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WATER, ENGINEERS, DEVELOPMENT, and DISEASE in the TROPICS

Schistosomiasis engineering applied to planning, design, construction and operation of irrigation, hydroelectric and other water development schemes.

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FOREWORD

Development of water resources is increasingly important to many developing countries. In many areas the development of new or expansion of existing irrigation systems is essential for greater food production. Unfortunately the environmental changes resulting from construction of dams, man-made lakes, irrigation and draining systems, flood control works, and other water resources development can bring burdens as well as benefits. Too often these burdens include increased incidence of serious human diseases such as schistosomiasis, bilharzia and malaria.

These diseases are neither new nor mysterious. Existing knowledge and engineering technology offer many opportunities to control or at least to mitigate the dangers of these man-made environmental changes, provided that health implications are recognized and taken into account from the earliest planning stages and the necessary control measures incorporated throughout each stage of water resource development.

Development of water resources is generally entrusted to engineers. In this monograph, Professor McJunkin, himself an engineer, outlines and warns his colleagues of the many implications that water resources development can have on human health, especially in the transmission of schistosomiasis. He also describes what engineers can do to control schistosomiasis and other water-related, vector-borne diseases.

In considerable degree 'schistosomiasis engineering' is simply good engineering properly applied. It results in effective measures of disease control to the benefit of all.

Daniel Parker
Administrator

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BACKGROUND

Environment and Development

The current concern with the human environment arises at a time when the developing countries are becoming increasingly devoted to the goal of development. Yet current concern with environmental issues has been fostered in large part by the environmental problems that have accompanied economic development in the industrially advanced countries. Rapid multiplication of industrial and agricultural output; massive urbanization; escalating demands for energy; creation of complex transportation networks on land, sea, and air; large population increases, and growing demands on fixed natural resources have too often resulted in serious environmental hazards.

The developing countries obviously do not want to repeat the historical mistakes of the industrialized societies. However this does *not* imply, in the words of World Bank President Robert S. McNamara, "that latecomers to the development process must forego industrialization and technological advance. That would mean stagnation. It is easy enough for the wealthy to romanticize about the supposed charm of pretechnological society. The plain fact is that there was nothing pretty at all about the squalid poverty that the common man had to endure in the pretechnological period in what are now the affluent nations. For the vast majority it was a life of destitution and disease." McNamara further suggests that "human degradation is the most dangerous pollutant there is." The Founex Report on Development and Environment (prepared for the Stockholm Conference on the Environment) suggests that "developing countries must view the relationship between development and environment in a different perspective. In their context, development becomes essentially a cure for their major environmental problems."

However, many environmental problems arise from the development process itself. These problems, though possibly of lesser significance in early stages of development, are likely to increase in importance as the process of development gains momentum. Fortunately, many adverse environmental effects might well be avoided, or

at least mitigated by environmentally sound planning, design, construction, and operation.

This publication attempts to identify health-related environmental effects of water resources development in the developing countries. Attention is focused primarily on water resources development which changes the natural environment through spatial and temporal relocation of surface water as exemplified by the man-made lakes, canals, channels and changes in natural flows associated with irrigation and hydroelectric projects in particular, and with fisheries, roadway and agricultural drainage, navigation, recreation, water supply reservoirs, and other water-related projects.

Although strictly speaking, community water supply and sewerage are water resources development activities, a primary purpose of their development is improvement of the public health. Other water resources development is generally directed to a specific, non-health purpose or purposes. irrigation for example, and health effects, favorable or not, are secondary.

Population and Water Resources Development

The population of the world in 1970 was estimated at some 3,500 million of whom 71 percent live in rural areas or small towns with fewer than 20,000 inhabitants (See Table 1). About 80 percent of the population of the developing countries live in rural areas or small towns. (See Table 2).

TABLE 1. WORLD POPULATION PROJECTIONS (Lower Estimate)

Year	Total World population (millions)	World Rural population[a] (millions)	Rural population as % of total population
1970	3 572.5	2 545.4	71
1980	4 231.9	2 847.3	67
1990	4 938.0	3 123.2	63
2000	5 670.4	3 378.1	59

Source: United Nations Population Division (1969) Unpublished document.

[a] Including rural population living in communities of less than 20,000.

TABLE 2. WORLD RURAL POPULATION PROJECTIONS (Lower Estimate)

Year	World Rural population (1)	In more developed regions (2)	In less developed regions[a] (3)	(3) as % of (1)
1970	2 545.4	538.8	2 006.6	79
1980	2 847.3	545.7	2 401.6	81
1990	3 123.2	548.6	2 574.6	82
2000	3 378.1	550.1	2 828.0	84

Source: United Nations Population Division (1969) Unpublished document.

[a] Africa, Asia (excluding Japan), Central America, South America (excluding temperate zone), Oceania (excluding Australia and New Zealand).

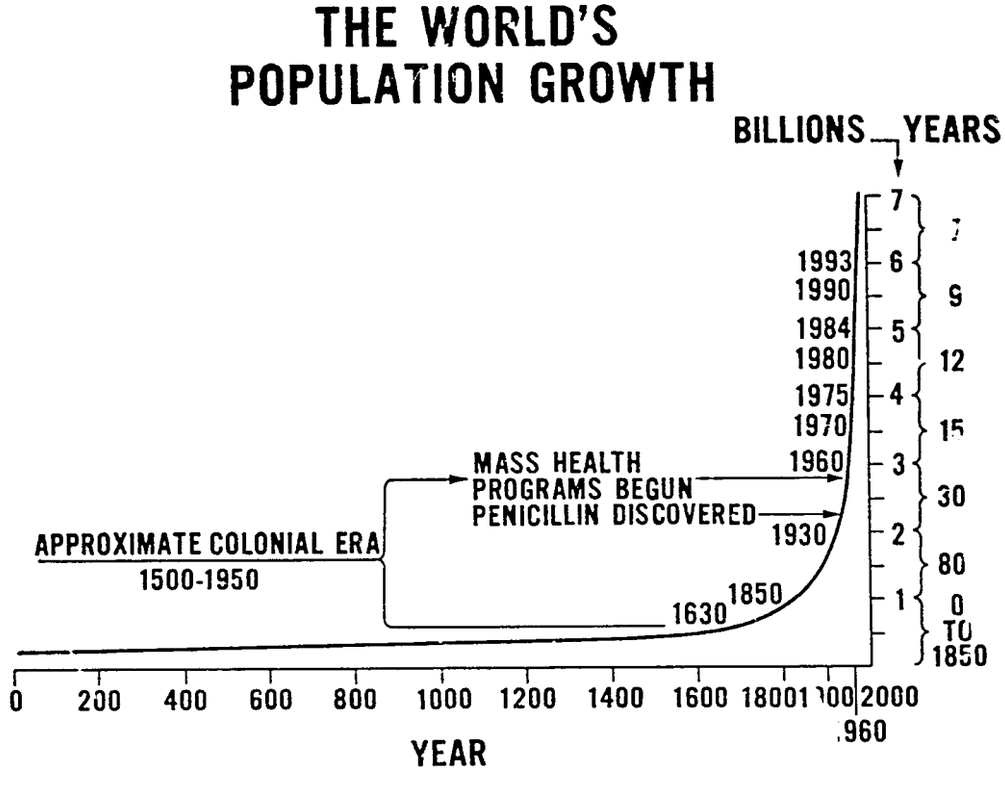
The rapid growth of world population is well-known and is dramatically illustrated in Figure 1. Even under optimistic assumptions regarding birth control, world population will increase by over 2,000 million people by the turn of the century.

If fulfillment of Malthusian prophecies is to be avoided, then this larger population must be fed. During recent years spectacular progress has been made in increasing wheat, rice, and maize production in several of the most populous countries of southern Asia, where widespread famine appeared inevitable only a few years ago. The popular press has recognized this program by the term "Green Revolution" and much has been written about the new cereal varieties. Norman Borlaug, awarded a Nobel prize for his role in the Green Revolution, points out that "it must be emphasized that thus far the great increase in production has been in irrigated areas." For example in India during the 1969-70 crop season, 70,000 private tubewells were sunk which brought about 1.4 million hectares of additional land under controlled irrigation.

The International Commission on Irrigation and Drainage estimates that, world wide, acreage under irrigation has grown steadily (See Table 3).

The race between population growth and irrigation is strikingly shown in the case of Egypt where despite many

Figure 1



Source: AID

FIGURE 1

TABLE 3. LAND IN IRRIGATION

Year	Irrigated Land in Millions of Acres
1800	20
1900	120
1949	230
1959	370
1969	500
"potentially irrigable"	1,250

Source: Framj and Mahajan (1969).

increases in irrigated acreage, the per capita share of the crop area has decreased from 0.69 acre in 1897, to 0.52 acre in 1937, to 0.42 acre in 1947, to 0.40 in 1960. The Sadd-el Aali (Aswan High Dam) will bring 1,195,990 acres of new land under irrigation and convert 726,490 acres of land from basin (flood) to perennial irrigation. But without population control the land per capita will continue to drop.

Table 4 illustrates the large land area not presently cultivated, but potentially arable. The largest remaining uncultivated but arable lands are in Africa and South America.

Many developing countries are unable to optimally utilize potentially arable land due to the presence of vector-borne diseases such as malaria, trypanosomiasis (African sleeping sickness), and onchocerciasis.

Historically malaria has precluded land development where natural conditions permitted the breeding of mosquitoes under conditions which permitted a high potential for transmission. Anti-malaria programs have reclaimed the foothill area of north India and agriculturally productive plains in Thailand. Major settlement population in the inland hilly malarious areas of the Philippines has been possible only since major reduction of the parasite reservoir occurred within the general population.

Much of Central African land is unused due to the tsetse fly and the sleeping sickness which it transmits. Agricultural efforts at vector control are being attempted because of the adverse effect of the fly on cattle.

Forty million West Africans are precluded from farming fertile river valleys because of the Simulium fly and the filaria-like worm it transmits. The frightening complication of this disease, which has very little mortality, is blindness from migration of the parasite into the eye. Figure 13 illustrates onchocerciasis-induced migration away from the Red Volta and White Volta Rivers in northeastern Ghana.

TABLE 4. "CULTIVATED" LAND ON EACH CONTINENT, COMPARED WITH POTENTIALLY ARABLE LAND

	AREA IN BILLIONS OF ACRES		
Continent	Total	Potentially arable	"Cultivated"
Africa	7.4	1.81	0.39
Asia	6.76	1.55	1.28
Australia and New Zealand	2.03	0.38	0.04
Europe	1.18	0.43	0.38
North America	5.21	1.15	0.59
South America	4.33	1 68	0.19
U.S.S.R.	5.52	0.88	0.56
Totals	32.49	7.88	3.43

Source: Howard (1970).

In summary it can be said that additional millions of acres will, and must be brought under irrigation in coming years.

Dams and Reservoirs

Inasmuch as millions of acres of land will be brought under irrigated cultivation in coming years, the construction of many new dams and reservoirs is inevitable. In addition to storing water for irrigation, dams will be constructed for purposes of flood control, water supply, fish propagation, navigation, and hydroelectric power generation. Construction of power dams can only be accelerated by increasing costs of fossil fuels.

