Tropical Medicine and International Health

VOLUME 6 NO 9 PP 677–687 SEPTEMBER 2001

Efficacy and cost-effectiveness of environmental management for malaria control

Jürg Utzinger[1], **Yesim Tozan**[2] **and Burton H. Singer**[1]

1 *Office of Population Research, Princeton University, Princeton, USA*
2 *Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, USA*

Summary Roll back malaria (RBM) aims at halving the current burden of the disease by the year 2010. The focus is on sub-Saharan Africa, and it is proposed to implement efficacious and cost-effective control strategies. But the evidence base of such information is scarce, and a notable missing element is the discussion of the potential of environmental management. We reviewed the literature and identified multiple malaria control programmes that incorporated environmental management as the central feature. Prominent among them are programmes launched in 1929 and implemented for two decades at copper mining communities in Zambia. The full package of control measures consisted of vegetation clearance, modification of river boundaries, draining swamps, oil application to open water bodies and house screening. Part of the population also was given quinine and was sleeping under mosquito nets. Monthly malaria incidence rates and vector densities were used for surveillance and adaptive tuning of the environmental management strategies to achieve a high level of performance. Within 3–5 years, malaria-related mortality, morbidity and incidence rates were reduced by 70–95%. Over the entire 20 years of implementation, the programme had averted an estimated 4173 deaths and 161 205 malaria attacks. The estimated costs per death and malaria attack averted were US$ 858 and US$ 22.20, respectively. Over the initial 3–5 years start-up period, analogous to the short-duration of cost-effectiveness analyses of current studies, we estimated that the costs per disability adjusted life year (DALY) averted were US$ 524–591. However, the strategy has a track record of becoming cost-effective in the longer term, as maintenance costs were much lower: US$ 22–92 per DALY averted. In view of fewer adverse ecological effects, increased sustainability and better uses of local resources and knowledge, environmental management – integrated with pharmacological, insecticidal and bednet interventions – could substantially increase the chances of rolling back malaria.

keywords cost-effectiveness, efficacy, environmental management, integrated control, malaria, Roll Back Malaria

correspondence Jürg Utzinger, Princeton University, Office of Population Research, Princeton, NJ 08544, USA. Fax: 00-1-609-258 1039; E-mail: utzinger@princeton.edu

Introduction

Thirty years after the abandonment of the first ‘global’ campaign to eradicate malaria, the disease is again high on the international health agenda. Roll Back Malaria (RBM) is the new initiative and was first announced in May 1998 (WHO 1998). Its ambitious goal is halving the current malaria burden by the year 2010 and again 5 years later (Nabarro & Tayler 1998). There are four central features which distinguish RBM from the former attempts to eradicate malaria. First, emphasis is placed on malaria control instead of eradication. Second, the main focus is on sub-Saharan Africa, whereas before interventions were mainly targeted to the Americas, Asia and endemic areas of Europe (Baird 2000). Third, it is a global partnership between development agencies, banks, the private sector, non-governmental organizations, foundations and a network of researchers. Fourth, it follows a horizontal approach and promotes the strengthening of local capacities and health systems, so that malaria can be dealt with locally (Nabarro & Mendis 2000). As RBM has been launched, the initiative has obtained wide publicity and a pledged financial support of US$ 1 billion per year in the form of grants and loans (Dove 2000). In view of a figure of this order of magnitude and the commitment by the various partners, RBM should not be allowed to fail (Anonymous 2000).

With the emphasis currently shifting from campaigning to implementation, there is a pressing need for information about the efficacy and cost-effectiveness of different intervention strategies, which might guide policy makers about how available resources can be used to obtain the maximum possible social benefit (Hutubessy *et al.* 2001). However, the existing evidence-based knowledge is sparse and has been derived from a very limited number of studies. This was emphasized in a recent analysis of the cost-effectiveness of several malaria control measures in sub-Saharan Africa (Goodman & Mills 1999; Goodman *et al.* 1999). The researchers identified 14 individual studies which aimed at prevention and treatment of malaria, and assessed cost-effectiveness by using a modelling approach. The interventions included insecticide-treated bednets, indoor house spraying, chemoprophylaxis in childhood or pregnancy, intermittent treatment for pregnant women, improved malaria treatment and a hypothetical vaccine. Importantly, under the assumption of a low-income country with high levels of malaria transmission, all interventions assessed appear to be cost-effective, at least in the short run. At present, no comparable cost-effectiveness analysis has been undertaken for environmental management, although this might be a potentially important component of a package of interventions to control malaria and sustain it in the long term (Goodman *et al.* 1999; Lerer 1999). Lack of data may have precluded such analyses.

We reviewed the literature about effective malaria control programmes in sub-Saharan Africa and identified a comprehensive study implemented at copper mines of the former Northern Rhodesia (now Zambia) between 1929 and 1949 (Watson 1953). The programme applied a multiplicity of interventions, most of which were centred on environmental management (vegetation clearance, modification of river boundaries, draining swamps, oiling and house screening). For some of the employees, it also included quinine administration for prevention and cure of malaria, and provision of mosquito nets. Costs were recorded, including physical resources and unit prices, and systematically accounted to the same cost position throughout the programme. Mortality, morbidity, malaria incidence rates and vector densities were monitored. We re-analysed the data and estimated the number of deaths, malaria attacks and DALYs averted, which allowed subsequent comparison of efficacy and cost-effectiveness of environmental management with other, currently more widely used malaria control interventions.

Materials and methods

Study identification

We searched electronic on-line abstracting databases (Biological Abstracts®, BIOSIS, Philadelphia, PA, USA; and MEDLINE®, US National Library of Medicine, Bethesda, MD, USA) for successful malaria control programmes in sub-Saharan Africa that incorporated environmental management as the central feature. We used the following keywords: environmental management, malaria control, Africa, cost(s) and cost-effectiveness analysis. As a result we obtained a large number of references, which were scrutinized for detailed cost data of environmental management interventions and specific malaria related outcomes. None of the publications matched our requirements. We then hand searched the bibliographies of the most relevant manuscripts and also discussed the topic with malariologists. These two approaches guided us to the old literature of the pioneering work carried out in the first decades of the last century, before the advent and widespread use of dichlorodiphenyltrichloroethane (DDT).

