Schistosomiasis and water resources development: systematic review, meta-analysis, and estimates of people at risk

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An estimated 779 million people are at risk of schistosomiasis, of whom 106 million (13·6%) live in irrigation schemes or in close proximity to large dam reservoirs. We identified 58 studies that examined the relation between water resources development projects and schistosomiasis, primarily in African settings. We present a systematic literature review and meta-analysis with the following objectives: (1) to update at-risk populations of schistosomiasis and number of people infected in endemic countries, and (2) to quantify the risk of water resources development and management on schistosomiasis. Using 35 datasets from 24 African studies, our meta-analysis showed pooled random risk ratios of 2·4 and 2·6 for urinary and intestinal schistosomiasis, respectively, among people living adjacent to dam reservoirs. The risk ratio estimate for studies evaluating the effect of irrigation on urinary schistosomiasis was in the range 0·02–7·3 (summary estimate 1·1) and that on intestinal schistosomiasis in the range 0·49–23·0 (summary estimate 4·7). Geographic stratification showed important spatial differences, idiosyncratic to the type of water resources development. We conclude that the development and management of water resources is an important risk factor for schistosomiasis, and hence strategies to mitigate negative effects should become integral parts in the planning, implementation, and operation of future water projects.

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Introduction

This review is the fourth of a series of systematic literature reviews pertaining to water resources development and management and its effects on water-associated diseases. The previous reviews covered three water-related vector-borne diseases, namely malaria,[1] lymphatic filariasis,[2] and Japanese encephalitis.[3] The current focus is on the most important water-based disease from a global public-health perspective—ie, schistosomiasis.

Known since ancient times,[4] schistosomiasis ranks second only to malaria among the parasitic diseases with regard to the number of people infected and those at risk. According to previous estimates, the disease causes the annual loss of between 1·7 and 4·5 million disability adjusted life years (DALYs).[5–7] A recent meta-analysis challenges these burden estimates; they could be several-fold higher.[8] Most of the present schistosomiasis burden is concentrated in sub-Saharan Africa[9] with the highest prevalence and infection intensities usually found in school-age children, adolescents and young adults.[10,11] Schistosomiasis negatively impacts on school performance and the debilitation caused by untreated infections undermines social and economic development in heavily affected areas.[12–15]

One way to meet the increasing food and energy demands of the growing world population is through the construction of dams and irrigation schemes. Irrigated agriculture usually results in increased crop outputs, and hydropower reduces dependency on domestic or imported fossil fuels and generates export earnings. In addition, reservoirs are one way to address water scarcity through increased storage capacity.[16] Water resources development takes place in most parts of the world, at different scales and at a rapid pace. Over 33 000 dams are listed in the latest edition of the World Register of Dams; 3000 of them were built in the 1990s.[17] The total area under irrigation was 277 million ha in 2002, an increase of almost 10% over the past 10 years.[18]

However, the development and management of water resources in tropical and subtropical climate zones has often resulted in transmission intensification or the introduction of diseases into previously non-endemic areas.[19–22] Schistosomiasis is considered a sensitive indicator disease for monitoring ecological transformations since it is widely distributed and infection rates can change promptly.[23]

The objectives of the present review are (1) to update estimates of at-risk populations and number of people infected with schistosomes in endemic countries, and (2) to estimate the number of people at risk of the disease due to close proximity of irrigated areas and large dam reservoirs. In addition, we identify generic features of the changing epidemiology of schistosomiasis following implementation and operation of water resources development projects and provide pooled random risk ratios of schistosomiasis associated with dam and irrigation scheme construction.

Methods

Search strategy and selection criteria

A systematic literature review was done with the aim to identify all relevant studies that examined the effects of water resources development and management on schistosomiasis.

We did computer-aided searches of the following electronic databases: PubMed, BIOSIS preview, Web of Science, Science Direct, Literatura Latino Americana e do Caribe em Ciências da Saùde (LILACS), ArticleSciences, and African Journals OnLine (AJOL). Next, we searched the electronic archives of international organisations—ie, WHO, the Food and Agricultural Organization (FAO), and the World Bank. Books, dissertations, and unpublished documents ("grey literature") were also considered. The following keywords and combinations thereof were used: "schistosomiasis" in combination with "dam(s)", "barrage", "impoundment", "reservoir(s)", "pool(s)", "flood control", "irrigation", "paddy rice", "swamp rice", "water management", "environmental management", and "ecological transformation". Neither temporal limits nor language restrictions were set for database searches. The bibliographies of all recovered documents were hand-searched for additional references.

The decision tree for the inclusion or exclusion of articles is shown in figure 1. Only publications reporting pre-development and post-development schistosomiasis prevalence data from one area, or cross-sectional data obtained from otherwise comparable settings with specified differences in water resources development and management, were included. Articles reporting only pre-development prevalences were included if case matching follow-up publications could be identified.

People at risk of schistosomiasis and number of people infected

The number of people at risk of schistosomiasis and those infected in schistosome-endemic countries at mid-year 2003 were obtained as follows. First, whenever possible, the country estimates of the at-risk population[24–29] and numbers of people infected[24–45] were obtained from the latest available surveys. Second, for countries where no recent data were available, the proportions of people "at risk" and those actually "infected" as of 1995 were calculated from numbers presented by Chitsulo and colleagues[9] and applied to the United Nations (UN) total population estimates by mid-year 2003.[46]

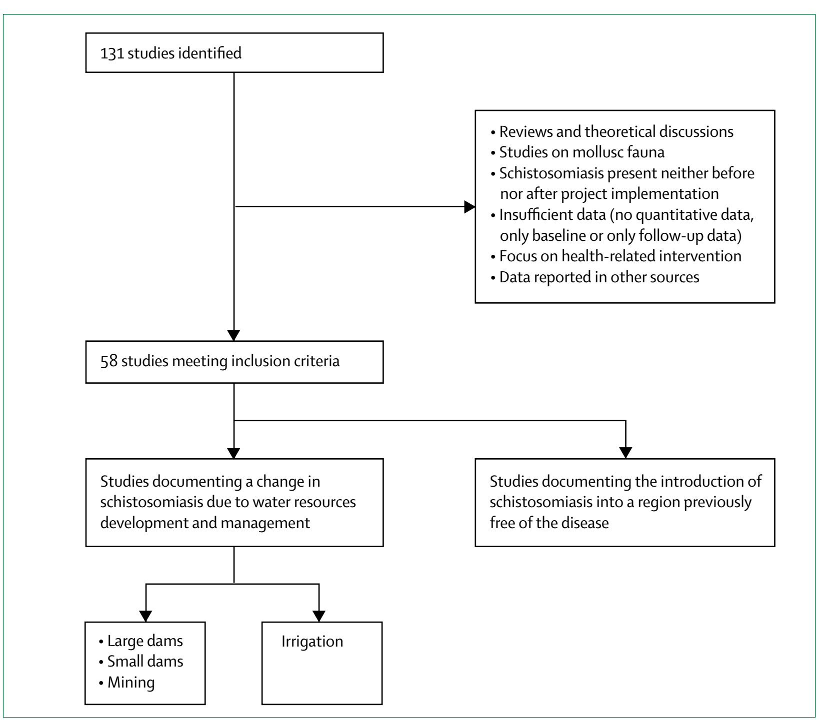

Figure 1: **Decision tree showing inclusion and exclusion of studies identified on the interface of schistosomiasis and water resources development and management**

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Figure 2: **Partly lined irrigation canal in Yunnan province, China, where *Schistosoma japonicum* is endemic**

Proximity to irrigated agriculture

Information on total agricultural area (sum of arable land, permanent crops, and permanent pasture[18]) and area under surface irrigation[47] was obtained for all schistosome-endemic countries. Data on rural population numbers were obtained from the UN.[46] The population density in arable areas was calculated by dividing the total rural population of the country by its total area classified as "arable" or "planted with permanent crops". A similar population density was assumed for irrigated areas. Due to the lack of data on the distribution of irrigated agriculture with regard to schistosome-endemic areas, the number of people at risk of schistosomiasis in irrigated areas (irrigated population at risk) was estimated by multiplying the surface-irrigated area by the mean population density in arable areas of the respective country and the national population fraction at risk of schistosomiasis (figure 2).