Three of the world's largest dams and reservoirs were constructed in Africa during the 1960's: Kariba Dam and Reservoir on the Zambesi River, between Rhodesia and Zambia; the Aswan High Dam (an earlier, lower dam

was built in 1902) on the Nile, and its reservoir, Lake Nasser, flooding upper Egypt and lower Sudan; and Akosombo Dam and Lake Volta on the Volta River in Ghana. Kariba and Akosombo were built primarily for power production, Aswan for power and for irrigation.

FIGURE 2

KARIBA DAM ON THE ZAMBESI RIVER (AFRICA)

According to the International Commission on Large Dams, over 350 dams greater than 50 feet in height come into existence each year, joining an inventory of 10,000 to 12,000 such dams. Such mighty river basins as the Amazon, the Congo, and the MeKong have hardly been tapped.

"Ecological Horror Stories"

Large water resources projects have been frequently attacked in the popular press as environmental "disasters", "boomerangs", and "horror stories", perhaps none

Super Dams: The Perils of Progress

Condensed from THE ATLANTIC MONTHLY
CLAIRE STERLING

> Huge man-made lakes were supposed to mean instant advance for developing nations. Too late we are learning that they can wreak social and ecological havoc

WHAT HAPPENS when we dam the flow of a great river and create an immense body of water where there was none before? Not enough thought was given to this ecological question in the 1950s and '60s a dozens of big dams went up [illegible] in to Ghana, Egypt to [illegible] big dams [illegible] fauna, the way of life for all the people who lived on the land before the lake came, the fertility and salinity of the soil downstream, the pressures on the earth's crust and the tendency [illegible] earthquakes and land- [illegible] the promised

FIGURE 3
EXAMPLE OF RECENT JOURNALISTIC CONCERN OVER ENVIRONMENTAL IMPACT OF INTERNATIONAL DEVELOPMENT

more so than the Aswan High Dam. Among the charges have been that this project has spawned water-borne diseases, particularly schistosomiasis; destroyed downstream fisheries; caused earthquakes; increased salinization and waterlogging in associated irrigation projects; displaced population; flooded archeological sites; incurred massive seepage losses; resulted in land subsidence; accelerated eutrophication; altered climate; choked in aquatic weeds; increased evaporation losses;

trapped fertile sediments behind the dam; and increased erosion downstream and at the delta. While many criticisms of this and other projects carry an element of truth, it should also be remembered that project-associated environmental costs or risks must sometimes be taken in order to secure the overall benefits sought. (The United States for example, accepts 50,000 traffic deaths per year in exchange for the benefits of private motor vehicle transportation). It has been wrongly assumed that in the past all adverse side effects come as a surprise. In fact many of the same arguments were advanced prior to construction of the Low Aswan Dam in 1902.[a,b]

Indeed reservoir development may present many environmental problems. Annex C describes these in some detail. The Annex reproduces selections from a report on *Man-Made Lakes, Planning and Development* published by the Food and Agricultural Organization of the United Nations (Lagler, 1969) and reproduced in part by the United Nations Department of Economic and Social Affairs in its 1970 Report, *Integrated River Basin Development*.

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[a] Post-project studies are now underway by the World Health Organization, the Food and Agriculture Organization and others. Post-project economic analysis has been distorted by the 1967 and 1973 wars. According to the editor of *Al Ahram*, the Egyptian military budget *each year* is equivalent to the construction cost of Aswan Dam.

[b] A female American journalist who visited Egypt and wrote a scathing article on Aswan and its impact on schistosomiasis was described to this author by an Egyptian health official as a "neo-Marie Antoinette" but "where Marie Antoinette responded 'let them eat cake' when told the people had no bread, would respond, 'don't let them eat any cake either, it's bad for their teeth'."

WATER AND HEALTH

General

The role of water supply as a vehicle for direct transmission of bacterial and viral diseases such as typhoid, cholera, infectious hepatitis, and gastroenteritis is well established (see Miller, for example) and will not be discussed further except to warn that they often attack migrant and resettling populations such as exist at every major water resources project. They are most readily controlled by adequate water supply and sanitation.

Attention is directed rather to those vector-borne, parasitic diseases that find attractive or compatible the new ecological systems or niches created by irrigation or other public works. Seemingly non-water related projects such as highway construction may be very much involved through vector breeding influenced by such features as abandoned, non-draining borrow pits. Table 5 summarizes communicable and vector-borne water related diseases. The seriousness of the water-related parasite diseases is summarized in Table 6.

Epidemiological Considerations

Each parasitic infection has its specific mode of transmission by which the infection is spread, and the particular cycle necessary to pass an infection from one man to another—that is, to establish a new infection—varies greatly from one parasite to another. In all instances, however, it is a highly complicated process, based on the inter-relationship between the human host, the parasite and, often, a vector or intermediate host species. Transmission generally requires certain prescribed environmental conditions in order to take place. In this respect, water, either by its mere existence or its specific condition, often plays an important role in the epidemiology of parasitic diseases. Thus, many parasitic infections are, to some extent, water related diseases.

Man himself often creates the basic conditions (see Figure 5) for the multiplication of breeding places for vectors of such diseases as malaria, schistosomiasis, river blindness (onchocerciasis), distomatosis, paramphistomiasis, and a number of other infections capable of causing disease in man and livestock in endemic proportions.

TABLE 5. WATER AND HEALTH

Role of Water	Disease	Remarks
Major Vehicle for Direct Transmissions	Cholera	Classic example of water-borne-disease
	Diarrhea and Enteritis	Symptomatic of many infections and toxemias; often non-specific
	Dracontiasis (Guinea worm disease)	Ingestion of infected *Cyclops;* 50,000,000 active cases
	Hepatitis, Infectious	100,000 cases in 1955 Delhi outbreak
	Leptospirosis (Weil's disease)	A zoonosis; ingestion of urine of infected animal
	Paratyphoid Fever	Milder than typhoid
	Schistosomiasis (Bilharziasis)	Requires aquatic snail as intermediate host and water contact, with skin penetration by cercariae, or, less often, their ingestion; over 150,000,000 active cases
	Typhoid Fever	Major 19-Century U.S. disease
Occasional Vehicle	Dystentery, Amebic (Amebiasis)	World-wide endemicity
	Dystentery, Bacillary (Shigellosis)	Many outbreaks due to cross-connections
Possible Vehicle	Poliomyelitis	Virus is found in sewage
	Pleurodynia	Non-fatal; Coxsackie virus
	Tularemia	A zoonosis; usually direct contact
Clean Environment (Lack of Safe Water)	All above except Schistosomiasis and Dracontiasis	
	Ancylostomiasis (hookworm)	Water-borne sanitation best preventive
	Ascariasis	Avoid ingestion
	Echinococcosis (Hydratidosis)	Food and drink contaminated by dog feces
	Enterobiasis	Personal hygiene
	Mycoses	Fungal diseases, personal hygiene
	Relapsing Fever	Louse-borne; poor sanitation
	Scabies	Personal hygiene
	Trachoma	150,000,000 victims with impaired vision
	Trichomoniasis	*Trichomonas hominus, Giardia lamblia;* contaminated food and drink

Role of Water	Disease	Remarks
	Typhus Fever	Louse-borne; crowding, poor sanitation
Vector Habitat	Clonorchiasis	Ingestion of parasitized fish
	Dengue	Mosquito
	Dilphyllobothriasis	Ingestion of parasitized fish
	Encephalitis	Mosquito
	Fasciolopiasis	Ingestion of water chestnuts containing cercariae
	Filariasis	Mosquito
	Loaiasis	Aquatic fly *(Chrysops)*
	Malaria	Mosquito
	Onchocerciasis	Aquatic fly *(Simulium)*
	Paragonimiasis	Ingestion of parasitized crabs and crayfish
	Rift Valley Fever	Mosquito
	Yellow Fever	Mosquito
Carrier	Chemical Poisoning	Natural and polluted waters; acute and chronic
	Radiation Exposure	Cumulative

TABLE 6. ESTIMATED WORLD-WIDE PREVALENCE OF CERTAIN DISEASES RELATED TO WATER RESOURCE DEVELOPMENT

Disease	Prevalence
Schistosomiasis	200,000,000
Filariasis	200,000,000
Onchocerciasis	40,000,000
Malaria	25,000,000

Modern technology and science offer the means to prevent or at least reduce the dangers of such man-made environmental changes, provided the health factor is recognized and taken into account from the early planning stages of a project and the necessary remedial action integrated in each program through its implementation.

Three different patterns of water-related transmission of parasitic disease can be distinguished:

(1) The parasite is picked up from an infected person by a vector (for instance a mosquito). It then undergoes a period of development in the vector before it can be

passed on to another person. In this type of transmission pattern water provides the essential "breeding places" or larval habitats of the vector. The presence or absence of water, or its specific condition, will therefore influence significantly the size of the infection. The parasite itself does not exist free in the environment. The principal diseases of man belonging to this category are malaria, filariasis (elephantiasis), and onchocerciasis (river blind-

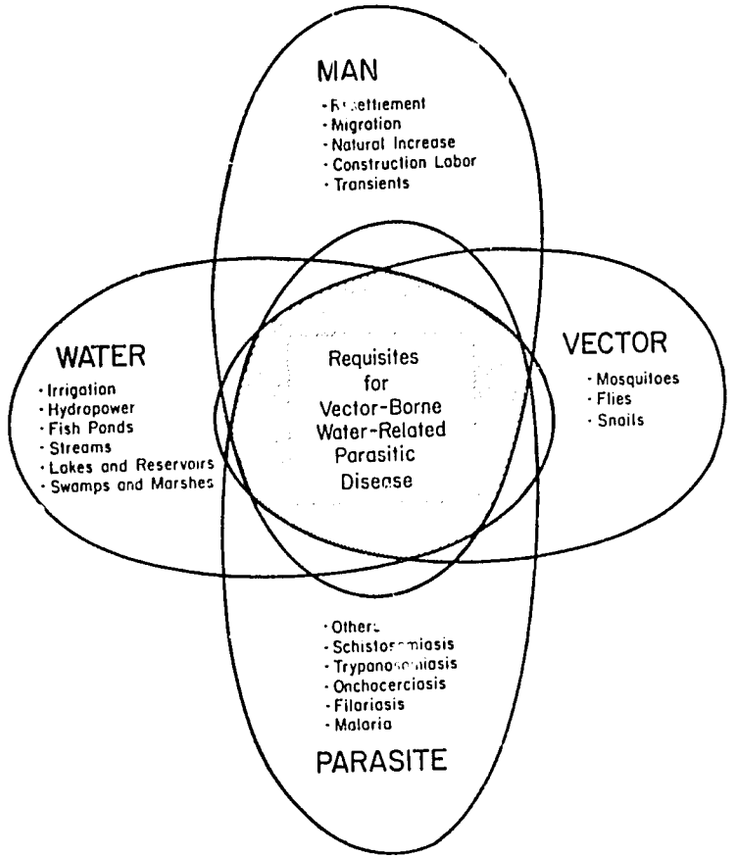


FIGURE 4

ness). To some extent perhaps trypanosomiasis (sleeping sickness) could also be included as some species of its

vector, the tsetse fly, although not requiring water for breeding purposes, are nevertheless closely dependent on the shelter of evergreen forest associated with river banks and lake edges.