Roan Antelope copper mine

We identified a large-scale, multifaceted malaria control programme that incorporated environmental management as the central feature. The records included a detailed account of costs, specifying for each environmental management intervention its physical resources and unit prices. The programme was initiated towards the end of 1929 at the Roan Antelope copper mine of Zambia, located in the Ndola Rural district, near the town of Luanshya. The area was known to be hyperendemic for malaria, as seen from the earliest medical records at the beginning of the programme implementation (Watson 1953). Subsequently, control interventions were extended to several copper mining sites nearby and control strategies implemented for two decades (Watson 1953). At the time, Zambia was known as Northern Rhodesia and was governed by the British colonial authority.

Zambia's first national malaria survey between 1969 and 1972 confirmed that malaria was highly endemic in the Ndola Rural district: 26.4% of the participants taken from a random population sample had malaria parasites in their blood. *Plasmodium falciparum* was the predominant species accounting for 86.8%, while *P. malariae* was found in 13.2% of malaria-positive subjects (Wenlock 1978). Recent empirical approaches, assessing the distribution limits of *P. falciparum* transmission in sub-Saharan Africa, confirmed that the Ndola Rural district is characterized by stable endemic malaria conditions (Snow *et al.* 1999).

Entomological surveys

At the beginning of the anti-malarial work at the Roan Antelope copper mine, detailed entomological surveys were conducted in the designated control area. Mosquito larvae and adults were collected and identified. Adult mosquitoes were examined for the presence of blood, so that potential malaria vectors could be distinguished from other species of no medical importance. Subsequently, the larval habitat preferences of the malaria vectors were investigated ecologically in detail. This formed the knowledge base for tailoring environmental management strategies, designed to remove or modify these larval habitats. Finally, a system of vector surveillance and monitoring was established, with weekly catches of adult mosquitoes in a number of selected locations within and outside the designated control area.

Environmental management

Multiple interventions, focusing on environmental management and targeting the larval stages of *Anopheles gambiae* and *A. funestus*, were put in place from November 1929 onwards. In the beginning, 300 men were recruited for implementing environmental management strategies, which consisted of:

- vegetation clearance along the Luanshya River and its tributaries;
- modification of river boundaries and removal of man-made obstructions; and
- draining flooded areas and swamps.

After the first year of interventions, the water level of the main river had decreased substantially and the velocity was high enough to interrupt larval development. Subsequently, these interventions were maintained and accompanied by the regular application of oil to open water bodies. Finally, houses were screened to stop adult malaria vectors entering the houses. Surveillance and monitoring of weekly adult mosquito catches and monthly malaria incidence rates served as tools for ongoing programme evaluation. After successful testing of the residual effect of DDT outside the designated control area, DDT was widely applied as an additional intervention strategy from late January 1946 onwards and served mainly as an adulticide.

Mortality, morbidity and malaria incidence

During the first 12 months of copper exploitation at the Roan Antelope mine, detailed records were kept with an appraisal of the causes of death among Europeans. The total number of Europeans who died of malaria between 1932 and 1938 are also available. Annual mortality rates as a result of diseases, recorded separately for Europeans and Africans, were monitored for the entire 20 years of programme implementation. The splenomegaly rates of children younger than 15 years living on the mine's compound were assessed at the beginning of the programme and again 5 years later. These rates were also compared with splenomegaly rates measured among children living outside the control area. Monthly malaria incidence rates among the mine employees were recorded throughout the 20-year implementation period.

Death, malaria attacks and DALYs averted

The total number of deaths averted because of the implementation of the malaria control programme was estimated by the reduction of the malaria-related mortality rate and the total person life years at risk over the entire intervention period. The total malaria attacks averted were estimated by the reduction of the annual malaria incidence rate multiplied by the total person life years at risk.

Disability adjusted life years averted were estimated following the methodology developed for the Global Burden of Disease study (Murray & Lopez 1996). We assumed equal malaria mortality and morbidity rates for Africans and Europeans of both genders. We stratified the Roan Antelope mine population into three age groups:

- 0–4 years;
- 5–15 years; and
- over 15 years.

Population estimates and corresponding age-specific percentages were calculated according to figures provided by Snow *et al.* (1999) for Africans living under stable malaria transmission. The annual population estimates of the mine were extrapolated from the available population data at the beginning of the control programme, and in 1939/1940 and 1949/1950 (Watson 1953). DALYs were calculated using a life expectancy at birth of 50 years from a West African model life table (United Nations 1982). A discount rate of 3% was used as suggested for standard calculation of DALYs without weighting for age, as its quantitative effect has been demonstrated to be of minor importance (Murray & Lopez 1996). The annual malaria mortality rates before and after programme implementation were calculated by dividing the total number of deaths caused by malaria by the corresponding population at risk. The number of clinical attacks and deaths for each age group in a given year were estimated by using age-specific morbidity and mortality rates provided by Snow *et al.* (1999). As no data were available on neurological sequelae and anaemia, we only used the number of clinical malaria attacks before and after programme intervention to calculate years of healthy life lost because of disability. From the original treatment records, disability duration of 9 days was derived for a single malaria attack (Rodger 1944; Watson 1953). DALYs averted were then estimated as the difference between those that would have been obtained without programme intervention and those with intervention.

Programme efficacy and cost data

Programme efficacy was evaluated by comparing data obtained at baseline surveys, i.e. before the implementation of control measures, with those obtained during the maintenance phase of the environmental management interventions. We used site-specific historical controls of malaria-related mortality, children's splenomegaly rate, malaria incidence and vector densities and estimated the reduction rates of these indicators over the course of programme implementation.