Proximity to dam reservoirs

All data on reservoirs of large dams (ie, height ≥15 m and/or storing volume >3 million m^3) were derived from the World Register of Dams.[17] The assumptions and calculations underlying the estimate of the at-risk population due to proximity to large dam reservoirs are detailed in our previous work focusing on malaria.[1] The following adjustments were made. First, the distance from the lakeshore was extended from 2 km to 5 km. Justification for this cut-off value arises from studies on *Schistosoma mansoni* around Lake Victoria.[24,48] Thus, the formula for calculating the approximate area at risk (a hollow rectangle, having rounded corners, which surrounds the water body) became: 2 × (length × 5) + 2 × (width × 5) + $5^2\Pi$. Second, we stratified all reservoirs 1 km^2 or larger on the schistosome-endemic continents of Africa and South America (all reservoirs) and Asia (reservoirs ≥10 km^2) for which information on both reservoir surface and reservoir length was available according to surface area and calculated their median length, width, and at-risk area. A square-shape was assumed for reservoirs smaller than 1 km^2.

Subsequently, we determined the number of dams for each schistosome-endemic country, stratified the lakes by surface area and multiplied their number with the respective area at risk. The mean area at risk per lake was used for reservoirs for which information on surface area was unavailable. The country-specific at-risk population due to proximity to large dam reservoirs was obtained as detailed for the irrigated areas.

Statistical analysis

We stratified the studies according to schistosome species and type of water resources development—ie, studies in irrigated areas were classified as "irrigation" even if the irrigation water was supplied by an artificial lake. Data for population subgroups (prevalence, sample size) were extracted and analysed with version 2.4.5 of StatsDirect software (StatsDirect Ltd, Cheshire, UK). Risk ratios and corresponding 95% CI were calculated. Heterogeneity between studies was determined with Cochrane's Q statistics. A random effect model was used for the summary risk ratio, because the test of heterogeneity was highly significant ($p<0.001$). Whenever consecutive results from a single study were available, only the most recent data point was considered. Furthermore, only the data from the project area with the most extensive water development activity was used.

Results

The creation of dam reservoirs and the implementation of irrigation systems often lead to an expansion of the habitats of intermediate host snails, and hence new potential transmission sites for schistosomiasis. Improvements in water supply and sanitation, on the other hand, can break the transmission cycle through reduced human-water contact and diminished environmental contamination with excreta. In addition, there are ancillary benefits of such improved water-related infrastructure.[49] Water resources development can result in better socioeconomic conditions with additional resources available for health-related interventions—eg, procurement of efficacious anti-schistosomal drugs such as praziquantel.

Current global status of schistosomiasis

According to WHO, schistosomiasis is endemic in 76 countries and territories.[50] The disease also occurs in Djibouti, where it probably was introduced by refugees,[51,52] and its presence in Nepal is suspected.[53]

WHO subregion	Schistosomiasis burden expressed in DALYs lost in 2002 (%)*	Number of people infected with *Schistosoma* spp by mid-2003 (%)†	Number of people at risk of schistosomiasis by mid-2003 (%)†	Number of people at risk of schistosomiasis living in irrigated areas (%)‡	Number of people at risk of schistosomiasis living in proximity to large dam reservoirs (%)‡	Fraction of population at risk living in proximity to	
						Irrigated areas	Dams
1	621 (36·6)	98 118 (47·3)	275 404 (35·3)	6082 (9·6)	6162 (14·5)	2·2%	2·2%
2	713 (42·0)	89 066 (43·0)	283 344 (36·4)	3923 (6·2)	22 543 (53·2)	1·4%	8·0%
4	74 (4·4)	1809 (0·9)	36 033 (4·6)	537 (0·8)	1220 (2·9)	1·5%	3·4%
6	29 (1·7)	306 (0·1)	12 629 (1·6)	941 (1·5)	209 (0·5)	7·5%	1·7%
7	197 (11·6)	16 920 (8·2)	125 344 (16·1)	42 627 (67·4)	2129 (5·0)	34·0%	1·7%
9	0 (<0·1)	0 (<0·1)	72 (<0·1)	4 (<0·1)	7 (<0·1)	5·6%	9·7%
11	3 (0·2)	0 (<0·1)	108 (<0·1)	8 (<0·1)	2 (<0·1)	7·4%	1·9%
12	4 (0·2)	0 (<0·1)	13 (<0·1)	3 (<0·1)	3 (<0·1)	23·1%	25·5%
13	0 (<0·1)	0 (<0·1)	Eliminated	0	0	0%	0%
14	55 (3·2)	1065 (0·5)	46 371 (5·9)	9125 (14·4)	10 081 (23·8)	19·7%	21·7%
Total	1696 (100)	207 284 (100)	779 318 (100)	63 250 (100)	42 356 (100)	8·1%	5·4%

*x10^3, source: WHO[5]. †x10^3, based on Chitsulo and colleagues,[9] updated from various sources and recalculated with figures from UN[46]. ‡x10^3

Table 1: **Summary of schistosomiasis burden (expressed in DALYs lost), numbers of people infected, and at-risk population due to proximity to water resources development and management, stratified by WHO subregion**

Active transmission is reported from 67 countries and territories, down from 71 in the mid-1990s.

For mid-year 2003 we estimate that 779 million people were at risk of schistosomiasis, and 207 million people were infected (webappendix 1 and webappendix 2). Large-scale morbidity control programmes, socioeconomic development, and environmental changes, including the sometimes deliberate introduction of competitor snail species, have resulted in transmission interruption or disease elimination in nine countries (Iran, Japan, Lebanon, Malaysia, Martinique, Montserrat, Thailand, Tunisia, and Turkey), and considerable reductions of