(2) The parasite is discharged by an infected person to the water environment and must find and enter a specific intermediate host (usually a snail, a crustacean or a fish). In this secondary host it has to pass through one or more developmental stages before becoming infective to man.

This is a more complex cycle of transmission because the presence of water may be essential *both* for the survival of the parasite and for the life of the intermediate host. The most important parasitic infections following this transmission pattern are schistosomiasis, paragonimiasis (oriental liver fluke), fascioliasis, and dracontiasis (guinea worm).

(3) The third form of transmission is by indirect contact, the parasite is excreted by an infected person, enters the environment, and is picked up there by another person. In the parasitic diseases which follow this pattern of transmission, the parasite (in the form of eggs or larvae) usually has to be deposited for its survival on *moist* soil as the favoring element (e.g., hookworm and other helminthic infections).

In any of these diseases alterations in the water environment can have an impact on the relationships between man, parasite, vector or intermediate host, that is, on the epidemiology of the infection, resulting in an increase or decrease of transmission, thus causing a change in the prevalence of the disease.

Malaria

Of all water-related parasitic diseases malaria is probably the most commonly known. Until very recently this infection was highly prevalent in the entire tropical and subtropical belt and extended into temperate climates. The disease is considered one of the most serious public health problems.

Owing to its characteristic fever attacks the infection has been easily recognized since ancient times. The human malaria infection has been easily recognized by four different parasite species of the protozoan genus *Plasmodia;* apart from morphological differences, the

species differ mainly in regard to life span and the periodicity of the fever attacks they cause.

The malaria parasite is introduced into the human blood stream as a sporozoite through the bite of an infective mosquito. The parasites develop and multiply, first in the liver and later in the blood stream, where they invade the red blood cells. Some of the parasites develop into sexual forms, called gametocytes, which are eventually taken up by the bite of an *Anopheles* mosquito. In the mosquito the parasite undergoes various stages of development leading to the formation of sporozoites. These accumulate in the salivary glands and are injected into man during a blood meal.

Malaria infection may be transmitted by about 60 different species of *Anopheles* mosquitos. All of these are aquatic breeders; however, their preferences for specific types of water vary greatly. A peculiarity of most of the malaria vectors—of which advantage is taken for control—is that they bite humans in or near their houses and rest indoors after a blood meal.

Malaria is essentially a chronic disease. Apart from its classic fevers, malaria is characterized by high infant mortality, stillbirths and abortions; with enlargement of the spleen; and the predisposition of its victims to other infections. Where agricultural production and levels of life are already low, its economic effects are obvious: food supplies are further reduced by the large malarial areas left untilled, and social and economic development are retarded.

With modern chemotherapy, malaria infections can be cured radically, and it is also possible to effect prophylactic protection.

In view of the encouraging results obtained in malaria control campaigns with insecticide spraying against the adult vector, a world-wide malaria eradication program was inititaed in 1955, based mainly on indoor spraying with DDT and drug treatment of the parasite in humans. The aim is to achieve complete interruption of transmission, but not the elimination of the vector species, a much more difficult, if not impossible task.

Malaria control directed at the larval stages of mosquito vectors is still practiced where (1) house spraying is impractical or uneconomical as in densely populated

urban areas, (2) where there are few breeding places, such that a relatively small effort will substantially reduce the adult vector population, and (3) where other methods have failed. Larval control methods include naturalistic control, fish predators for example; source reduction through planned modification of the environment, water regulation for example; and chemical control or larvaciding.

Environmental modification measures directed at mosquito control are generally beneficial in controlling aquatic snail vectors of schistosomiasis and vice versa.

As long as malaria still exists in some parts of the world the danger of its being re-introduced in freed areas must be considered, especially in those developing areas where population movements take place, with new water projects creating at the same time, new favorable breeding conditions for *Anopheles*.

Figure 5 illustrates areas where malaria transmission occurs or might occur.

Schistosomiasis (Bilharziasis)

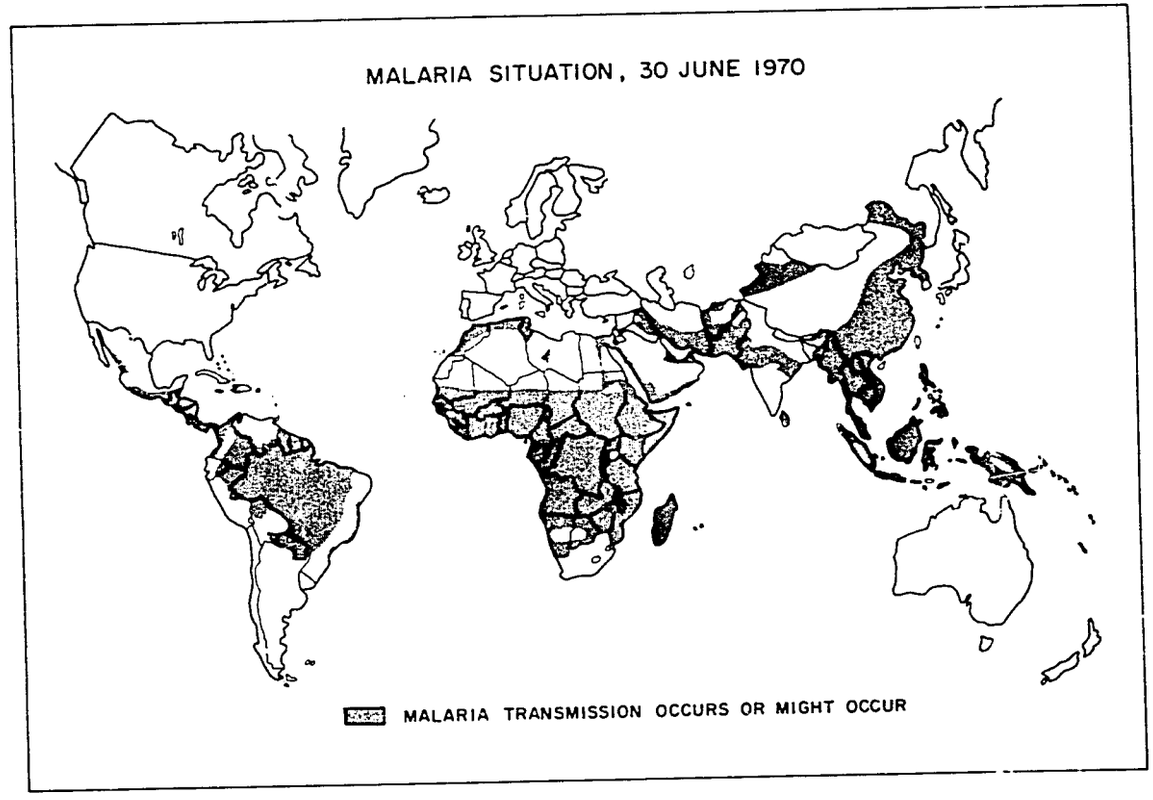
Schistosomiasis is a disease caused by certain parasitic worms known as schistosomes (Greek for "split, divided body") after the appearance of the adult male worm which is flat with the sides of its body inverted so as to form a groove, in which it carries the female.

Three species of schistosomes are important parasites of man. Two cause intestinal and hepatic (liver) disease: *Schistosoma japonicum* and *Schistosoma mansoni*. The third, *Schistosoma haemotobium*, causes vesical or bladder disease. Some other species also may infect man.

The larvae of certain other schistosomes of birds and rodents may penetrate the human skin causing a dermatitis known as swimmer's itch. This is prevalent among bathers in lakes in many parts of the world including North America; also in certain coastal sea water beaches. These schistosomes do not mature in man.

Life Cycle of Schistosomes.

The sexually mature schistosomes vary in length from about 7 to 26 millimeters (mm) and in width from about 0.3 to 1 mm and have the appearance of elongated threads. Once mated the male and female schistosomes proceed in pairs, *S. mansoni* and *S. japonicum* to the



Source: WHO

FIGURE 5

veins of the bowel, and *S. haemotobium* to the veins of the bladder. The females periodically leave their mates (partially or entirely), squeeze their slender bodies into the smallest veins, deposit their eggs, and return to their mates. A few eggs are carried in the blood stream to the liver, lungs, and other parts of the body, but must go through the vein walls into the surrounding tissues. Some become trapped in the tissues and die but others work their way into the bowel or bladder and leave the body in feces or urine. As the disease progresses, tissues around the veins thicken and the proportion of arrested eggs increases.

To survive, the eggs (70 to 170 microns long, 40 to 70 microns wide) must reach water within a month, a task greatly aided by inadequate sanitation. The change of osmotic pressure in the water results in the hatching from each egg of a small, ciliated, swimming larva known as a "miracidium." Miracidia must penetrate the body of a suitable freshwater snail (the intermediate host) within 24 hours or die.

In the snail the miracidia undergo an essential development stage, lasting 4 to 8 weeks, and, by a process of asexual reproduction, each miracidium may produce thousands of larvae known as cercariae. Liberation of cercariae may continue over a period of several months. The barely visible fork-tailed cercariae may average 0.4 to 0.5 millimeters in length, swim about vigorously, tail first, for 24 to 72 hours without feeding and die if they fail to contact their definitive host which as a rule * must be man in *S. mansoni* and *S. haematobium* and is often man in *S. japonicum* but may also be dogs, cats, rats, cattle, pigs, deer, or horses.

Upon making contact with human skin, the cercariae attach by means of suckers and penetrate their host within several minutes. Within hours they are in the blood stream and are eventually carried to the liver, where they grow to maturity within a few weeks. They mate and travel together against the flow of blood to small blood vessels in the wall of the intestine or bladder. Egg production starts about the fortieth day after pene-

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* Strictly speaking, *S. mansoni* and *S. haematobium* have been reported from lower animals.

tration of the skin by the cercariae. The infection has been known to persist for 28 years in man but the life-span of the schistosomes is generally much less than that, typically from 1 to 4 years.

The life cycle of *Schistosoma haematobium* is shown in Figure 6.

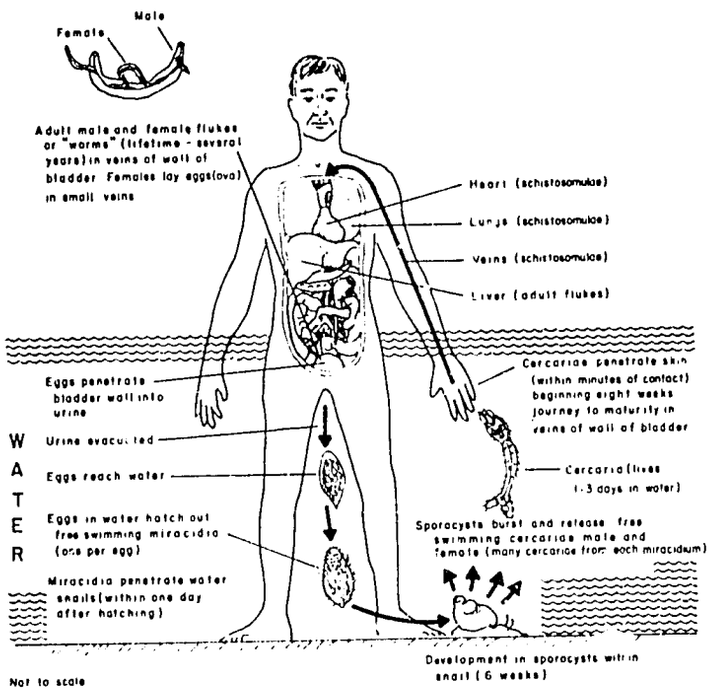

FIGURE 6

Life Cycle of *Schistosomiasis haematobium*

Clinical Manifestations of Schistosomiasis.