Detailed cost data for the control programme were obtained from the published programme budget. It included the high capital investment (recruitment of 300 men for vegetation clearance, modification of river boundaries and drainage of swamps) and the annual maintenance costs of these interventions, together with regular oiling of open water bodies. For each intervention, the physical resources and unit prices were specified. All costs were recorded in British pounds and the records suggest that costs were systematically accounted to the same cost position throughout programme implementation (Watson 1953). We converted these total annual costs in US$ according to British historical statistics, which use an average of daily quotations (Mitchell 1988). Costs were then converted into 1995 US$, using the purchasing power of the dollar, derived from the US consumer price index (US Census Bureau 1966, 1999).

Cost-effectiveness analysis

The costs per death and malaria attack averted were estimated by using the cumulative costs of the environmental management interventions implemented over the entire 20 years, and the estimated number of deaths and malaria attacks averted as a result of control measures. We estimated the costs per DALY averted during the initial 3–5 years start-up period. Our calculations of the costs per DALY averted included the high initial capital costs. Costs per DALY averted were also calculated for 3-year intervals during the maintenance phase of the programme. These time periods are analogous to the short duration of current studies that are the basis of cost-effectiveness analyses (Goodman & Mills 1999).

Results

Roan Antelope copper mine

When copper mining commenced at the Roan Antelope mine in mid 1927, malaria was highly endemic and probably the leading cause of death. It was difficult to attract labour, particularly for night shifts, and workers expressed great fear of dying if they were to stay permanently. The first official labour register recorded a total work force of 1100 men, but within a few months only 700 remained at the mines. The others had abandoned the site. According to the traditional beliefs in the local communities, the nearby Luanshya River was the major source of illness. In order to avoid the risk of becoming sick, people had moved away from the vicinity of the river many years before copper mining started (Watson 1953). However, shortly after environmental management strategies for malaria control were put in place, the local people's beliefs about the danger of the river disappeared. New labour forces were attracted with ease, and the company grew rapidly. The designated control area had a size of approximately 32 km^2 and is depicted in Figure 1.

Initially, housing conditions were improved and houses were screened. Water supply and sanitation facilities were also improved and a hospital with basic diagnostic services was established. In addition to the environmental management strategies that protected everyone, additional control measures for Europeans and some of the African employees consisted of:

- quinine administration for prophylaxis and treatment of malaria; and
- sleeping under mosquito nets.

Baseline surveys

The total population initially living on the mining compound was estimated at 6067, more than 80% of whom were Africans. Re-analysis of the first health statistics among 1067 Europeans in the years 1929–1930 confirmed that malaria was hyperendemic; 11 deaths were directly or indirectly related to malaria, therefore accounting for 44% of the total deaths. At this time, the overall annual mortality rate as a result of diseases was 23.4 per 1000. During the first year of record keeping, the malaria incidence rate among company employees was high and reached 514 per 1000 (Table 1). The monthly incidence rates revealed that malaria transmission occurred