See Online for webappendices 1 and 2

Country, project, design, and period	Reference	Sample size	Age group	Species	Prevalence		Risk ratio (95% CI)	Comment
					No irrigation	Irrigation		
WHO subregion 1								
Burkina Faso, Sourou, 1954 *vs* 1998/99	55	..	SC	*S h*	19%	8·5–70·3%	NA	Léry dam closed: 1976 Main canal opened: 1985
Burkina Faso, Kou valley, 1957 *vs* 1987	55	..	SC SC	*S h* *S m*	14% 1·3% (1987)	80% 45% (1998)	5·7 NA	Start of irrigation: 1968
Burkina Faso, Kaya, cross-sectional, late 1970s	56	Swamp: 120 Natural lake: 800	TP	*S h*	Swamp: F=25%, M=40·5% Lake: F=9%, M=18%	F=8%, M=12%	..	Start of irrigation: 1967–68
		Irrigation: 1500	TP	*S m*	Swamp: F=14·5%, M= 49% Lake: F=23%, M=31·5%	F=19%, M=21%	..	
Cameroon, SEMRY II, cross-sectional, 1980	57	Not irrigated: 174 Irrigated: 816	TP	*S h*	20·1%	48·5%	2·4 (1·8–3·3)*	Start of irrigation: 1971
1979–85	58	March 1979: 1780 Nov 1979: 1558 May 1981: 1458 Nov 1981: 1139 April 1985: 1661	TP	*S h*	March 1979: 5·2% (baseline)	March 1979: .. Nov 1979: 6·5% May 1981: 6·2% Nov 1981: 5·7% April 1985: 5%	NA 1·2 (0·9–1·6) 1·2 (0·9–1·6) 1·1 (0·8–1·5) 1·0 (0·7–1·3)*	Impoundment of lake: 1979 Improved sanitation, decreased rainfall
Liberia, Bong county, cross-sectional, 1980	59	No swamp: 174 Swamp: 423	TP	*S h*	11%	42%	3·6 (2·5–6·0)*	Swamp rice started: 1974 Villages 50 km apart
		No swamp: 168 Swamp: 384	TP	*S m*	9%	87%	9·7 (6·0–15·8)*	
Madagascar, Ankilivalo, 1971 *vs* 1986 and cross-sectional, 1986	60	1971: .. 1986: 279	SC	*S m*	13%	74%	5·7	Morondava dam closed: 1979
		Distant village: 84 Close village: 413	SC	*S m*	7%	69·2%	9·7 (4·5–21·0)*	Distance between villages: 8 km
1986 *vs* 1994	61	1986: 413 1994: 369	SC	*S m*	34·1%	69·2%	2·0 (1·7–2·4)*	Dam destroyed: 1990 Prevalence among 79 SC in distant village: 7·6%
Mali, general, cross-sectional, 1980–..	62	Savannah: 10744 Irrigated: 8955	TP	*S h*	13·4%	64·4%	4·8 (4·6–5·1)*	Data from national survey
		Savannah: 7776 Irrigated: 6146	TP	*S m*	1·6%	53·9%	33·8 (28·3–40·3)*	
Senegal, Senegal river, baseline, 1977–78	63	Delta: 214 "walo": 803 "diéré": 375	SC	*S h*	Delta: 0% "walo": 0·7% "diéré": 10·4%	NA	NA	Diama dam closed: 1985 Manantali dam closed: 1993
Baseline, 1985	64	Delta: 1441 "walo": 1653 "diéré": 327	SC	*S h*	Delta: 0·9% "walo": 3·6% "diéré": 27·2%	NA	NA	Prevalence in 246 people from delta villages with irrigation: 29·7%
Cross-sectional, 1994–95	65	Delta: 2920 "walo": 2585 "diéré": 1011	TP	*S h*	Delta: .. "walo": .. "diéré": ..	Delta: 1·9–41·1% (4/23–18/21) "walo": 11·5% (20/59) "diéré": 51·6% (2/28)	NA NA NA	Percentages refer to endemic villages. Values in brackets refer to the number of endemic villages/ number of total villages Prevalence in 1139 people from Lac de Guiers: 29·7% (1/18)
Senegal, Upper valley, cross-sectional, 1997–99	66	1997: 835 with irrig 610 without irrig	SC	*S h*	1997: 27·0%	1997: 48·0%	1·8 (1·5–2·1)	Increase in irrigated area between 1997 and 1999 in some locations
		1999: 373 with irrig 382 without irrig			1999: 20·2%	1999: 78·3%	3·9 (3·2–4·8)*	
Sierra Leone (southeast), cross-sectional, late 1970s	67	No swamp: 221 Swamp: 6668	TP	*S h*	11·7%	8·1%	0·7 (0·5–1·0)*	Swamp rice. 6 villages without and 68 villages with swamps
		No swamp: 146 Swamp: 4840	TP	*S m*	4·7%	2·4%	0·5 (0·2–1·1)*	Gbakima:[68] 1106 people in areas with swamps, prevalence *S h*: 0·6%, *S m*: 0·3%

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WHO subregion 2								
Côte d'Ivoire, savannah and forest, cross-sectional, 1997–99	69	966–1420	SC	*S h*	Savannah: 0·7%	Savannah: 2·3/4·8%	3·5 (1·5–7·8)/ 7·4 (3·4–16·0)*	Inland valleys with and without swamp rice, those with swamp rice with partial (first number)/full (second number) water control
					Forest: 1·7%	Forest: 4·4/0·9%	2·5 (1·5–4·3)/ 0·5 (0·3–1·1)*	
			SC	*S m*	Savannah: 2·1%	Savannah: 11·9/16·1%	5·7 (3·6–9·1)/ 7·8 (5·0–12·2)*	
					Forest: 17·5%	Forest: 46·6/61·3%	2·7 (2·3–3·1)/ 3·5 (3·0–4·0)*	
Tanzania, Mbarali, 1962 *vs* 1965	70	1962: 63; 1965: 263	TP	*S h*	9·5%	8·7%	0·9 (0·4–2·1)*	Start of settlement: 1961
		1962: 62; 1965: 263	TP	*S m*	14·5%	28·9%	2·0 (1·1–3·8)*	
WHO subregion 7								
Egypt, Difra, 1935 *vs* 1979	71	1935 and 1979: 315	TP	*S h*	74·3%	2·2%	0·03 (0·01–0·06)*	Aswan low dam closed: 1933
			TP	*S m*	3·2%	73%	23·0 (12·5–42·5)*	Aswan high dam closed: 1970
Egypt, Nile delta, 1935 *vs* 1983	72	1935: 14 815	TP	*S h*	56%	5%	0·09 (0·08–0·1)*	
		1983: 15 166	TP	*S m*	33%	39%	1·18 (1·15–1·22)*	
Egypt, Aswan and Quena provinces, 1934 *vs* 1937	73	..	..	*S h*	2–11%	44–75%	NA	Shift from basin to perennial irrigation
Egypt, Assiut, Quena and Suhag provinces, cross-sectional, 1955	74	Basin irrigation: 47 748 Perennial irrigation: 62 006	..	*S h*	Basin irrigation: 16·2%	Perennial irrigation: 63·9%	3·9 (3·8–4·0)*	Basin versus perennial irrigation
Egypt, Bitter Lakes area, 1985 *vs* 1992	75	..	..	*S h*	7·8%	1·7%	0·2	Land reclamation
			..	*S m*	21·7%	42·1%	1·9	Only people settled ≥7 years
Sudan, Gezira,	76	1926–39: various nos.						
1926–39 *vs* 1942–45		*S h* 1942–45: 4773	..	*S h*	<1%	30%	30; baseline 1%	Sennar dam closed: 1925
Late 1940–50s		*S m* 1944: 3596	..	*S m*	..	1·3%	NA	Taken as indication of baseline
1973	77	81 027	TP	*S h*	..	8·9%	8·9; baseline 1%	
			TP	*S m*	..	8·8%	4·4; baseline 2%	
1973–74	78	1655	TP	*S h*	..	0·2%	0·2; baseline 1%	Roseires dam closed: 1960
End 1970–80s			TP	*S m*	..	49·3%	24·7; baseline 2%	
	79	1608	SC	*S m*	..	82·1%	41·1; baseline 2%	
1981–82	80	229	TP	*S h*	..	17·9%	17·9; baseline 1%	
			TP	*S m*	..	67·7%	33·9; baseline 2%	
1983	81	1981: 3486	TP	*S m*	..	51%	25·5; baseline 2%	
		1982: 3521	TP	*S m*	..	61%	30·5; baseline 2%	
1986–87	82	4481	TP	*S h*	..	20·8%	20·8; baseline 1%	Only villages with haematuria in schools
			TP	*S m*	..	47·4%	23·7; baseline 2%	
	83	3648	TP	*S h*	..	10–15%	NA	
			TP	*S m*	..	52%	26·0; baseline 2%	
WHO subregion 4								
Brazil, Bahia, cross-sectional, 1986–94	84	No irrigation: 96 ≥500 ha irrigated: 40	TP	*S m*	Prevalence <5%: 40·6%	Prevalence <5·0%: 50·0%	0·27	Mean prevalence data of villages compared
			TP	*S m*	Prevalence ≥20%: 18·8%	Prevalence ≥20·0%: 5·0%		

..=not reported; F=female; irrig=irrigation; M=male; NA=not applicable; SC=school-age children; *S h=Schistosoma haematobium*; *S m=Schistosoma mansoni*; TP=total population. *Included in meta-analysis.