The symptoms and signs of schistosomiasis caused by *S. japonicum* and *S. mansoni* are much alike. During the incubation period there is often a skin rash and charac-

teristic diarrhea with liver enlargement and tenderness, variable fever, and sometimes lung disturbances. During the period of egg laying and extrusion there is typical dystentery with frequent bloody stools, liver and spleen enlargement and tenderness, often rectal lesions and other serious complications. In the final period of tissue reaction and repair, various lesions such as intestinal papillomata, ulceration and fistulas may develop. The spleen and the liver are often greatly enlarged, there is usually serious diarrhea and there may be ascites and other major disturbances.

In *S. haematobium* infections the urinary system is involved and there are often serious lesions of the bladder, ureters, and other organs, with fever and general distress. Bloody urine is a usual sign. In uncomplicated cases there is usually no diarrhea or dysentery in *S. haematobium* infections.

During the incubation period the symptoms and signs of bilharziasis are due chiefly to toxic products of the worms and to allergic reactions. In the egg-laying period the extrusion of the eggs causes various tissue damage with consequent bleeding and distress. Gradually, cellular reactions tend to block the eggs and to cause fibrosis of the affected organs. This impairs functional activity of the liver and intestines or of the urinary system. Bacterial infections of damaged tissues may cause abscesses and fistulas.

One larva penetrating the skin can develop into only one worm. Thus, the seriousness of the disease depends on the number of larvae acquired, the frequency of reinfection, and the length of time the individual is subject to reinfection. Ordinarily, the disease develops slowly as more and more worms are acquired during childhood, and the maximum number is reached at about 20 years of age. Although the factors involved in the rate of acquisition differ greatly in different places, the slow, insidious nature of the disease and the great disability it causes are always important aspects.

With modern treatment in uncomplicated cases the chances of avoiding death are quite good and in early cases full recovery may be expected. But as the disease becomes chronic, vital tissues are destroyed and in advanced cases the prognosis is hopeless.

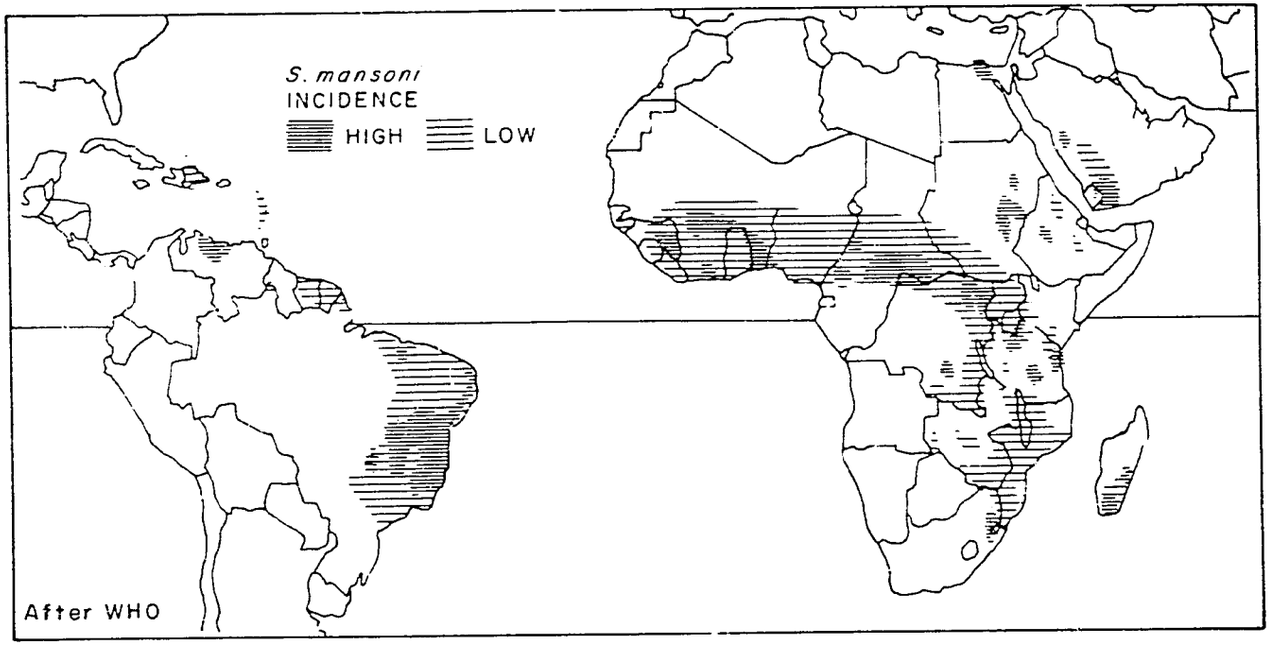

FIGURE 7

The World Distribution of *Schistosomiasis mansoni*

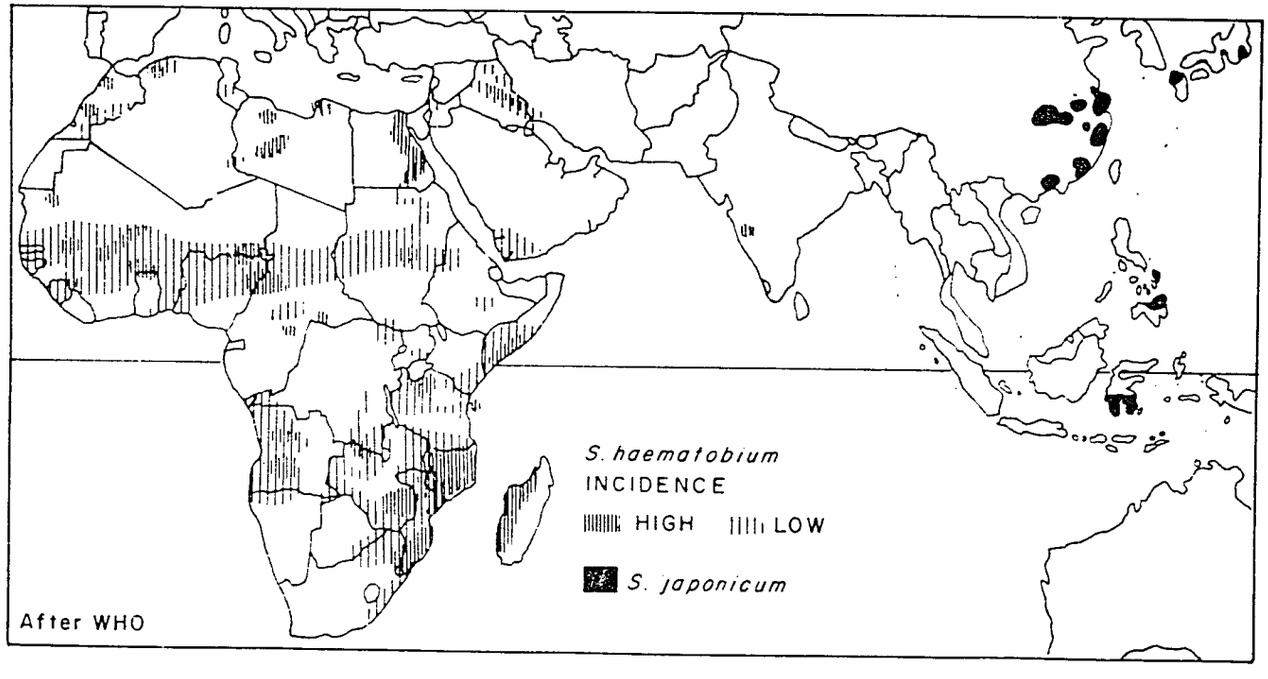

FIGURE 8

The World Distribution of *Schistosomiasis haematobium* and *Schistosomiasis japonicum*

Distrbution and Prevalence.

S. mansoni occurs in Africa, the Arabian peninsula, northeastern and eastern South America and the Caribbean area. *S. haematobium* occurs in Africa, the Middle East, and a small focus in India. *S. japonicum* occurs in the Orent (China, Japan, Philippines, Celebes, Laos and Thailand). In some endemic areas more than half of the population is affected. None of these species is indigenous to North America.

Figures 7 and 8 are graphic presentations of the worldwide distribution of schistosomiasis.

There are no precise or reliable data on worldwide schistosomiasis morbidity and mortality. There are wide differences of opinion even within single countries on the significance of schistosomiasis infection (WHO, 1965a, p. 8). A WHO Expert Committee on Bilharziasis [a] (WHO, 1965a, p. 7) has estimated that "there are at present 180-200 million persons infected with bilharziasis throughout the world."

Wright (1968), more conservative, estimates the number of persons exposed and infected to be about 125 million. His estimates by regions are shown in Table No. 7. It should be noted that of the 25,223,650 infections shown for the Orient, 24,741,000 are attributable to China (mainland). Similarly, of 6,144,130 infections estimated for the Americas, almost 6,000,000 are Brazilian. To illustrate the data difficulties, during the two-year period 1963 to 1964, only 6,425 cases were reported to the Pan American Health Organization; more than 10 times more cases were reported from New York State than from the whole of Brazil. (The New York cases were contracted in Puerto Rico.)

Schistosomiasis is a serious, potential threat in many areas where it is not now endemic. Any new reservoir or irrigation scheme anywhere in Africa, for example, should be rigorously reviewed in this respect.

Economic Impact.

There seems to have been little formal analysis of the

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[a] Schistosomiasis is sometimes called Bilharziasis after Dr. Theodor Bilharz, a German physician who discovered the schistosome worm in Cairo in the 1850's.

TABLE 7. WORLD DISTRIBUTION OF SCHISTOSOMIASIS, TOTAL REGIONAL POPULATION, POPULATION EXPOSED AND POPULATION INFECTED [a]

Region	No. of countries or islands	Total population	Population exposed	Population infected
Africa	43	308,021,000	226,102,740	91,200,310
Mascarene Islands	2	741,000	370,500	66,690
Southwest Asia	9	87,003,000	10,745,050	2,271,020
The Orient (except eastern Asia)	6	868,531,000	337,051,500	25,223,650
The Americas	11	98,339,000	18,199,750	6,144,130
	71	1,362,635,000	592,469,540	124,905,800

[a]After Wright (1972).

economic impact of schistosomiasis. Farooq (1963) in a study of economic losses in the Philippines due to schistosomiasis estimated them at $6.5 million annually, considering only expense of medical care and impaired productivity. This was $26 average annual loss per infected person, higher than per capita malaria loss. The cost of a long-range (15 years) control plan to eliminate these losses was estimated to be about $500,000 per year.

Farooq (1964) reports annual loss per infected person in Egypt as $3.50 to $15.00, Iraq as $24.00, and Japan as $26.00.

Wright (1972) has estimated monetary loss for all Africa as perhaps 450 million dollars and on a worldwide basis, perhaps 650 million dollars.

Farooq (1967) has estimated the annual economic loss for Egypt alone to be $560 million.