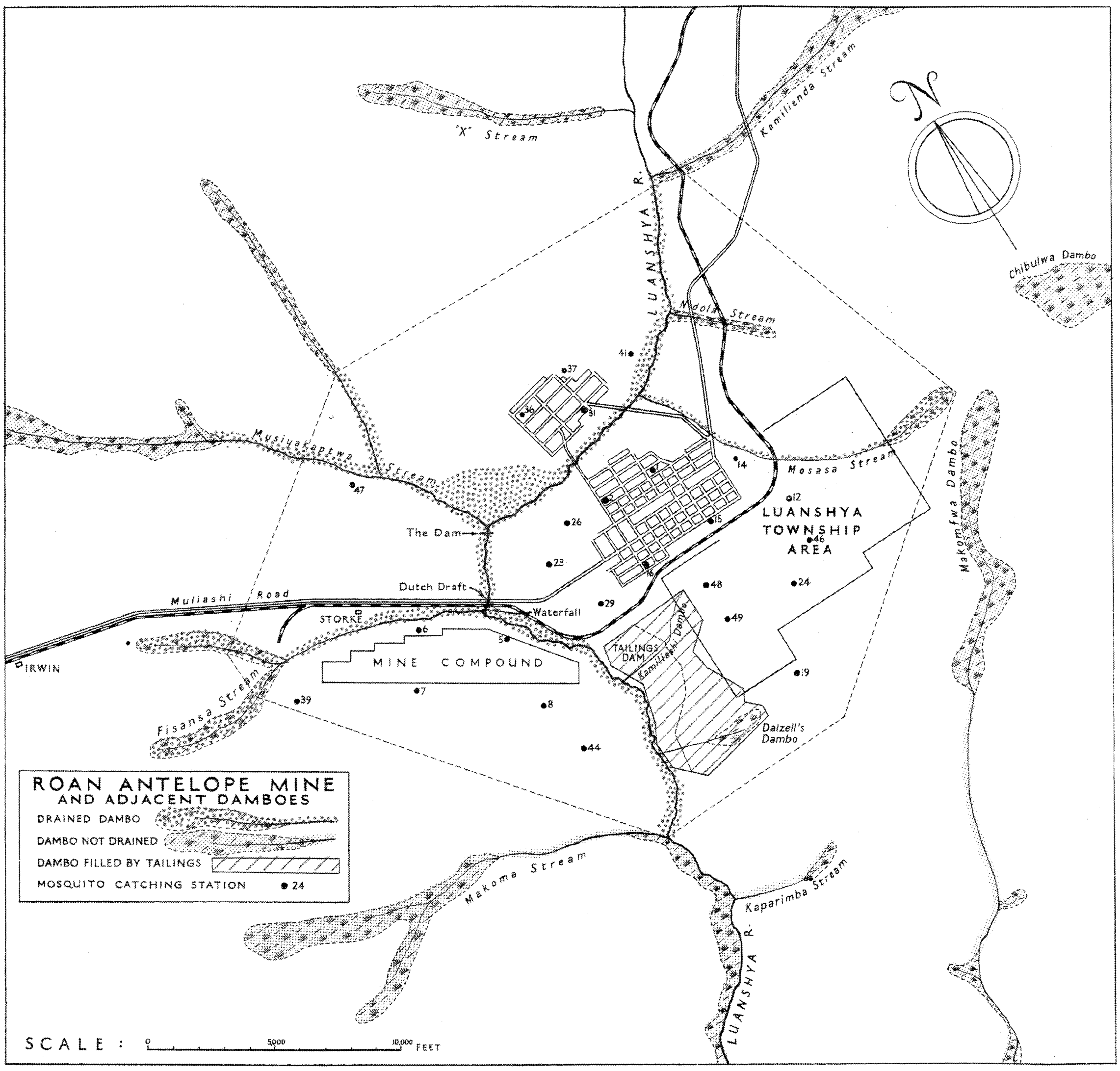

Figure 1 Roan Antelope copper mine with designated malaria control area for environmental management interventions (Source: Watson 1953).

throughout the year with a distinct peak towards the end of the rainy season in March/April. The baseline splenomegaly rate measured in 232 children younger than 15 years and living on the mining site was 36% (Table 1).

Entomological baseline surveys revealed that *A. funestus* and *A. gambiae* were the predominant malaria vectors. While *A. funestus* accounted for approximately 80% of adult catches, *A. gambiae* was the most abundant species encountered in larval catches. Detailed ecological studies on the larvae's habitat preferences showed that *A. gambiae* was found in open and unshaded natural or man-made pools close to the Luanshya River and its tributaries, as well as in open water tanks and in native wells loosely overgrown with grass. Reduction and elimination of such habitats was relatively straightforward. In contrast, *A. funestus* larvae preferred the shaded banks of the Luanshya River and its tributaries, and were also found in flooded areas and swamps, which were normally formed and sustained for an extensive period after the rainy season. Management of this aspect of the ecosystem was more challenging.

Table 1 Characteristics of the mine population, disease- and malaria-related mortality, children's splenomegaly rate and malaria incidence rate before the implementation of malaria control measures (1929/1930) 10 years later (1939/1940) and at the end of the programme (1949/1950)

	Year		
	1929/1930	1939/1940	1949/1950
Population			
Africans	5000	20 610	36 481
Europeans	1067	1976	4025
Overall mortality as a result of diseases (per 1000 per annum)			
Africans	32.3	3.5*	3.7
Europeans	23.4	3.9*	4.6
Malaria-related mortality (per 1000 per annum)			
Europeans	10.3	0.5†	–
Splenomegaly rate in children < 15 years (%)	36	6‡	
Malaria incidence (per 1000 per annum)	514	135§	16¶

*Average for years 1938, 1939, 1940 and 1941.

†Between 1932 and 1938, there were approximately 10 000 European life years at risk of malaria, with five deaths occurring because of malaria.

‡Assessed in April 1935, among 203 children born on Roan Antelope mine (splenomegaly rate among children living in a nearby village: 45%).

§Between November 1937 and October 1942 a total of 1619 malaria attacks were recorded among Europeans, with an estimated population of 2300–2500 (Source: Rodger 1944).

¶Malaria incidence dropped substantially after the extension of the control area and regular DDT application from 1946 onwards.

Reduction in mortality, morbidity and malaria incidence

Mortality rates as a result of diseases over the entire period of programme implementation, stratified by Europeans and Africans, are shown in Figure 2. There was a tremendous decrease in overall mortality rates, which occurred shortly after environmental management strategies were put in place. The mortality rate among the European community, which was 23.4 per 1000 from April 1929 to March 1930, dropped to 13.2 in the year 1930 and was reduced by more than 50% in the subsequent year. Very similar reductions were also observed for the African population. Between 1935 and 1948 the annual mortality rates as a result of diseases remained relatively stable at a low level of 3–6 per 1000 (Table 1). Although individual accounts of the exact causes of each death are not available for the entire 20 years of programme implementation, it is most likely that the overall reduction of mortality is mainly because of the reduction of malaria. This is well illustrated by the fact that the initial malaria-related mortality rate of 10.3 per thousand Europeans was reduced to 0.5 between 1932 and 1938, as only five Europeans died of malaria, with approximately 10 000 years of European lives at risk during this period (Watson 1953) (Table 1).

The reduction in children's splenomegaly rate was equally impressive. The initial splenomegaly rate of 36% before programme implementation dropped to 6%, as measured among 203 children < 15 years of age, 5 years after the malaria control programme was initiated. A cross-sectional survey in the mid-1930s among European children attending the Government school of Luanshya confirmed that malaria control measures were efficacious. There were only three of 207 children presenting evidence of malaria. At the same time the splenomegaly rate among 51 children living outside the control area was 45%.

The baseline annual malaria incidence rate among mine employees of 514 per 1000 was halved after the first year of intervention (263 per 1000 in 1930) and again 1 year later (151 per 1000 in 1931). It remained stable at the lower level for the next 2 years, following a seasonal pattern with a distinct peak occurring towards the end of the rainy season in March/April (Figure 3). There were a total of 1619 malaria cases among Europeans between the end of 1937 and the end of 1942 (Rodger 1944). In this period, the European population was estimated at 2300–2500. Thus, there were between 11 500 and 12 500 person years at risk of malaria attacks, accounting for an annual malaria incidence rate of 130–141 (mean 135). Another sharp decline in the annual malaria incidence rate occurred shortly after the control area was expanded and DDT was systematically applied in the mid-1940s (Table 1).