Table 2: **Identified studies on schistosomiasis in irrigated areas, stratified by WHO subregion**

people infected and disease-attributable morbidity in Brazil, China, Egypt, Morocco, the Philippines, Venezuela,[50] countries of the Caribbean,[54] as well as Cambodia and Laos.[27] The reported or estimated number of infections is below 1000 in Antigua and Barbuda, India, Indonesia, Jordan, Oman and Saint Lucia. In some countries—eg, Jordan—most detected cases are imported rather than autochthonous.[39]

Of all countries with ongoing transmission, 46 are in Africa. They are home to about 97% of all infections and 85% of the global population at risk. At present, 29 African countries, Brazil, and Yemen harbour more than one million cases each.

Irrigation, dams, and schistosomiasis stratified by WHO subregions

The estimates of the number of people at risk of schistosomiasis due to irrigation and large dam reservoirs, stratified by WHO subregion, are summarised in table 1. Overall, 58 articles reporting data from 39 settings met our inclusion criteria. Table 2 summarises the effects of irrigation on schistosomiasis.[55–84] Table 3 shows the relation between large and small reservoirs, as well as fishponds, and the disease.[62,85–103] Introduction of schistosomiasis into previously non-endemic areas following water resources development and mining activities is summarised in table 4.[55,63,65,93,94,99–113]

Country, project, study, and period	Reference	Sample size	Age-group	Species	Prevalence		Risk ratio (95% CI)	Comment
					No dam	Dam		
WHO subregion 1								
Cameroon, Lagdo lake, cross-sectional, 1986	85	Distant: 188 Close: 1145	TP	*S h*	13%	26%	2·0 (1·4–2·9)*	Lagdo dam closed: 1982 Distant village: 20 km away from lake
		Distant: 185 Close: 964	TP	*S m*	3%	15%	5·5 (2·3–13·3)*	
Cameroon, Bafia, fish pond, cross-sectional, year: ..	86	Distant: 89 Close: 245	TP	*S m*	7·8%	21·2%	2·7 (1·3–5·7)*	Fish pond in one quarter of city
Ghana, Lake Volta, 1959–61 *vs* 1968	87	1959–61: .. 1968: 442	SC	*S h*	1%	70·1%	NA	Akosombo dam closed: 1965 Village: Kete Krachi
1967 1968		1967: 1114 1968: 968	SC	*S h*	..	1967: 29·8% 1968: 85·6%	6·0 (baseline 5%[87]) 17·1	During impoundment, villages: Ampem, Amete, Kete Krachi
1974	88	1974: 2824	TP	*S h*	..	1974: 73·4%	14·7 (baseline 5%[87])	26 communities at Pawmpawm and Afram branch of the lake
Ghana, below Kpong dam, 1972 *vs* 1980s	89	1972: .., 1980s: 59 (Bator), 50 (Mepe)	SC	*S h*	Bator: 27·1% Mepe: 36·4%	Bator: 74·6% Mepe: 88·0%	2.8 2·4	Kpong dam closed: 1981
Ghana, Barekese dam, 1966 *vs* 1999	90	3 exposed and 1 control village, 18 households each (180–255 people)	TP	*S h*	1966, exposed: 17·5%	1999, exposed: 36·9%	2·1 (1·8–2·1)*	1966: pre-construction 1999: late operational phase Control: 0% in 1966/72 and 1·1% in 1999 (imported cases)
Ghana, upper east region, small dams, cross-sectional, 1960–61	91	Without dams: 15 districts With dams: 23 districts	TP	*S h*	Median: 17% Mean: 19·8%	Median: 50·5% Mean: 45·3%	3·0	Prevalence data of districts compared Dams constructed 1951–65
Mali, general, cross-sectional, 1980–..	62	Savannah: 10 744 Small dams: 3289 Sélingué: 3140	TP	*S h*	13·4%	Small dams: 67·2% Sélingué: 31·8%	5·0 (4·8–5·3)* 2·4 (2·2–2·6)*	Data from national survey
		Savannah: 7776 Small dams: 2841 Sélingué: 2132	TP	*S m*	1·6%	Small dams: 12·0% Sélingué: 4·4%	7·5 (6·2–9·2)* 2·8 (2·1–3·6)*	
WHO subregion 2								
Côte d'Ivoire, Lake Taabo, 1976–77 *vs* 1992	93,94	1976–77: 120 1992: 134	SC	*S m*	3%	2%	0·7 (0·2–2·9)*	Taabo dam closed: 1979 Baseline data: one village Follow-up data: five villages
Côte d'Ivoire, Lake Kossou, 1970 *vs* 1992	93	1970: 1031 1992: 290	SC	*S h*	13·7%	53%	3·9 (3·2–4·7)*	Kossou dam closed: 1972 Baseline data: four villages Follow-up data: five villages
Democratic Republic of the Congo, Lwiro, 43 fish ponds, 1996	95	Distant: 397 Close: 390	TP	*S m*	4%	6·1%	1·5 (0·8–2·8)*	Ponds built: 1988 10% of inhabitants of distant villages also work in ponds
Ethiopia, Tigray, small dams, cross-sectional, 1997	96	Distant: 337 Close: 341	SC	*S m*	29·7%	48·4%	1·6 (1·3–2·0)*	Distant: 8–10 km, close: <3 km Incidence not significantly different
Nigeria, Ruwan Sanyi dam, 1971–79	97,98	1971: 199 boys 1976: 194 boys 1979: 217 boys	SC	*S h*	1971: 59·3% 1975: 33·8% 1976: 41·2%	55·8%	0·9 (0·8–1·1)*	Dam closed: 1977 1973: drought, made responsible for decline, afterwards normalisation
Zambia, Lake Kariba, Siavonga, 1968	99	1968: 726	TP	*S h*	Low incidence before 1956[100]	28·8%	5·8; baseline 5%	Kariba dam closed: 1959 Intermediate host snail absent from construction site
Siavonga and Matinangala, 1991	101	516	TP	*S h*	..	16·7%	3·3; baseline 5%	
Siavonga, 1994	102	338	TP	*S h*	..	35·3%	7·1; baseline 5%	
Siavonga, 2002	103	527	SC	*S h*	..	19·4%	3·1; baseline 5%	

..=not reported; NA=not applicable; SC=school-age children; *S h*=*Schistosoma haematobium*; *S m*=*Schistosoma mansoni*; TP=total population. *Included in meta-analysis

Table 3: **Identified studies on schistosomiasis in proximity to dam reservoirs, stratified by WHO subregion**

WHO subregions 1 and 2 (sub-Saharan Africa)

Approximately 49 000 km² are currently under surface irrigation in sub-Saharan Africa, which translates to only 3% of the total arable area. More than half of the area under surface irrigation is located in South Africa and Madagascar. The irrigated population at risk of schistosomiasis is estimated at 10 million, or 1·8% of the local population at risk.