Relation of Schistosomiasis to Irrigation.

The importance of irrigation in the spread of this

disease is stressed by many authorities (Lanoix, 1958; McMullen, 1962ab; Mozley, 1953; Scott, 1938, 1969; Van der Schalie, *et al.*). A striking example of such a situation is quoted by Lanoix (1958) in connection with a scheme for perennial irrigation of four areas in Egypt. The following increase in schistosomiasis prevalence was noted three years after introduction of irrigation:

TABLE 8. SCHISTOSOMIASIS PREVALENCE IN SELECTED AREAS OF EGYPT BEFORE AND AFTER INTRODUCTION OF IRRIGATION

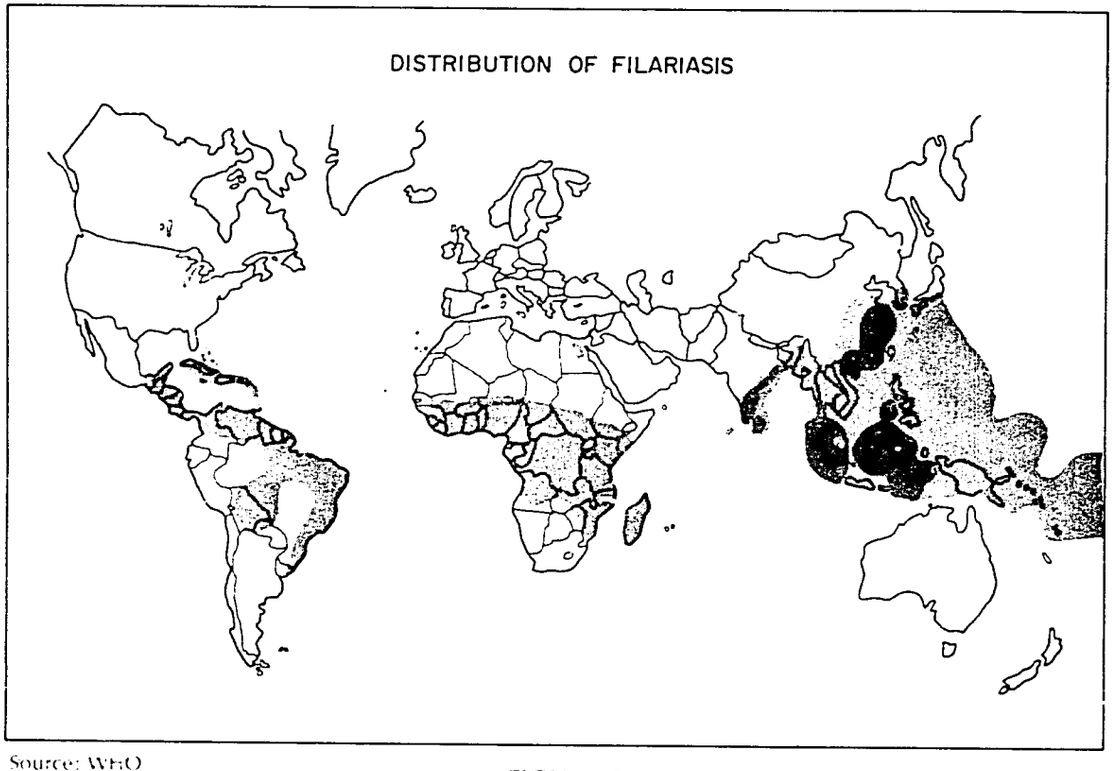
Area	Percentage of Population Infected 1934	1937
Sibaia	10	44
Kilh	7	50
Mansouria	11	64
Binban	2	75

Water is the medium in which eggs, miracidia, cercariae, and snails exist. Without water there can be no transmission of schistosomiasis. Provision of water where none existed before increases human population density and the population density of their aquatic messmates, snails.

Filariasis

In human filariasis there are two forms of the infection caused by filarial worms, one due to the parasite *Wuchereria bancrofti*, the other to *Brugia malayi*. Both are prevalent in vast areas of the world, the former in all tropical and sub-tropical regions, especially in the warmer parts of Asia, where some of the largest and most densely populated areas of endemity exist. The latter spreads over much of South-East Asia and extends along the coastal regions as far north as Korea and into Indonesia. It is estimated that filariasis affects over 200 million people at present throughout the world. (See Figure 9.)

Both *W. bancrofti* and *B. malayi* are nematode worms; the adult form lives in man, mainly in the lymphatic system. Their life span is approximately 10 years, during which time the female worm produces innumerable microfilariae, which invade the lymphatic and blood



Source: WHO

FIGURE 9

vessels. These larval forms are ingested by blood-sucking mosquitoes when feeding on an infected man. They undergo a series of moults until the infective stage is reached. Then they enter a new host, during the vector's next blood meal.

Clinical filariasis may be acute or chronic. The common early manifestations of the two forms of the diseases are painful swelling of the lymphatic vessels and glands of the groin, genitals and thigh. Characteristics of the chronic phase are hydrocele, enlargement of the lymph glands, inflammation of the scrotum and finally elephantiasis of the genitals and lower extremities. In *W. bancrofti* infection elephantiasis may involve the breast and arms.

Not all infected persons develop clinical symptoms, but the proportion of clinical cases is high, especially in highly endemic areas with exposure to constant superinfection. In such areas 30 percent of the adult population may be affected by elephantiasis and hydrocele. The severity of the filarial complications and their frequency determine the importance of the resulting disability and of the ensuing social and economic consequences.

The vectors of filariasis throughout the world are numerous and varied, being either culicines (*Culex*, *Aedes*, *Mansonia*, etc.) or anophelines. The culine mosquitoes constitute the majority of human filaria vectors. Enlargement of surface water bodies for irrigation and other purposes naturally increases the possibility for new breeding sites to be created and for the disease to spread or to become more intense.

In many areas of the world the provision of underground sewage systems has lagged behind the provision of water supplies. Some cities in tropical or semi-tropical developing countries have practically no public sewage system except for that provided by open roadside ditches and no centralized treatment plants. In many tropical countries the highly polluted liquid wastes move slowly through open earthen ditches or at best through concrete drains originally intended for the disposal of storm waters; both of these types of open ditches or drains are, unfortunately, highly suitable larval habitats for a number of mosquito species; the

most important is *Culex pipiens* and especially its tropical form *C.p. fatigans* which finds its optimal breeding conditions in water with a high degree of organic pollution. *C.p. fatigans* breeds throughout the entire year where climatic conditions permit and is highly domestic, readily entering and resting in houses where it freely and avidly feeds on man. It is this subspecies which is the main vector of Bancroftian filariasis and is found not only in urban centres but in towns and villages throughout much of the tropics.

The infection can be cured with currently available antifilarial drugs. Chemotherapy alone, however, has little action on developed elephantiasis. Treatment is often associated with allergic reactions. The available drugs destroy microfilariae but those aimed at destruction of adult worms are either ineffective or too toxic for general use.

Control of filariasis can be effected by various methods which are either directed against the parasite through mass drug treatment or against the vector. In the latter case larviciding and/or engineering devices are usually employed to reduce breeding facilities.

Owing to the diverse habits of the vectors, attempts to control the disease by mosquito control alone have so far not given satisfactory results. Furthermore, vector control alone does not affect the parasite in the human host reservoir and would have to be continued over a long period of time on account of the long life-span of the parasite. Mass treatment, on the other hand, has proved effective in many endemic areas. Depending on local circumstances, mass treatment supplemented by vector control measures seems to offer the best approach to filariasis control.

Onchocerciasis (River Blindness)

Onchocerciasis is a vector-borne infection caused by *Onchocerca volvulus*, a nematode worm. It is most prevalent in Africa, extending from Senegal and Sudan in the north to Angola in the south. It also occurs in circumscribed areas of Mexico, Guatemala and Venezuela. (See Figures 10 and 11.) The adult parasites live mainly in the subcutaneous tissues of the human host, where they may form visible nodules in which one or

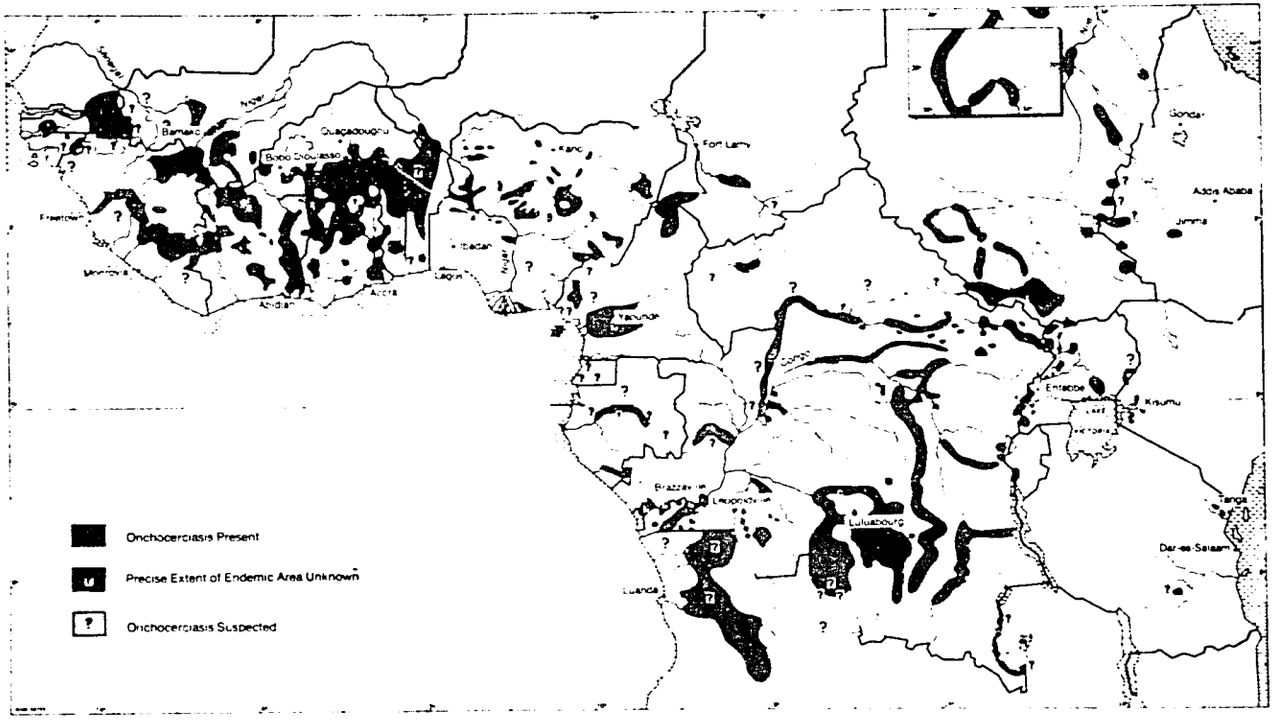
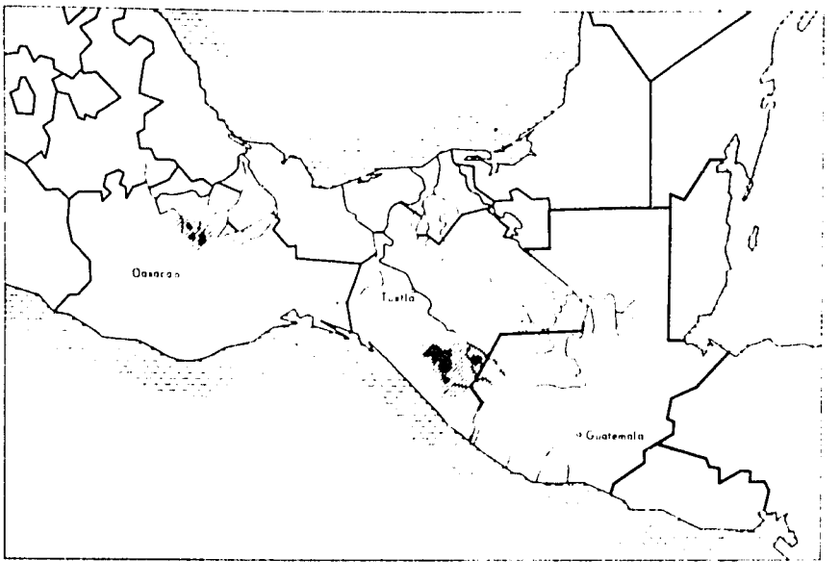