Death, malaria attacks and DALYs averted

Based on the annual population estimates, 425 342 person life years were at risk of malaria during the entire 20 years

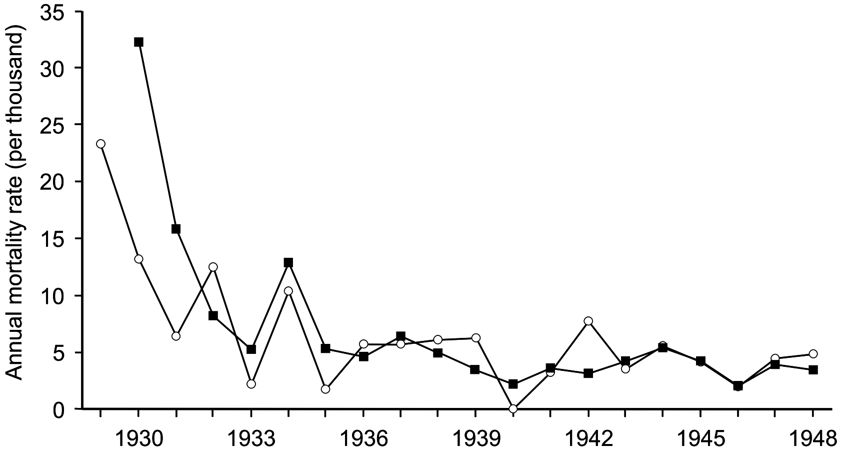

Figure 2 Annual mortality rates due to diseases among Europeans (○) and Africans (■) living and working at the Roan Antelope copper mine (Source: Watson 1953).

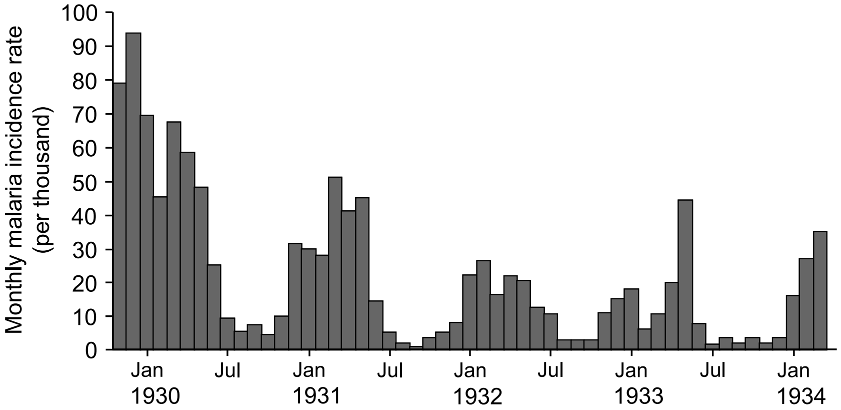

Figure 3 monthly malaria incidence rates among copper mine employees between November 1929 and March 1934 (Source: Watson 1953).

of programme implementation. The control programme reduced the annual malaria-related mortality rate from 10.3 to 0.5 per 1000 and the incidence rate dropped from 514 to 135 per 1000. Therefore, the control programme averted an estimated 4173 deaths and 161 205 malaria attacks (Table 2).

During the 3–5 years start-up period, the implementation of the control programme averted an estimated 2439–3172 DALYs. Because the population grew steadily over the course of programme implementation, and malaria-related mortality and incidence rates remained stable, the number of DALYs averted increased in proportion to the total population estimates. For example, the number of DALYs averted during the 3-year period of 1934–1936 was 3618, and increased to 10 976 for the period of 1947–1949 (Table 2).

Cost of environmental management

Table 3 shows the capital investment and the annual maintenance costs of the environmental management interventions for the entire 20 years implementation period in British pounds and corresponding 1995 US dollars. The cumulative costs were almost US$ 3.6 millions. There was a high initial capital investment of more than US$ 1 million, or US$ 167 per person living at the Roan Antelope copper mine. Before widespread use of DDT in 1946, the annual maintenance costs ranged between US$ 103 666 and 190 279, or US$ 5.2–23.4 per person.

The estimated cost per death averted over the entire programme implementation was US$ 858. Averting a malaria attack was estimated to cost US$ 22.20 (Table 2). During the first 3–5 years of programme implementation, the costs per DALY averted were relatively high, ranging from US$ 524–591, largely because of the high initial capital investment. Costs per DALY averted decreased substantially over the course of programme implementation. They were US$ 92 for the 3-year maintenance period of 1934–1936 and dropped to US$ 22 for the last 3-year increment of 1947–1949.

Table 2 Estimated deaths, malaria attacks and DALYs averted because of malaria control measures and corresponding costs

	Estimated cases averted	Cumulative costs (1995 US$)	Cost/case averted (1995 US$)
Deaths			
Entire period: 1930–1949	4173	3 578 611	857.56
Malaria attacks			
Entire period: 1930–1949	161 205	3 578 611	22.20
DALYs			
3 years start-up: 1930–1933	2439	1 442 767	591.49
5 years start-up: 1930–1935	3172	1 663 424	524.36
Maintenance: 1934–1936	3618	331 240	91.56
Maintenance: 1937–1939	5366	417 121	77.73
Maintenance: 1940–1942	6969	419 828	60.24
Maintenance: 1943–1946	9034	724 873	80.24
Maintenance: 1947–1949	10 976	242 782	22.12

Table 3 Total monetary investment for environmental management in the Roan Antelope copper mine for the entire programme implementation between 1930 and 1949. Annual costs in British pounds (£) were converted into 1995 US$. Cumulative costs and annual costs per person were also calculated based on population estimates