According to the World Register of Dams, 1506 large dams have been built in these two WHO subregions. We estimate that an area of 205 000 km² lies within 5 km of the lakeshores; approximately half is located in South Africa and Zimbabwe. We estimate that 28·7 million people at risk live within this area, representing 5·1% of the at-risk population. No data on large dams were available for Burundi, Central African Republic, Chad, Equatorial Guinea, Eritrea, The Gambia, Guinea-Bissau, Mauritania, Niger, Rwanda, and São Tomé and Prìncipe.

We identified 14 articles from six countries that examined the relation between water resources development and the prevalence of schistosomiasis in the Sahelian zone. Two cross-sectional studies, comparing mean prevalence rates in areas with and without water resources development in Mali and Ghana, both found higher rates in areas where water resources development had been implemented.

The effects of irrigation on the changing epidemiology of schistosomiasis, including the introduction of

Country, project, and period	Reference	Sample size	Age group	Species	Baseline confirming absence	Prevalence after water resources development	Comment
WHO subregion 1							
Burkina Faso, Sourou, irrigation scheme, 1999	55	..	SC	*S m*	First case diagnosed: 1987	8–69%	Léry dam closed: 1976 Main canal opened: 1985
Cameroon, Yaoundé, fishponds, 1960	104	61	..	*S m*	Not known before by inhabitants	64%	
Nigeria, Oyan river dam, 1988–89	105	1988/89: 355	TP	*S h*	Not known before by inhabitants	1988–89: 80·6%	Oyan river dam closed: 1984
1991–92	106	1991: 650	TP	*S h*		1991: 35·5%	Treatment of 1988/89 study participants
		1992: 591	TP	*S h*		1992: 61·6%	
Senegal, Senegal river basin, cross-sectional, 1994–95	65	Delta: 2920 “walo”: 2585 “diéré”: 1011	TP	*S m*	692 samples from delta, “walo” and “diéré” in 1977–78: *S m* 0%[63]	Delta: 4·4–43·6% (3/17–22/23) “walo”: 0% “diéré”: 0%	Diama dam closed 1985 and Manantali dam closed 1993. Percentages refer to endemic villages. Values in brackets represent the number of endemic villages/number of total villages. *S m* prevalence among 1139 people from Lac de Guiers villages: 71·8% (18/18)
Sierra Leone, Yengema town, pits from diamond mining, 1980s	107	451	TP	*S m*	First case diagnosed 1970	27·5%	Alluvial diamond mining and rice swamps, snails abundant in abandoned workings and in rice swamps
WHO subregion 2							
Côte d’Ivoire, Lake Taabo, 1992	93,94	258	SC	*S h*	120 samples in 1976–77: *S h* 0%[94]	73%	Taabo dam closed: 1979 Baseline data from one village, follow-up data from five villages
Democratic Republic of the Congo, open cast tin mining, 1980s	108	6433	TP	*S m*	Known to be absent until about 1960	87·4%	Mining started: 1932 Data from heavily infected villages. Mean prevalence in area is 10–15%
Ethiopia, Awash valley, irrigation, 1973–76	109	Upper valley: 1516 Middle valley: 992	TP	*S m*	Believed to be absent throughout the region	Upper valley: 9·0% Middle valley: 2·0%	Start of large-scale irrigation: 1950s
Ethiopia, Awash valley, Wonji sugar estate, 1980	110	1980: 2251	TP	*S m*	First case diagnosed: 1964	20% (1968: 7·5%, 1972: 9%, 1975: 17%)	Irrigation started: 1954
1988	111	1988: 267	SC			1988: 81·9%	Children of one labour village
Kenya, Mwea irrigation scheme	112	1966: 1875 1971: 2978	..	*S m*	Not reported in area	1966: 12·5% 1971: 24·4% 1982: 25%	Irrigation started: 1952, first case diagnosed: 1959 Prevalence after temporary cessation of molluscicidng (1972): 40%
Zambia, Lake Kariba Siavonga, 1968	99	1968: 726	TP	*S m*	*S m* or intermediate host snail not mentioned[100]	1968: 5·9%	Kariba dam closed: 1959
Siavonga and Matinangala, 1991	101	1991: 474	TP	*S m*	*S m* or intermediate host snail not mentioned[100]	1991: 54%	
Siavonga, 1994	102	1994: 323	TP	*S m*	*S m* or intermediate host snail not mentioned[100]	1994: 60·1%	
Siavonga, 2002	103	2002: 391	SC	*S m*	*S m* or intermediate host snail not mentioned[100]	2002: 33·5%	
WHO subregion 4							
Puerto Rico, Guayama/ Arroyo region, sugar cane irrigation	113	1906–09: 623/2612 1930–50: 400–4000 1960: 1127 1965: 1693	TP	*S m*	0% (1906–09)	6–40%, generally about 25% (1930–50) 6% (1960) 1% (1965)	Irrigation started: 1914, Carite and Patillas reservoirs constructed: 1916 Control started in 1950s. Prevalences calculated for 6-year-old children

..=not reported; SC=school-age children; *S h*=*Schistosoma haematobium*; *S m*=*Schistosoma mansoni*; TP=total population.

Table 4: **Identified studies reporting the introduction of schistosomiasis into an area following water resources development and management, stratified by WHO subregion**

Figure 3: **Human and animal water contact in an irrigation canal in the Senegal river basin where a major outbreak of *S mansoni* occurred after the construction of the Diama barrage in the late 1980s and early 1990s**

S mansoni into areas previously free of this parasite, were studied in different settings in Burkina Faso, Cameroon, and Senegal. The most dramatic effect of water resources development and management on schistosomiasis in recent years was observed in northern Senegal, following the construction of the Diama barrage close to the estuary of the Senegal river in 1985, which blocked the intrusion of saltwater into the river in the dry period, and hence enabled large-scale irrigation. Pre-development prevalence rates of *Schistosoma haematobium* in children and young adults were 0–0·9% in the delta zone, 0·7–3·6% close to the river in the middle valley ("walo") and 10·4–27·2% at some distance from the river in the middle valley ("diéré").[63,64] In an irrigated area, the prevalence of *S haematobium* was 29·7%. Meanwhile, *S mansoni* was absent throughout the area. The first cases of *S mansoni* in the Senegal river basin were diagnosed only 18 months after the closure of the Diama dam.[114] In 1995, the prevalence of *S mansoni* was 4·4–43·6% in endemic villages in the delta (figure 3).[65] From Lac de Guiers, situated at the margin of the delta, a prevalence of 71·8% was reported. The levels of *S haematobium* had increased to 1·9–41·1% in endemic delta villages, 11·5% in "walo" villages, and 51·6% in "diéré" villages.

We identified 18 articles examining the effect of water resources development and management on schistosomiasis in tropical west and central Africa. In Côte d'Ivoire, Ghana, and Nigeria, the creation of large dam reservoirs was followed by the introduction of urinary schistosomiasis or an increase in its prevalence among residents living in close proximity to these reservoirs. The prevalence of intestinal schistosomiasis remained stable. For example, a study by N'Goran and colleagues[93] carried out in villages located around Lake Taabo in central Côte d'Ivoire (figure 4) reported the introduction of urinary schistosomiasis into the area, reaching a prevalence of 73% in 1992, while the prevalence of intestinal schistosomiasis remained stable at about 3%.