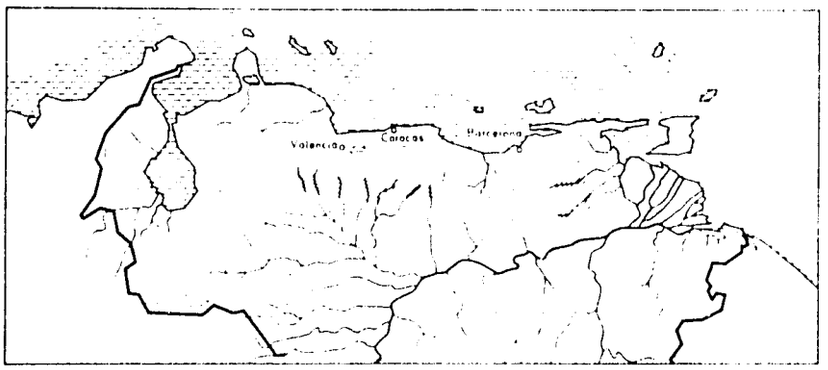
FIGURE 10

Geographical Distribution of Onchocerciasis in Africa

MEXICO AND GUATEMALA



VENEZUELA



Onchocerciasis level of endemicity unknown or infection rate of less than 75 %

Onchocerciasis infection rate higher than 75 %

FIGURE 11
Geographical Distribution of Onchocerciasis
in the Americas, Mexico and Guatemala

more worms are coiled up. The female worm discharges innumerable microfilariae during its life-span, i.e. approximately 15 years. The mobile microfilariae are found in the skin of the entire body, but may also penetrate the eyes.

The infection is transmitted by certain species of black flies (Simuliidae): *Simulium damnosum* in most parts of Africa, together with *S. neavi* in East and Central Africa, and *S. ochraceum*, *S. metallicum*, and *S. callidum* in the New World. In biting an infected person the fly takes up one or more microfilariae which, in the course of several days, develop into effective larvae. These are in turn liberated at the fly's next human blood meal on the skin of another man, thus completing the life cycle. It requires several months for the parasite to reach maturity.

The clinical symptoms of onchocerciasis, produced primarily by the microfilariae, are slow to appear so that an early diagnosis of the infection is often difficult. Frequently, the earliest complaint is of itching of the skin (pruritus), which can be extremely severe. At a later stage thickening and depigmentation of the skin may be observed. However, the most serious onchocercal lesions are caused through microfilariae that have reached the eye, leading eventually to impairment of vision and ultimate blindness. Typical lymphatic swelling called "hanging groin" is another complication of the infection.

The severity of the disease is usually related to the degree of exposure. In highly endemic areas, such as occur in large river systems—the Volta River basin for instance—the incidence of blindness in the rural population may reach 10 percent or more, and some of the most fertile valleys have been abandoned by the riverine populations.

As mentioned above, the infection depends for its transmission upon the presence of a *Simulium* vector species. Furthermore, its distribution and intensity depend chiefly on the density of the vector population. Common to all *Simulium* vectors is their requirement for flowing or turbulent water for the development of their aquatic stages (that is, egg, larval and pupal stages) which takes from 10 to 40 days. Particularly favorable conditions are, therefore, found at waterfalls, rapids,

spillways, etc. The adult *Simulium* is most readily found close to its breeding site, but can fly for considerable distances, up to 50 km or even more in the case of *S. damnosum*. This ability to fly long distances is of significant consequence in the spread of infected areas and the planning of control operations.

For the treatment of the disease drugs are used which kill the parasite, thus curing the infection. Treatment, however, is often complicated by unpleasant side reactions and of little benefit to those cases in which permanent damage, especially to the eyes, has already occurred.

Control of the infection aims therefore at interrupting the transmission, which can best be achieved by attacking the vector population. The larval stage of *Simuliidae* is highly susceptible to insecticides, and dosing of water courses with DDT at regular intervals can greatly reduce and even eliminate the black-fly population.

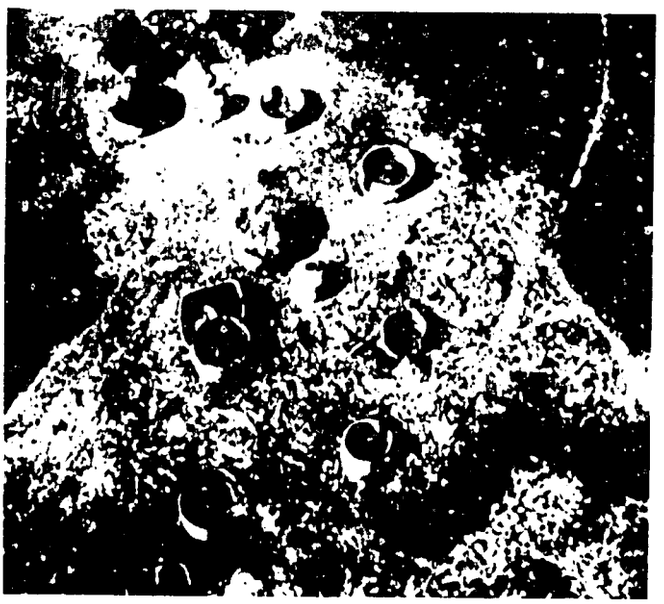


FIGURE 12
Village Abandoned Because of Onchocerciasis

CONTROL OF SCHISTOSOMIASIS

Life Cycle of Schistosomiasis

Figure 14 summarizes the life cycle of schistosomiasis outlined in the preceding section. Opportunities for breaking the cycle are summarized thereon and below.

Therapeutic Treatment of Human Victims

Limitations. Mass human treatment would seem to be the easiest, most promising, most humane method of schistosomiasis control. However, therapeutic measures alone have always proved inadequate. The reasons include:

(1) lack of a satisfactory drug, easily administered over a short period of time, free from side effects, and producing a high rate of parasitological cure,
(2) impossible to reach all the infected population,
(3) among discovered positive cases, there will always be a certain number of unfit cases for whom chemotherapy is contraindicated,
(4) many who start treatment will fail to complete it,
(5) even among those who complete the full course, there will be positive refractory cases and relapses,
(6) human treatment does not overcome the problem of animal reservoir hosts, especially of *S. japonicum* and to a lesser extent, *S. mansoni*,
(7) with many positive cases and unchanged habits of pollution and water use, reinfection and new infection will take place and the life-cycle will be maintained, and
(8) lack of funds and personnel to implement programs on scale needed. Many developing countries spend less than $3 per capita annually for health programs.

Although *chemotherapy* alone will not interrupt transmission of schistosomiasis, it does ameliorate the condition of the individual and fewer cases reach an advanced state.

Outlook.

A recently developed drug, hycanthone, shows great promise as the long-sought one-shot drug (Katz, 1968; Gottschalk, 1969). Hycanthone has proved 80 to 90 percent effective in tests with 2,000 persons in Brazil,

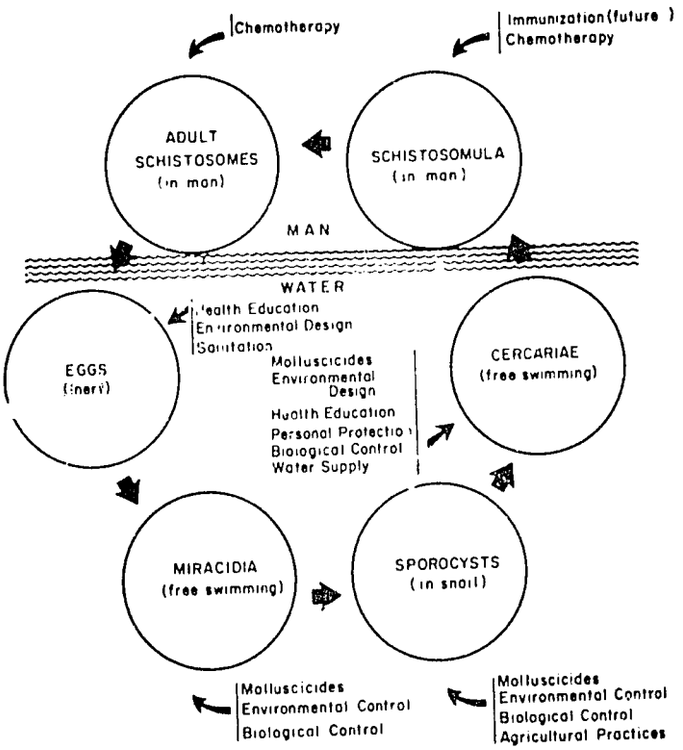


FIGURE 14

Life Stages of Human Schistosomes Showing Possible Entry Points for Control of Transmission

Venezuela, South Africa, Rhodesia, and Egypt. Even if it were 100 percent effective, however, it would not eradicate schistosomiasis (see above).*

Prevention of Eggs Reaching Water

Education (habits). If the eggs do not reach water, the transmission of schistosomiasis is halted. If the feces (or

* Hycanthone frequently has pronounced side effects and there is evidence that it might be mutagenic and carcinogenic. It has not been approved by the U.S. Food and Drug Administration.

urine for *S. haemotobium*) of infected individuals do not reach water, then the eggs do not. Therefore the public should be educated to the danger of defecating or urinating in or near water. The life-cycle of the parasite and the method of transmission, the effect on the health of the individual, and the economic impact of the disease on the community should be explained. Public support should be sought.

Unfortunately habits are difficult to change. The inhabitants of areas endemic for schistosomiasis include many farmers, herdsmen, or fishermen who spend their day outdoors, inconvenient to latrines. But children and adolescents are the most difficult problem. "They are the most important source of viable, hatchable, schistosome ova and snail-penetrating miracidia and, because of their habits, are also the main source of infection to snails and thus of the maintenance of the life-cycle of *Schistosoma*" (Ayad, in Wolstenholme, 1962, p. 341).

Sanitation

Adequate and acceptable facilities for excreta disposal, *if used*, can be an important support to a schistosomiasis-control program.

Environmental Design.

The location and layout of villages and housing relative to surface water; provision of safe and adequate water supplies, public laundries, and of washing, bathing and recreational facilities; and protection of nearby water with pipe, covers, or fencing reduce the need or eliminate the opportunity for water contact.