Year	Total annual costs (in £)	Exchange rate (£ to US$)	Purchasing power (1995 US$ = 1.000)	Annual costs (1995 US$)	Cumulative costs (1995 US$)	Population estimates	Annual costs per person
1930	25 000.00	4.862	8.335	1 013 119	1 013 119	6067	167.0
1931	3251.00	4.277	9.864	137 154	1 150 273	6919	19.8
1932	4749.00	3.504	11.103	184 759	1 335 032	7891	23.4
1933	2338.98	4.218	10.920	107 735	1 442 767	9000	12.0
1934	2142.81	5.041	9.597	103 666	1 546 433	10 264	10.1
1935	2654.18	4.903	8.990	116 991	1 663 424	11 706	10.0
1936	2498.10	4.971	8.905	110 583	1 774 007	13 351	8.3
1937	2727.97	4.944	8.335	112 415	1 886 422	15 226	7.4
1938	3405.85	4.890	9.148	152 356	2 038 778	17 365	8.8
1939	3660.83	4.460	9.331	152 350	2 191 128	19 804	7.7
1940	3937.43	4.030	9.148	145 159	2 336 287	22 586	6.4
1941	4225.41	4.030	8.232	140 178	2 476 465	24 100	5.8
1942	4582.23	4.030	7.283	134 491	2 610 956	25 717	5.2
1943	6213.00	4.030	6.979	174 743	2 785 699	27 441	6.4
1944	6829.00	4.030	6.914	190 279	2 975 978	29 281	6.5
1945	6805.00	4.030	6.792	186 265	3 162 243	31 244	6.0
1946	7249.00	4.030	5.942	173 586	3 335 829	33 339	5.2
1947	4586.00	4.030	4.848	89 599	3 425 428	35 575	2.5
1948	5235.85	3.680	4.478	86 282	3 511 710	37 960	2.3
1949	5070.68	2.800	4.712	66 901	3 578 611	40 506	1.7

Discussion

Our detailed re-analysis of a complex malaria control programme, built around environmental management and launched more then 70 years ago and sustained for two decades at the Roan Antelope mine of the copper belt in Zambia, revealed that the programme was highly successful. One year after interventions were put in place, the overall mortality and malaria incidence rates were reduced by approximately 50%. Malaria-related mortality and morbidity, as well as monthly malaria incidence rates continued to drop substantially, and they were reduced by 70–95% within 3–5 years after the onset of interventions. Reductions of this order of magnitude are striking, particularly for a malaria control programme being implemented in a highly endemic area of sub-Saharan Africa, where the most efficient malaria vectors occur (Rodger 1944; Watson 1953; Wenlock 1978). Calculation of reductions in malaria-related mortality, morbidity and incidence was obtained by comparing baseline rates before interventions with those observed over the course of programme implementation – an assessment based on historical controls.

The use of historical controls in this setting is justified on several grounds. First, the entire mining community is the unit of analysis, and the details of the environmental management components were tuned to the local ecology. Secondly, although data that are comparable, and largely concurrent, to that assembled for the Roan Antelope mine are available for three other mining communities in the Zambian copper belt (Watson 1953), the ecological variation across communities is sufficiently great that the notion of comparison, or even control communities makes no sense. This stands in stark contrast to the randomized controlled trials, assessing the efficacy of a single intervention (e.g. insecticide treated bednets or novel antimalarial drugs or combination therapy), where the notion of concurrent comparison groups can be justified (Choi *et al.* 1995; Goodman & Mills 1999; Goodman *et al.* 1999). In effect, by using a community in its pre-intervention condition as a control, we are comparing the consequences of an intervention with what would be the natural history of transmission in the unperturbed state of the same ecosystem. Analogous evaluation strategies for complex programmes arise in a myriad of contexts – e.g. rehabilitation programmes for chronic heroin addicts or alcoholics (Dole *et al.* 1982; Singer 1986).

Emphasis of the malaria control programme evaluated here was on environmental management, and an array of interventions was applied simultaneously. They were targeted at source reduction of larval habitats of the predominant malaria vectors. During the last 5 years of the programme, DDT also came into play. Compared with other, currently more widely used malaria control measures, the programme was unique in many ways. First, it ran for an extensive period of time; namely, 20 years. Second, monthly malaria incidence rates and weekly adult malaria vector densities were used as ongoing system of surveillance and monitoring. Although sharp declines in malaria-related outcome measures were observed shortly after the programme was initiated, it was only after 3–5 years that the package really performed well. Outcome indicators remained stable thereafter, at much lower levels than in the pre-programme years. Third, the programme was well organized and rigorously implemented by the mining authorities, using a flexible approach, and a system of mobilization, motivation and supervision of the local communities carrying out the control measures. Fourth, malaria control *per se* was not an altruistic goal in the context of health promotion for a community. It was simply a necessity to attract and sustain labour for the exploitation of a natural resource. It was a sound investment that led to prosperity. Fifth, there was sustained in-migration, because the total population grew at an annual rate of approximately 10%, which is unusual for sub-Saharan Africa and elsewhere, and can only be explained by an efficient malaria control programme that had been put in place. It is likely that the Roan Antelope mine would have suffered a ruinous outcome if it failed to control malaria, analogous to what the Dutch East India Company experienced in the 18th century (van der Brug 1997).

It is interesting to compare the efficacy and cost-effectiveness of the integrated control programme reviewed here with other malaria interventions that are currently used. The reductions in malaria-related outcome measures were considerably higher than those observed in other malaria control programmes, probably because of the nature of the integrated control approach, implementing a multiplicity of interventions simultaneously. In this context it is crucial that the performance of each intervention in the package of interventions contributes to the overall success of the programme. To achieve this goal, the design and the evaluation methods of the control programme need sufficient flexibility to retarget and redesign existing interventions to ultimately obtain the desired outcome. Interestingly, a promising experimental design stems from industrial management in the 1960s, known as ‘evolutionary operation’ (EVOP) for process improvement (Box & Draper 1969). The basic idea is to start with a given operation mode, based on the best available knowledge. It is then followed by an evolutionary development scheme, applying a carefully planned set of variations to the components of the process in consecutive cycles. The malaria control programme reviewed here is an excellent example of this approach, and it is surprising how creative the design was at the time of implementation. Malaria incidence rates and adult mosquito densities were monitored from the onset of implementation and facilitated the adaptive tuning of the interventions, so that the package displayed a high level of performance. Although the concept of EVOP has been successfully applied in many fields – e.g. selections among strains of crop plants or screening of chemical compounds for therapeutic uses (Finney 1984) – its application to tropical disease control has been neglected so far.