The effect of irrigated rice farming on schistosomiasis was investigated in three studies, but no clear trend became apparent.[59,67–69]

The few available studies on small reservoirs and schistosomiasis focused on *S mansoni*. A prevalence of 21·2% was observed in an endemic area close to fish ponds, compared with a prevalence of 7·8% in more distant sites in Bafia, Cameroon (risk ratio 2·7).[86] Two studies, one from Sierra Leone[107] and one from the Democratic Republic of the Congo,[108] documented the introduction of *S mansoni* into areas previously free of the disease following mining activities. The creation of open water bodies was probably the underlying reason.

In east Africa, the effects of irrigation and small agricultural dams on schistosomiasis were assessed in eight studies done in Ethiopia, Kenya, Madagascar, and Tanzania. The introduction of *S mansoni* into the upper and middle Awash valley, Ethiopia, following the establishment of large-scale irrigation schemes has been documented for the Wonji sugar estate, where irrigation commenced in 1954 and the first case of *S mansoni* was diagnosed one decade later. Prevalence steadily increased up to 20% in 1980[110] and in 1988, a prevalence of 81·9% was found among children of a village in the irrigation scheme.[111] *S mansoni* remained absent from the lower valley where *S haematobium* was endemic. *S haematobium* also did not increase in frequency.[109]

Both longitudinal and cross-sectional data are available for the Ankilivalo district in western Madagascar, where a dam was built in 1979 for irrigation purposes. Although the prevalence of *S mansoni* in

Figure 4: **Human exposure to schistosome-infested water at Lake Taabo, Côte d'Ivoire**

school-age children rose from 13% in 1971 to 74% in 1986 in Ankilivalo, it was only 7·1% in 1986 in neighbouring Morafeno, which was not connected to the irrigation network.[60] That the irrigation system was a main trigger for schistosomiasis transmission became apparent after the destruction of the dam by a natural disaster in 1990; the prevalence in Ankilivalo decreased to 34·1% in 1994 while it had remained at 7·6% in Morafeno.[61]

In southern Africa, we identified four studies reporting data over 34 years for the area of Siavonga, Zambia, on the shores of Lake Kariba. A low prevalence of *S haematobium* and the absence of intermediate host snails from the construction site had been noted in a baseline evaluation report of the medical aspects of the dam project. There was no mention of *S mansoni* transmission.[100] The first follow-up study done 8 years after completion of the dam found prevalences of 28·8% and 5·9% for *S haematobium* and *S mansoni*, respectively.[99] Several studies done in the 1990s reported further raised prevalence levels—ie, 16·7–35·5% and 33·5–60·1% for *S haematobium* and *S mansoni*, respectively.[101–103]

WHO subregions 6, 7, and 9 (Eastern Mediterranean and Northern Africa)

Irrigation is of paramount importance to facilitate crop production in many countries of WHO subregions 6, 7, and 9. It is estimated that 253 000 km² or 25% of the total arable area is currently under surface irrigation in these subregions. Three-quarters of this area is located in Egypt, Iran, Iraq, and Turkey. We estimate that 43·6 million people at risk of schistosomiasis live in irrigated areas (31·6% of the population at risk), mainly in Egypt (34 million).

Considering a 5-km belt around the reservoirs created by the 925 large dams in these subregions translates to an estimated at-risk area of 128 000 km², of which 82 000 km² are located in Turkey. An estimated 2·3 million people at risk of schistosomiasis, 1·7% of the total population at risk, live in these areas. No data on large dams are available from the World Register of Dams for Iran, Somalia, and Yemen.[17]

14 studies reporting changes in the prevalence of schistosomiasis following water resources development and management activities in Egypt and Sudan were identified. The spread of *S mansoni* and the concurrent decline in *S haematobium* in Egypt has been attributed to the building of the Aswan low and high dams and the subsequent intensification of irrigation. This shift was documented in a village in the delta where the prevalence of *S haematobium* declined from 74·3% in 1935 to 2·2% in 1979, whereas the prevalence of *S mansoni* rose from 3·2% to 73% over the same time.[71] This finding could not be corroborated in a large-scale study of the whole delta region.[72]

The history of schistosomiasis in Africa's largest irrigated area, the Gezira irrigation scheme in Sudan, is well documented. From the onset of irrigation (closure of the Sennar dam in 1925), the population was regularly screened for schistosomiasis and very low levels of urinary schistosomiasis were reported up to the 1940s when an increase to 30% was noted.[76] In the same year, the prevalence of intestinal schistosomiasis was reported to be 1·3%. In the 1950s, similar infection prevalences of about 9% were reported for both parasites.[77] The construction of the Roseires dam in 1960 allowed irrigation to be further enhanced. In the 1970s and

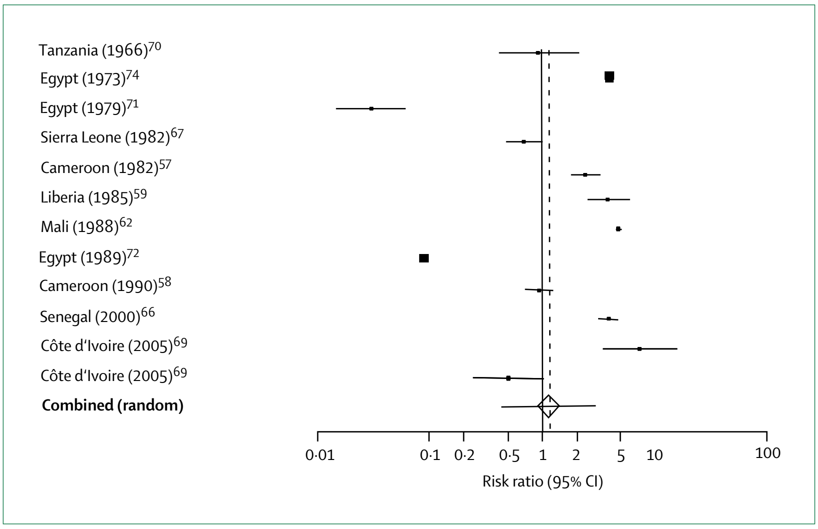

Figure 5: **Risk ratio estimates and pooled random risk ratio of urinary schistosomiasis due to living in irrigated areas**

The rectangles represent the risk ratios and the size of the rectangles represent the weight given to each study in the meta-analysis. The diamond and vertical broken line represent the combined risk ratio. The solid vertical line is the null value. Horizontal lines represent 95% CIs.

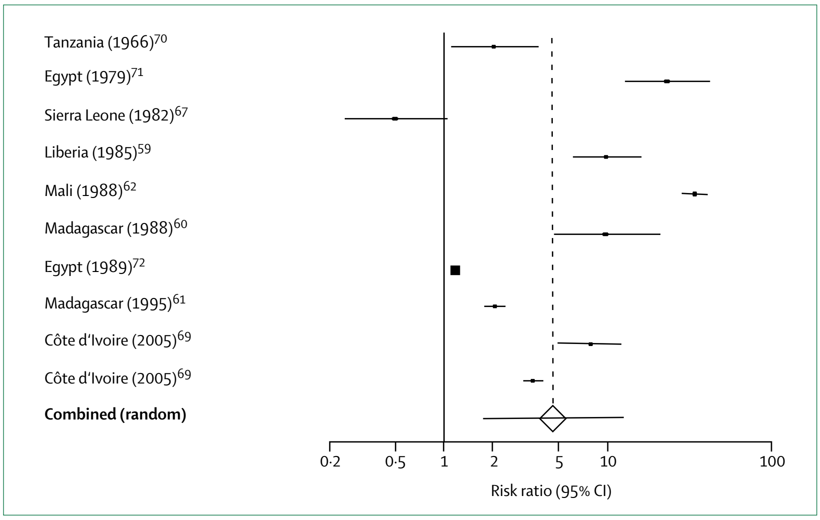

Figure 6: **Risk ratio estimates and pooled random risk ratio of intestinal schistosomiasis due to living in irrigated areas**

The rectangles represent the risk ratios and the size of the rectangles represent the weight given to each study in the meta-analysis. The diamond and vertical broken line represent the combined risk ratio. The solid vertical line is the null value. Horizontal lines represent 95% CIs.