Destruction of Eggs and Miracidia

Direct Destruction. Eggs and miracidia are destroyed by many of the molluscicides. They are also destroyed in anerobic waste treatment tanks, in trickling filters, and in long-detention time oxidation ponds.

Indirect Destruction. Eggs and miracidia perish when they fail to reach water, or reaching it, fail to find suitable host snails.*

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* Eggs may survive 30 days or more on land. Miracidia must find a suitable host snail within 24 to 72 hours. Survival varies greatly with environmental conditions.

Destruction of Intermediate Snail Hosts

Chemical Control (Molluscicides). Destruction of snail vectors using toxic chemicals has been the principal focus of control measures intended to interrupt transmission of schistosomiasis.

Molluscicide programs offer several advantages:

(1) rapid cessation of transmission is obtained,
(2) public cooperation is not required for success,
(3) administration is usually under one agency,
(4) complete eradication of snails is possible in certain situations, and,
(5) the technology is well-known.

Disadvantages include:

(1) reestablishment of snail populations,
(2) must be repeated,
(3) toxicity to other fauna and flora,
(4) development of molluscicide resistance, unknown as yet but a possibility.

Since snails are chemotropic, the use of baited traps is possibly an under-utilized measure (Cardarelli).

Biological Control.

This method has long enjoyed a wide appeal. A frequent suggestion is that snails might be controlled by predators such as certain species of ducks, fish, turtles, crustaceans, water rats, leeches, and aquatic insects; by competitors such as the snail *Marisa Cornuarietis*, which has rendered some Puerto Rican habitats unsuitable for the *S. mansoni* vector *Australorbis;* or by parasites and diseases of snails. Some predators attack miracidia or cercariae rather than the snails, e.g., the common guppy.

With the possible exception of the snail *Marisa*, most of these measures have been found to be ineffective, although little is known about snail diseases and parasites. In pools with steep banks, fish do appear to reduce the snail population.

Predator-prey relationships are unlikely to result in snail eradication. Continuous periodic fluctuations in the numbers of both species are more likely. Some predators are susceptible to certain molluscicides. There is no proven practical biological control technique in active use today.

Physical Control.

Since all vector snails require water, at least for breeding, management of water is a potential control method. This is described in specific terms in a later section.

Destruction of Cercariae

Failure of the cercariae to penetrate a host within 48 hours means their death. This observation is sometimes used to advantage in storing drinking water. Most of the previous comments pertaining to destruction of eggs and miracidia are relevant here—destruction by molluscicides, prevention of human contact, etc.

Prevention of Cercarial Infection in Man

Immunization. This is a theoretical possibility, but so far has not been made practical. Many epidemiologists who have worked with schistosomiasis are convinced that there must be some immunity to reinfection, or conditions would be much worse than they are (Scott, 1969). At present, however, the possibility of induction of immunity by vaccination or other means is too remote to influence control programs. Smithers (1969) has recently reviewed schistosomiasis immunology.

Education (Habits). See previous comments.

Personal Protection (Fabrics, Ointments, Repellents).

Military operations during and following World War II have stimulated the search for protective measures for avoiding schistosome infections. All types of uniform cloth afford some protection to the wearer, particularly if tucked into the top of boots with ample slack to form a cuff over the boot top. Protection is increased by impregnating fabrics with certain chemical and waterproofing agents. Certain ointments and repellents also provide protection including several made from natural plant oils, e.g., oil of cedar.

Ignoring problems of cost, distribution, and education, ointments are rubbed off by workers in constant contact with water. Clothing impregnated with protective substances or of sufficiently close weave to prevent the invasion of cercariae is intolerably hot and uncom-

fortable. Most importantly, schistosomiasis is a disease contracted by children and adolescents. Pellegrino (1967) has recently reviewed this topic.

Water Treatment.

Removal or destruction of cercariae from treated water is completely feasible. Transmission of schistosomiasis through drinking water, although possible, is not, however, a major route of infection.

Environmental Design.

The same actions that militate against eggs reaching water also tend to prevent human contact with cercariae. These measures include siting of housing away from canals, provision of adequate and safe water supply and sanitation, protection of surface water by covers, pipe, or fencing, provision of protected facilities for bathing, water recreation, and laundering, and similar measures which reduce human contact with cercariae-infested water.

ECOLOGY OF INTERMEDIATE SNAIL VECTORS OF SCHISTOSOMIASIS

Introduction

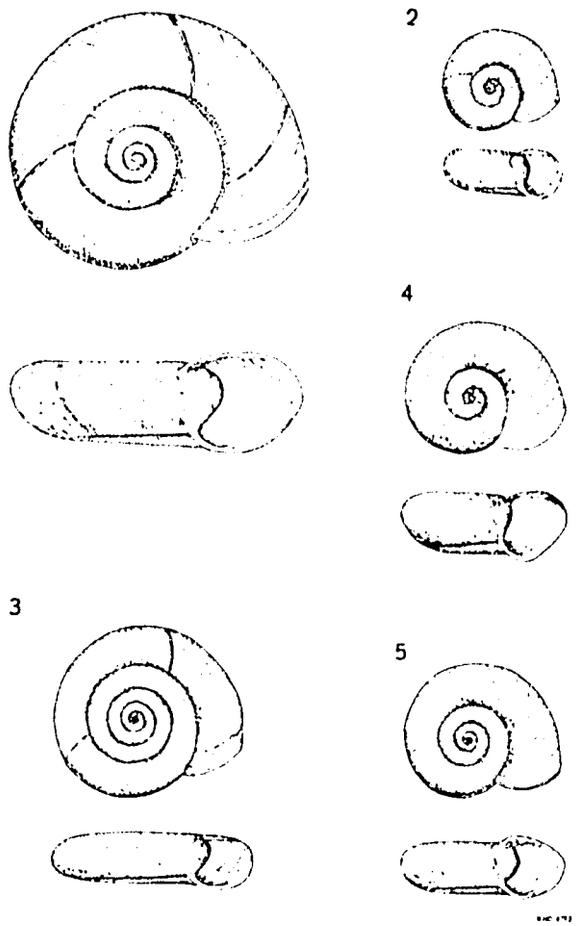
Before it attacks man, each schistosome worm lives as a parasite of a snail. Thus there is an opportunity to prevent the human disease by destroying the intermediate snail host, in much the same way as mosquito extermination is used to prevent malaria. Many methods of killing the snails, or otherwise eliminating them, are possible, but two are most common: direct destruction with toxic chemicals (molluscicides) and indirect elimination or prevention through creation of an untenable environment.

The schistosomes are specific in the choice of their intermediate hosts. *S. haemotobium* miracidia select snails of the genus *Bulinus* with isolated exceptions; *S. mansoni* prefer the genus *Biomphalaria* (also known as *Planorbis* in Africa and *Australorbis* in the Americas); and *S. japonicum* chooses snails of the genus *Oncomelania*. Members of the genera *Bulinus* and *Biomphalaria* spend their lives in water. *Oncomelaniae* are amphibious. Figures 15 and 16 show the shells of typical vector snails.

The factors that cause snails to favor certain waters and to be absent from others are not surely known. Prediction is further complicated in that different species and varieties of the same genera, with differing preferences, act as hosts in various places.

Roughly speaking however, *Bulinus* species, hosts of *S. haematobium*, exhibit a preference for stagnant or slowly moving water, are more numerous in moderately polluted waters, prefer pools with bottoms rich in silt and organic matter, and often occur in apparently barren water. Although generally found only in permanent pools in Egypt and Iraq, those responsible for schistosomiasis in equatorial Africa may often be found in seasonal water holes and borrow pits.

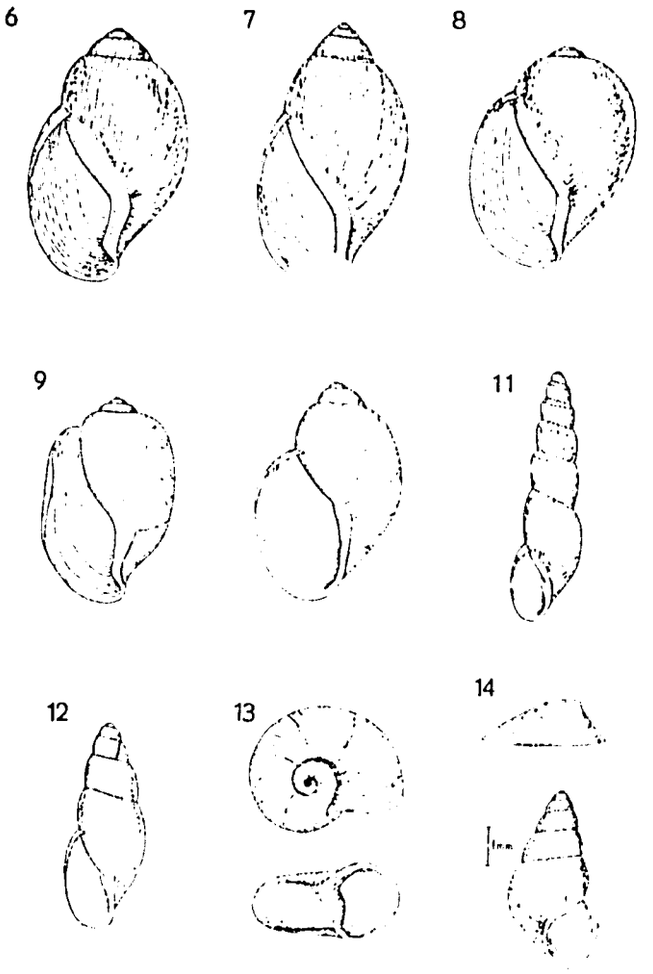
Biomphalaria, host of *S. mansoni*, happily accept running water of moderate velocity and therefore are common inhabitants of stream and irrigation systems. In contrast to man-promoted transmission closely related to agriculture, there are areas, such as Northern Brazil, where transmission is not closely linked with agriculture.



1 *Australorbis glabratus*, Brazil
2 *Tropicorbis stramineus*, Brazil
3 *Biomphalaria sudanica*, Uganda
4 *B. pfeifferi*, Southern Rhodesia
5 *B. alexandrina*, Egypt

Magnification 2 × natural size

FIGURE 15
Intermediate Hosts of *Schistosoma mansoni*



6 *Bulinus (Physopsis) africanus*, Kenya
7 *B. (Phys.) nasutus*, Tanganyika
8 *B. (Phys.) globosus*, Angola
9 *B. (Phys.) abyssinicus*, Somalia
10 *B. (Bulinus) truncatus*, Egypt
11 *B. (B.) forskalii*, Sudan
12 *B. (B.) senegalensis*, Gambia
13 *Planorbarius metidjensis*, Portugal
14 *Ferrissia tenuis*, India
15 *Oncomelania quadrasi*, Philippines

Magnification: Nos. 6-10, 13: 2.5 ×; Nos. 11-12: 3 ×; Nos. 14-15: 6.5 × natural size

FIGURE 16
Intermediate Hosts of Schistosoma haemotobium and *Schistosoma japonicum*

Australorbinae live in natural water courses and transmission occurs primarily through casual contact with infected water or through recreational and domestic activities.