Our estimated costs of US$ 858 per death averted was between the cost-range of US$ 219 and 2958 estimated for insecticide treated bednets in The Gambia, Ghana, Kenya and South Africa (Goodman & Mills 1999; Goodman *et al.* 2001). Our estimated cost of US$ 22.20 per malaria attack averted was only slightly higher than the one estimated for insecticide treated nets in The Gambia, which was US$ 15.75 (Graves 1998). The initial costs per DALY averted were relatively high, but were followed by an increasing cost-effectiveness in the maintenance phase, confirming previous studies that applied environmental management strategies (Bos & Mills 1987). Importantly, no long-term comparison of cost-effectiveness analyses can be made with the currently proposed malaria control interventions, as their long-term sustainability is yet to be demonstrated.

Interestingly, the discovery and widespread application of DDT and other powerful insecticides starting in the mid 1940s was followed by a conceptual change in malaria control, as it was believed that the disease could be eradicated by the use of insecticides alone (Harrison 1978). Consequently, environmental management was almost forgotten worldwide until the 1980s (Ault 1994). This is very unfortunate, because environmental management has a long-term track record of successful malaria control in a diversity of ecological, epidemiological and socio-economic settings. Before Watson started his work at the copper mines of Zambia, he was successfully engaged in malaria control on peninsular Malaysia, initially in urban and semiurban areas along the coast, and then in rural rubber and tea plantations (Watson 1921; Field & Reid 1956). In the 1910/1920s, malaria was also controlled successfully in the Indonesian archipelago (Swellengrebel 1950; Takken *et al.* 1990) and two decades later, selective vegetation clearance proved effective for control of malaria in Borneo (McArthur 1947, 1954). However, understanding the epidemiology of malaria in the tropical forests of Borneo is mandatory, as large-scale deforestation is certainly not an appropriate approach for disease control (Bradley 1994). Finally, several water management strategies have been successfully applied in South-East Asia to avoid or reduce breeding of malaria vectors in riceland habitats, including intermittent irrigation, periodical flushing of ricefields and shifting planting schedules outside the optimal mosquito breeding periods (Worth 1937; Russell *et al.* 1942; Lacey & Lacey 1990). However, water management, particularly the drainage of malaria vector-producing swamps, is conflicting with the interest of preserving the world's wetlands and needs to be taken into account by control programmes (Grillet 2000).

Interest in environmental management has renewed over the last 10–15 years, partly as a result of emergence and rapid spread of vector resistance to insecticides and more rigorous toxicological testing (Lacey & Lacey 1990; Ault 1994). A recent study in Sri Lanka demonstrated that the costs of periodical river flushing to eliminate mosquito breeding habitats compared favourably with impregnated bednets (Konradsen *et al.* 1999). In conclusion, environmental management is proven to be sustainable in the long-term, has no or fewer adverse ecological effects than currently used malaria control strategies, and can potentially make better use of local resources and knowledge, hence contributing to local self-reliance (Bos & Mills 1987; Singer 1989). Urban and periurban environments, which are rapidly growing in all malarious countries, are of particular interest, as the implementation of sound environmental strategies – integrated with concurrent malaria control tools – could form an intervention package to substantially reduce the current burden of the disease (Trape 1987; Knudsen & Slooff 1992).

Finally, one must ask what will replace the colonial infrastructure that facilitated the successful programmes mentioned above. We believe that a well-supported health service infrastructure expanded beyond curative medicine, including personnel with training and expertise in hydrology and entomology would be a response to meeting the tremendous challenge of halving the current burden of malaria within 10 years (Shiff 2000; Utzinger *et al.* 2001). In view of this conclusion, launching of a systemwide initiative on malaria and agriculture has to be applauded (SIMA; see web page: www.iwmi.org/sima.htm). Its collaborative organization should be encouraged, as it promotes an excellent platform for integrative approaches for sustainable malaria control.

Acknowledgements

Jürg Utzinger acknowledges the financial support from the Swiss National Science Foundation. Yesim Tozan is grateful to the Centre for Health and Wellbeing, Princeton University. We thank Prof. Dr Marcel Tanner and Dr Robert Bos for useful comments on the manuscript.

References

Anonymous (2000) Donor responsibilities in rolling back malaria. *Lancet* **356**, 521.

Ault SK (1994) Environmental management: a re-emerging vector control strategy. *American Journal of Tropical Medicine and Hygiene* **50** (Suppl.), 35–49.

Baird JK (2000) Resurgent malaria at the millennium: control strategies in crisis. *Drugs* **59**, 719–743.

Bos R & Mills A (1987) Financial and economic aspects of environmental management for vector control. *Parasitology Today* **3**, 160–163.

Box GEP & Draper NR (1969) *Evolutionary Operation: a Statistical Method for Process Improvement*. Wiley, New York.

Bradley DJ (1994) Watson, Swellengrebel and species sanitation: environmental and ecological aspects. *Parassitologia* **36**, 137–147.

van der Brug PH (1997) Malaria in Batavia in the 18th century. *Tropical Medicine and International Health* **2**, 892–902.

Choi HW, Breman JG, Teutsch SM, Liu S, Hightower AW & Sexton JD (1995) The effectiveness of insecticide-impregnated bed nets in reducing cases of malaria infection: a meta-analysis of published results. *American Journal of Tropical Medicine and Hygiene* **52**, 377–382.

Dole VP, Nyswander ME, DesJarlais D & Joseph H (1982) Performance-based rating of methadone maintenance programs. *New England Journal of Medicine* **306**, 169–171.

Dove A (2000) New economic analysis draws big money to malaria. *Nature Medicine* **6**, 612.

Field JW & Reid JA (1956) Malaria control in Malaya: an appreciation of the work of Sir Malcom Watson. *Journal of Tropical Medicine and Hygiene* **59**, 23–27.