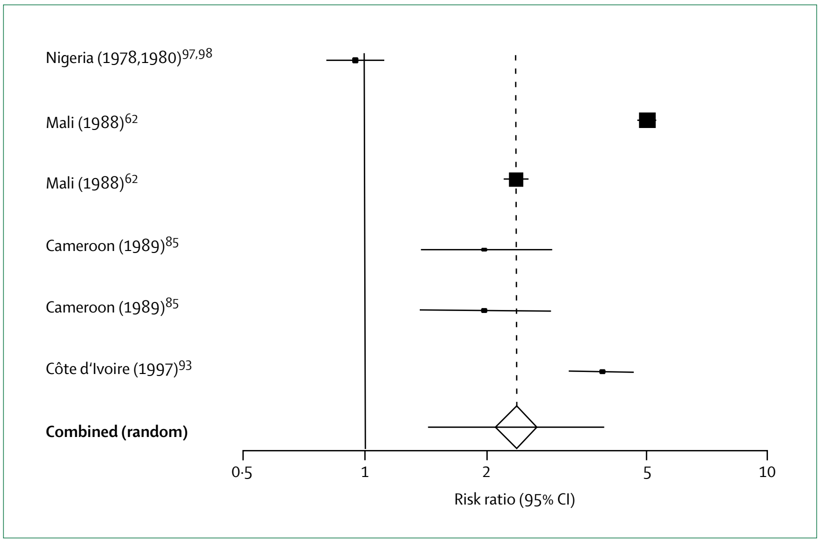

Figure 7: **Risk ratio estimates and pooled random risk ratio of urinary schistosomiasis due to living in close proximity to dam reservoirs**
The rectangles represent the risk ratios and the size of the rectangles represent the weight given to each study in the meta-analysis. The diamond and vertical broken line represent the combined risk ratio. The solid vertical line is the null value. Horizontal lines represent 95% CIs.

1980s, levels of *S mansoni* in excess of 50% were reported, while the prevalence of *S haematobium* stood at 0–20%.[78–83] To mitigate the public-health significance of intestinal schistosomiasis in the area, the "Blue Nile Health Project" was initiated in the area in 1979.[115] However, the project failed to make a dent, and the prevalence of schistosomiasis remained high.[20,83]

WHO subregion 4 (the Americas)
We estimate the area under surface irrigation of the endemic countries of this subregion to be 26 000 km², primarily in Brazil (17 000 km²). This represents 3·6% of the arable land. 537 000 people at risk (1·5% of the total in this subregion) are estimated to live in those areas; 67% of them in the Dominican Republic. Of the 755 large dams constructed in WHO subregion 4, 84% are located in Brazil, as are an estimated 80% of the total area of 128 000 km² situated within 5 km from reservoir shores. Overall, 3·4% (1·22 million) of all people at risk of schistosomiasis live in the Americas, with most in Brazil.

Only two studies in WHO subregion 4 could be identified. The first study describes the introduction of *S mansoni* into the Guayama/Arroyo region, Puerto Rico, following the introduction of irrigated sugar cane cultivation with peak prevalences of 40% in 6-year-old children.[113] The second study is from Bahia, Brazil, where no apparent correlation was observed between the size of the irrigated area, the prevalence of *S mansoni*, and its historical evolution.[84]

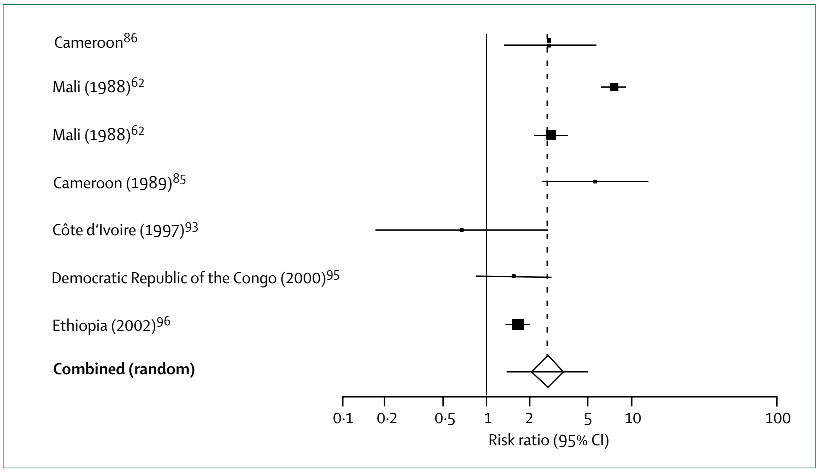

Figure 8: **Risk ratio estimates and pooled random risk ratio of intestinal schistosomiasis due to living in close proximity to dam reservoirs**
The rectangles represent the risk ratios and the size of the rectangles represent the weight given to each study in the meta-analysis. The diamond and vertical broken line represent the combined risk ratio. The solid vertical line is the null value. Horizontal lines represent 95% CIs.

WHO subregions 11, 12, 13, and 14 (Southeast Asia and Western Pacific)
Approximately 1 258 000 km² or 31% of the total arable land are currently under surface irrigation in these subregions, 90% of them in China and India. We estimate that 9·1 million people (19·7% of the total population at risk) live in irrigated, schistosome-endemic areas, 8·76 million of them in China and 0·35 million in the Philippines. The World Register of Dams lists 10 845 large dams in the schistosome-endemic countries of these subregions. The area within 5 km of the lakeshores is estimated at 1·43 million km²; China and India having equal shares of 0·62 million km² each. We further estimate that 10·1 million people live in at-risk areas or 21·7% of the total population at risk in these subregions. Virtually all of them live in China (9·97 million).

We could not identify a single study that looked at the effect of water resources development and management on schistosomiasis in these WHO subregions. This observation warrants further scrutiny—eg, screening of the Chinese literature that is not referenced in any of the electronic databases used in the current analysis.

Meta-analysis

Overall, 24 studies (including 35 datasets) reported sufficiently detailed data to calculate pooled random risk ratios of schistosomiasis with regard to the construction and operation of dams and irrigation schemes. All studies stem from Africa. Heterogeneity of these studies was significant ($p<0·001$). Risk ratio estimates for studies assessing the effect of irrigation on urinary and intestinal schistosomiasis ranged from 0·02–7·3 (summary estimate 1·1; figure 5) and 0·49–23·0 (summary estimate 4·7; figure 6), respectively. Pooled random risk ratios associated with dam construction were calculated as 2·4 (95% CI 1·4–3·9) and 2·6 (95% CI 1·4–5·0) for *S haematobium* (figure 7) and *S mansoni* (figure 8), respectively.

