, orchards and tree plantations (Rosenburg *et al.*, 1990 in<sup>105</sup>). As in Lao PDR, *An. dirus* larvae are found in temporary ground water in soil without vegetation<sup>122</sup> or in slow-moving streams in forested areas<sup>23</sup>. The other primary malaria vectors in Thailand, *An. minimus* and *An. maculatus*, feed more frequently on animals than does *An. dirus*, though the latter is an important early evening biting vector in southern and peninsular Thailand where it is associated with hilly forest zones and rubber-plantation areas<sup>123</sup>. *An. minimus* may be the principal vector in the dry season and early rainy season when *An. dirus* numbers are low<sup>122</sup>. Rainfall has less effect on the breeding and therefore the seasonal prevalence of *An. minimus*<sup>124</sup>. The early morning outdoor biting habit of *An. minimus* in the wet season may also increase the efficiency of this species as a vector<sup>125</sup>. Larvae of both *An. minimus* and *An. maculatus* have been found in a variety of habitats such as stream margins, gravel pits and water-filled animal tracks<sup>122,125</sup>. This may also reflect the fact that like *An. dirus*, both are species complexes<sup>23</sup>.

Vectors of secondary importance include *An. aconitus* and *An. philippinensis*, which breed in rice field habitats, and *An. sundaicus*, associated with coastal and mangrove wetland zones<sup>23</sup>.

#### *Solomon Islands*

Coastal malaria transmitted by *An. farauti* is of most importance in the Solomon Islands. This mosquito is an efficient vector, transmitting *P. falciparum* as well as *P. vivax*. It breeds in almost any type of water body and tolerates salinity in excess of 0.8%. *An. farauti* bites outdoors relatively early in the evening, though this is possibly a result of the genetic selection pressure of control interventions. *An. koliensis* and *An. punctulatus* are also important vectors but at a highly localised level<sup>24</sup>.

#### *Vanuatu*

*An. farauti* is the only vector of malaria on the islands of Vanuatu<sup>24</sup>.

#### *Viet Nam*

The important vector species *An. minimus* is found in the foothills throughout much of the country<sup>126</sup> where it breeds in open flowing brooks and streams<sup>127</sup>. *An. aconitus* and *An. jeyporiensis* are considered secondary vectors or of local importance in the north of the country<sup>37</sup>. *An. dirus* is absent in the north but predominates in the central provinces and has been found to carry infective stages of the malaria parasite (sporozoites). It is a forest vector dependent on rainwater collections and breeding in tree holes, small pools, footprints and wheel tracks<sup>127</sup>. *An. dirus* is still relatively sensitive to most insecticides and is the primary target for vector control in the area<sup>128</sup>. The effectiveness of spraying is however limited by the mosquito feeding and resting outdoors<sup>126</sup>. In coastal areas of southern Viet Nam *An. sundaicus* is the most important vector where it breeds in stagnant saltwater<sup>127</sup>. The larvae of both *An. sundaicus* and the potentially important *An. subpictus* occupy floating plant masses exposed to full sunlight<sup>129</sup>. Peak numbers of *An. sundaicus* coincide with an increase in malaria cases each year in April and May<sup>127</sup>. *An. nimpe* has been incriminated as a secondary vector by ELISA detection of *P. falciparum* and *P. vivax*<sup>130</sup>. It occurs sympatrically with *An. sundaicus* and *An. subpictus* in brackish water, but the larvae are found independent from those of the other species, preferring shaded spots among emergent grasses and plants<sup>129</sup>.

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