Finney DJ (1984) Improvement by planned multistage selection. *Journal of the American Statistical Association* **79**, 501–509.

Goodman CA, Coleman PG & Mills AJ (1999) Cost-effectiveness of malaria control in sub-Saharan Africa. *Lancet* **354**, 378–385.

Goodman CA & Mills AJ (1999) The evidence base on the cost-effectiveness of malaria control measures in Africa. *Health Policy and Planning* **14**, 301–312.

Goodman CA, Mnwava AEP, Dlamini SS, Sharp BL, Mthembu DJ & Gumede JK (2001) Comparison of the cost and cost-effectiveness of insecticide-treated bednets and residual house-spraying in KwaZulu-Natal, South Africa. *Tropical Medicine and International Health* **6**, 280–295.

Graves PM (1998) Comparison of the cost-effectiveness of vaccines and insecticide impregnation of mosquito nets for the prevention of malaria. *Annals of Tropical Medicine and Parasitology* **92**, 399–410.

Grillet ME (2000) Factors associated with distribution of *Anopheles aquasalis* and *Anopheles oswaldoi* (Diptera: Culicidae) in a malarious area, northeastern Venezuela. *Journal of Medical Entomology* **37**, 231–238.

Harrison G (1978) *Mosquitoes, Malaria and Man: A History of the Hostilities since 1880.* John Murray, London.

Hutubessy RCW, Bendib LM & Evans DB (2001) Critical issues in the economic evaluation of interventions against communicable diseases. *Acta Tropica* **78**, 191–206.

Knudsen AB & Slooff R (1992) Vector-borne disease problems in rapid urbanization: new approaches to vector control. *Bulletin of the World Health Organization* **70**, 1–6.

Konradsen F, Steele P, Perera D, van der Hoek W, Amerasinghe PH & Amerasinghe FP (1999) Cost of malaria control in Sri Lanka. *Bulletin of the World Health Organization* **77**, 301–309.

Lacey LA & Lacey CM (1990) The medical importance of riceland mosquitoes and their control using alternatives to chemical insecticides. *Journal of the American Mosquito Control Association* **6** (Suppl.), 1–93.

Lerer LB (1999) Cost-effectiveness of malaria control in sub-Saharan Africa. *Lancet* **354**, 1123–1124.

McArthur J (1947) Transmission of malaria in Borneo. *Transactions of the Royal Society of Tropical Medicine and Hygiene* **40**, 537–558.

McArthur J (1954) The control of malaria in Borneo. *Transactions of the Royal Society of Tropical Medicine and Hygiene* **48**, 234–241.

Mitchell BR (1988) *British Historical Statistics.* Cambridge University Press, Cambridge.

Murray CJL & Lopez AD (1996) *The Global Burden of Disease: A Comprehensive Assessment of Mortality and Disability from Disease. Injuries and Risk Factors in 1990 and Projected to 2020.* Harvard School of Public Health, Harvard University Press, Harvard.

Nabarro D & Mendis K (2000) Roll back malaria is unarguably both necessary and possible. *Bulletin of the World Health Organization* **78**, 1454–1455.

Nabarro DN & Tayler EM (1998) The 'Roll back malaria' campaign. *Science* **280**, 2067–2068.

Rodger LM (1944) Malaria as a non-relapsing disease. *Lancet* **246**, 533–534.

Russell PF, Knipe FW & Rao HR (1942) On the intermittent irrigation of ricefields to control malaria in south India. *Journal of the Malaria Institute of India* **4**, 321–340.

Shiff CJ (2000) Can roll back malaria achieve its goal? A challenge. *Parasitology Today* **16**, 271–272.

Singer B (1986) Self-selection and performance-based ratings: a case study in program evaluation. In: *Drawing Inferences from Self-selected Samples* (ed. H Wainer) Springer-Verlag, New York, pp. 29–49.

Singer B (1989) Social science and the improvement of tropical disease control programs. *Annals of the New York Academy of Science* **569**, 275–287.

Snow RW, Craig M, Deichmann U & Marsh K (1999) Estimating mortality, morbidity and disability due to malaria among Africa's non-pregnant population. *Bulletin of the World Health Organization* **77**, 624–640.

Swellengrebel NH (1950) How the malaria service in Indonesia came into being 1898–1948. *Journal of Hygiene* **48**, 146–157.

Takken W, Snellen WB, Verhave JP, Knols BGJ & Atmosoedjono S (1990) Environmental measures for malaria control in Indonesia: an historical review of species sanitation. *Wageningen Agricultural University Papers* **90.7**, 1–167.

Trape JF (1987) Malaria and urbanization in central Africa: the example of Brazzaville. Part I: description of the town and review of previous surveys. *Transactions of the Royal Society of Tropical Medicine and Hygiene* **81** (Suppl. 2), 1–9.

United Nations (1982) *Model Life Tables for Developing Countries.* UNO, New York.

US Census Bureau (1966) *Statistical Abstract of the United States: 1966*, 87th edn. US Census Bureau, Washington, DC.

US Census Bureau (1999) *Statistical Abstract of the United States: 1999*, 119th edn. US Census Bureau, Washington, DC.

Utzinger J, Tanner M & Singer BH (2001) The Internet: a valuable tool for Roll Back Malaria. *Trends in Parasitology* **17**, 159–161.

Watson M (1921) *The Prevention of Malaria in the Federated Malay States.* John Murray, London.

Watson M (1953) *African Highway: the Battle for Health in Central Africa.* John Murray, London.

Wenlock RW (1978) The incidence of *Plasmodium* parasites in rural Zambia. *East African Medical Journal* **55**, 268–276.

WHO (1998) *Roll Back Malaria: a Global Partnership.* World Health Organization, Geneva.

Worth HN (1937) The control of anopheline breeding in river beds. *Transactions of the Royal Society of Tropical Medicine and Hygiene* **30**, 521–530.