Discussion

Our estimates of 779 million people at risk of schistosomiasis and 207 million infections in 2003 translate to increases of 10·9% and 7·3%, respectively, when compared with the last comprehensive estimates in the mid-1990s (at-risk population: 702 million; number of infected people: 193 million).[9] However, the relative number of people infected compared with those at risk slightly decreased from 29·6% to 26·6%. This decrease may be a consequence of wider availability and use of praziquantel and socioeconomic development (often closely linked to improved water supply and sanitation), on the one hand, and the population growth and a scarcity of new estimates of people at risk on the other. Both the increases in numbers of people infected and those at risk primarily occurred in Africa, corroborating similar observations for soil-transmitted helminthiasis; case numbers increased in Africa, while they decreased in most other regions of the world.[116]

We were able to update national schistosomiasis prevalence or incidence data for 31 countries. Unfortunately, new data are only available for six countries of WHO subregions 1 and 2 where 90% of the global cases occur. These countries are Cameroon, Mauritius, Chad, Malawi, Togo, and Uganda. In the latter four countries, the reported prevalence rates were derived from surveys of school-age children. We applied these rates to the total population without further adjustment. Since school-age children usually have higher prevalence rates than younger or older population segments,[10,23,117] we are likely to overestimate the numbers of people infected in these countries. This was judged acceptable on three grounds. First, in sub-Saharan Africa the proportion of the population under 15 years of age is in the range of 40–50% in most countries.[118] Second, reported prevalence data are lower than "true prevalences" because of the lack of sensitivity of diagnostic tools.[119] Third, the total number of infections estimated for these four countries (ie, 9 447 000) translates to only 4·6% of the global estimate.

We estimate that 106 million people at risk of schistosomiasis (13·6% of the total at-risk population) live in proximity to large dam reservoirs and irrigation schemes, about three-fifths of which are in proximity to irrigation schemes. Only areas under surface irrigation were considered because we assumed that other irrigation techniques (eg, drip and sprinkler irrigation) pose little risk if they are well maintained.[6,120] Our estimates are primarily based on data from FAO[18,47] and the World Register of Dams.[17] At present, the number of people living close to reservoirs of small dams and on land under informal irrigation remains elusive. Ignoring small dams and informal irrigation inevitably results in an underestimate of the total number of people at risk of schistosomiasis due to water resources development. This issue has been discussed recently with an emphasis on malaria[1] and should not be underestimated since, at least in arid and semi-arid climate zones, agriculture heavily relies on small-scale artificial irrigation.[121,122] Additional groups of people affected, but not included in our at-risk estimates, are seasonal migrants working in irrigated agricultural areas in times of increased labour demand. Their number is very large in certain irrigation schemes—eg, in the Gezira, Sudan.[123] They can also spread the parasite to non-endemic areas given the presence of susceptible intermediate host snails.[124] The dampening effect of dams on the fluctuations of downstream water levels, which creates more stable snail habitats, was not assessed either, nor was the number of people at risk due to mining activities.

Underlying assumptions of our calculations were discussed in detail in our preceding work.[1] Additional points are offered for discussion here. We considered studies reporting pre-intervention and post-intervention data, as well as cross-sectional studies comparing settings affected by water resources development with close ecological replicates. Each type of study has some inherent limitations with regard to the generalisation of specific findings, thus also limiting the meaning of the meta-analysis. Our approximation of the rural population density overestimates the true population density in arable areas of countries with a considerable number of rural people living on land not classified as "arable" or "planted with permanent crops". This potential overestimate is expected to correct at least partly for the often higher-than-average population density in irrigated areas[1] while still taking into account country-specific differences. The calculated mean population density in arable areas of endemic countries is 329 people per km² and the range of values compares well with other estimates.[1,125] The multiplication of the population living in irrigated areas and in proximity to large dam reservoirs with the national fraction at risk to derive the at-risk population almost certainly results in an underestimate, as the risk of infection in rural settings is higher than the national average. Besides, the level of irrigation and dam construction in endemic areas of a country is not necessarily proportional to the population fraction living in the respective areas. Finally, it is not always possible to clearly assign projects to either "irrigation" or "man-made lake" because many dams serve multiple purposes—eg, flood control and provision of water for urban centres, irrigation, and hydropower generation.[122] Therefore, the distinction between the effects of dams and those of irrigation schemes is to some extent arbitrary.

An important finding of our work is that the fractions of the total population at risk of schistosomiasis, irrigated population at risk and total population at risk due to proximity to large dam reservoirs vary considerably (table 1) because of major differences in contextual determinants (eg, agricultural traditions and socioeconomic status). Only 15·8% of the irrigated population at risk live in WHO subregions 1 and 2, reflecting the current low level of irrigation in these countries and underscoring the risk for an increase in the schistosomiasis burden once irrigation developments in Africa take off. Irrigation is much more pronounced in WHO subregion 7 where 67·4% of all people at risk due to irrigation are estimated to live. Although the number of large dams is very low in most sub-Saharan African countries, there are two notable exceptions: Zimbabwe and South Africa. Here, 38% of the global at-risk population living in proximity to large dam reservoirs are found.

It is widely acknowledged in public-health circles that water resources development can amplify the risk of schistosomiasis, particularly in Africa,[19,20,23,73] but this association has also been challenged.[126] There also is a paucity of studies from other regions.[19,23,126] Whereas actual or suspected increases in the prevalence and intensity of schistosome infections repeatedly have been attributed to such activities, there are often no quantifiable baseline and follow-up data available[127]—eg, in Khuzestan province, Iran,[128,129] in eastern Uganda,[130] and in the Kainji lake area, Nigeria.[131,132]

The summary random risk ratio of schistosomiasis due to proximity to dam reservoirs in Africa was 2·5. Although we found no raised overall risk of *S haematobium* in irrigation schemes, the risk of intestinal schistosomiasis due to irrigation was found to be strongly correlated. This result is governed by studies documenting the so-called "Nile shift"[20] in Egypt and the inconclusive data from rice farming areas in tropical west Africa. Nevertheless, other studies showed a clear increase of urinary schistosomiasis when irrigation was initiated. The preferred habitat of the intermediate host snails offers at least some explanation for this finding. *Biomphalaria* spp snails (intermediate host of *S mansoni*) require more stable water levels than *Bulinus* spp and thus are likely to benefit more from intensive irrigation.

Some interesting regional trends emerge from our analysis. First, urinary schistosomiasis often increased in populations living close to large dam reservoirs in west Africa while the introduction or spread of *S mansoni* was associated with smaller water bodies. Second, the introduction or spread of intestinal schistosomiasis was reported in almost all studies on the effects of irrigation in east Africa. Third, both irrigation and dam reservoirs resulted in increased levels of schistosomiasis or the introduction of intestinal schistosomiasis in the Sahelian zone. Fourth, the introduction of *S mansoni* into areas previously free of the parasite was observed eight times in Africa and once in the Caribbean, but the introduction of urinary schistosomiasis has been documented only twice, both times following the construction of a large dam in west Africa.

We conclude that globally, a large number of people live in areas under surface irrigation or in close proximity to large dam reservoirs, and both the irrigated area and the number of large dams are ever increasing. Our meta-analysis shows that an increase in the prevalence of schistosomiasis can result from water resources development projects. This stresses—once more—the need to include health impact assessment, including schistosomiasis risk profiling of affected populations into the screening, scoping, and monitoring stages of future water projects, and to implement sound mitigation strategies.[20,133] Identified research needs include the effects of small dams and informal irrigation schemes on schistosomiasis, the interplay of water resources development and schistosomiasis in Asia (eg, the impact of the Three Gorges dam project in China on the frequency and transmission dynamics of *Schistosoma japonicum*[134]) and the Americas and the nature of the conditions that determine why schistosomiasis is introduced into some non-endemic areas and why others remain unaffected.

Search strategy and selection criteria

Details of the search strategy and selection criteria can be found in the Methods section.

Conflicts of interest

We declare that we have no conflicts of interest.

Acknowledgments

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