Oncomelaniae, hosts of *S. japonicum*, are amphibious, being able to live on land and to withstand drying due to the presence of a protective operculum or shield. Basically swamp animals, they have adapted themselves to irrigation systems, rice fields, roadside ditches, and other manmade habitats.

The World Health Organization (WHO) has published a monograph (Mandahl-Barth, 1958) on snail species that have been incriminated as snail hosts. However location and identification of snail hosts, or potential snail hosts, generally require the skill and experience of a biologist. Snails under suspicion must be tested to determine whether they can, in fact, pass the infection. If the tests are positive, then the offending species can be specifically identified at a WHO central reference laboratory.

Although specific identification of the suspect or proven intermediate host may not be absolutely essential to development of a snail control program, it is generally helpful inasmuch as the biology of the species incriminated may have some bearing on control procedure. What relationships then between the snail hosts and their environments offer opportunities for control?

General Characteristics of Snail Habitats [a]

The snail intermediate hosts of schistosomiasis are adapted to a wide range of environmental conditions. They breed in many different sites, the essential conditions being the presence of water, relatively solid surfaces for egg deposition, and some source of food. These conditions are met by a large variety of habitats: streams, irrigation canals, ponds, borrow-pits, flooded areas, lakes, water-cress fields, and rice fields. Thus in general they inhabit shallow waters with organic content, moderate light penetration, little turbidity, a muddy substratum rich in organic matter, submergent or emergent aquatic vegetation, and abundant microflora. The snails may be found in isolated habitats quite independent of major drainage systems because snails or

[a]As described by Malek (1972).

their eggs are sometimes carried passively to such habitats which seem favorable. Accordingly, to determine their habitats systematic search for the snails must be conducted by skilled observers over a period of several seasons.

There are certain physical, chemical and biological characteristics or factors which make a habitat suitable or unsuitable for the snails. The principal conditioning factors appear to be the amount of food available, the extent of growth of aquatic weeds, the oxygen content of the water, the strength of the current, the nature of the substratum, and the ionic composition of the water. Several of these factors are interdependent. Although there are differences between the various host species in their habitat requirements, their ranges of tolerance overlap greatly. Theoretically, extremes of certain factors should be capable of eliminating snails from a body of water; in practice, however, such extremes rarely occur, and the absence of snails must be attributed to the combined effect of several factors. Moreover, to alter one factor enough to accomplish control of the snails is not easy. There are certain foci or microhabitats which the snails prefer. Thus even in habitats not generally suited for snails there are always some microhabitats where the snails may occur.

There is a wide range of tolerance of the intermediate snail hosts to temperature and hydrogen-ion concentration. Although the range of tolerance is usually about 0° to 37°C, the optimum temperature range for many species is 18° to 28°C. A more important aspect for control purposes is the effect of annual temperature variations on the breeding season. Thus *Bulinus truncatus* in northern Iraq produces only a single generation annually, whereas *Biomphalaria glabratus* in Brazil breeds all year around.

Changing the pH of the habitat is not feasible because the lethal limits are usually beyond any practical range of artificially imposed variation.

The snail intermediate hosts prefer a partly shaded habitat, although direct sunlight is not harmful to them. Snails can be raised in the laboratory in complete darkness provided ample food supply is available. Sunlight in the snail's habitat means a flourishing of the aquatic

weeds, an abundance of microflora (food supply for the snails) and a high dissolved oxygen content. Sunlight also increases the rate of decomposition of the animal and plant remains on the bottom, so that instead of fouling the habitat they play their usual role in the food chain, contributing dissolved materials and detritus.

For a snail colony to become established the water current should not be strong. The snails are not normally found at falls, in torrential rivers, on exposed shores of large lakes, or in irrigation canals with very swift flow. Under these conditions the snails are dislodged; a few, however, may be able to survive by attaching themselves to weeds or flotsam or by sheltering in quiet pools near the bank where the current is less pronounced.

The effect of animal and human excrement on intermediate hosts of schistosomiasis has been reported by several workers. In general, the snails are abundant near human habitations which pollute the water directly or indirectly. Some investigators even consider that these snails appear to be true "messmates" of man. It appears, however, that although vectors thrive better in the presence of animal and human excrement, they do occur in unpolluted habitats, as long as their food is plentiful. That is, they occur not only in polluted parts of canals close to villages but are distributed throughout these canals.

The type of substratum associated with intermediate host snails is a firm mud bottom, rich in decaying organic matter. This provides support for aquatic plants and a surface upon which flourish algae and other microorganisms that snails eat, and upon which the snails crawl and deposit their eggs. Aquatic plants are a desirable but not an essential requirement in the habitat of aquatic snails. The amphibious *Onclomelania* spp. are usually found in habitats with emergent vegetation, or vegetation growing along the bank near the water's edge. Decaying vegetation from water plants helps in the formation of a suitable substratum and provides additional food for the snails.

A suggested engineering means of control for aquatic snails is the lining of irrigation canals and drains with concrete. Concrete-lined water courses would, indeed, remain free of snails for some time. However if a suf-

ficient layer of silt to support rooted aquatic vegetation settles on the bottom snails may be reintroduced. Floating vegetation and a layer of algae developed on the cement also may provide a good habitat for the snails.

Many freshwater snails have remarkable powers of toleration of desiccation of the habitat. Moreover, it has been shown in Brazil that the early stages of *Schistosoma mansoni* in the snail host can also withstand desiccation and will resume development when the water comes back to the habitat and the snail resumes its aquatic life. In many habitats of aquatic snails where dessiccation takes place gradually, humidity and the level of subsoil water are high, adequate growth of weeds is present, and the dry season is not too long, several snails of a colony are likely to survive until rain or irrigation water arrives again.

Seasonal and Climatic Factors

The effects of season and climate demographics are profound and must be understood if normal decreases in numbers are not to be mistaken for effects of control measures. Variations in snail population and cercarial production may reduce the time period during which molluscicides must be applied.

Man-Made Habitats

The long-established endemic areas of schistosomiasis in Africa, the Middle East, and the Western Hemisphere have apparently been undergoing natural expansion and many areas suitable for transmission have been invaded by the parasites.

While water resource developments are essential for economic progress, they unfortunately may prove to be health hazards in countries where schistosomiasis is endemic. They may increase the number of breeding places of the snail intermediate hosts and result in increased prevalence and intensity of the disease. This is because the same factors that make an area more satisfactory for man may also make it more suitable for the snail hosts. Some areas once inhospitable for man and the snail now have dense populations of both. This combined with human contacts and with water polluted by excretions make them suitable for the transmission of schistosoiasis.

The risks of schistosomiasis transmission associated with irrigation and hydropower development has been described previously. In many parts of Africa fish farming in artificial ponds has been encouraged by government authorities. This is especially the case where fish is the only, or a supplemental, animal protein available for the undernourished population. Fishfarming is also recommended and encouraged by international organizations such as the Food and Agriculture Organization of the United Nations (FAO). Unfortunately, conditions favorable for rearing fish are also favorable for establishment of the snail hosts of schistosomiasis and fascioliasis. These fish ponds are usually filled by river water and snail hosts are liable to be introduced into them. Snail hosts, uninfected and infected with the schistosomes, have been found in some of the ponds.

Industrialization is another important factor in creating man-made schistosomiasis. Lightly or partially infected populations, previously scattered, are massed together by industrialization, frequently under very unhygienic conditions. An increase in infection rates may result. In certain industrialized states of Brazil recruitment of laborers from the endemic Northeast has caused an increase in cases in other areas where schistosomiasis was previously rare and sporadic. Various industries in Africa have also attracted laborers from endemic areas. New roads and railways to serve new industries and agricultural developments facilitate population movements and increase the possibilities for extension of the disease.

Although the immediate effect of industrialization may be to aggravate the disease, the process of raising the standard of living and fostering urbanization, with purified water supply, improved sanitation, and improved standards of hygiene eventually improve the situation.

ENGINEERING MEASURES FOR CONTROL OF SCHISTOSOMIASIS

Disruption of Life Cycle

The six stages of the life cycle of human schistosomes, together with possible control measures for each were shown in Figure 14. Complete disruption of any one stage would terminate transmission. Four stages occur generally in a water environment (eggs are initially deposited in the human host, then found in the host's excreta, but they must ultimately find water; sporocysts of *S. haemotobium* are specific to the snail genus *Oncomelania*, an amphibian). Engineering opportunities for disruption of the life cycle include classical sanitation, creation of a land environment that limits contact with water, and creation of a water environment unfavorable to snail vectors. Engineers are also often assigned the task of applying molluscicides.

Creation of Unfavorable Environment for Intermediate Snail Hosts

Elimination of the snail intermediate host is at present the most effective single method of controlling schistosomiasis. Snails can be killed outright using molluscicides or the aquatic environment can be molded so as to disfavor their continued propagation. The latter course of action is one that engineers are uniquely qualified to implement. The relationship of irrigation and schistosomiasis is well known, however to a large extent it is defective and untidy irrigation, wasted water, and waterlogged land, rather than irrigation *per se*, that spreads the disease. Schistosomiasis engineering in considerable degree is simply good irrigation practice.

Good engineering practices can eliminate or reduce many snail habitats, but engineering alone is usually insufficient for complete control and must be reinforced by application of molluscicides. The efficiency and effectiveness of molluscicides are much enhanced and the cost reduced by proper engineering of irrigation systems. Increased agricultural productivity, sometimes trebled (WHO, 1960a), is another benefit. Control of malaria and fascioliasis, a schistosome disease of livestock, is also made easier.

The relative ease of application and proven effective-

ness of molluscicides suggest it as the method of choice but proponents sometimes fail to consider its economic feasibility. The fact that estimates indicated that the annual cost for molluscicides alone in the Philippines would have exceeded the total annual budget of the Ministry of Health stimulated an interest in studies of ecological methods (ponding, filling, drainage, removal of vegetation, etc.) for reducing the extent of the snail colonies and transmission sites. The evidence gathered as a result indicates that proper water management and improved agricultural methods can be used to greatly increase crop production and to eliminate 95 percent of the snails at the same time. The few remaining colonies in such areas became amenable to control by molluscicides (Hairston and Santos, 1961; McMullen, 1962).*

Distribution and Drainage Systems

Channel Velocity. The frequent observation that vector snails are rarely seen in streams and canals having average flow velocities in excess of 30 to 35 centimeters per second, cm/sec (approximately 1.1 feet per second, fps) leads to the question: "What is the minimum velocity which will discourage establishment of snails?" The question is not as simple as it might appear. Snails can more easily cling to a firm smooth surface, such as that of concrete or stone, than to a loose and shifting surface such as silt or loam. Snails with conical shells such as *Oncomelania* and *Bulinus* may have lower drag coefficients than snails with flat discoidal shells, such as *Planorbidae*. Aquatic vegetation may shelter snails from the current. As velocity increases, snails are first immobilized, then dislodged. Immobilization may suffice for control where velocity is maintained constant. An important design note is that it is not the *mean* velocity in the channel but the peripheral velocity that dislodges snails.

The latter question has been extensively examined (500 measurements) by De Araoz (1962) in a study of earth canals of stabilized parabolic cross section. De Araoz's findings are best summarized by reproduction of his diagram of equal velocity lines (see Figure

* Reviewers had divided opinions on whether this work has meaning for other areas.

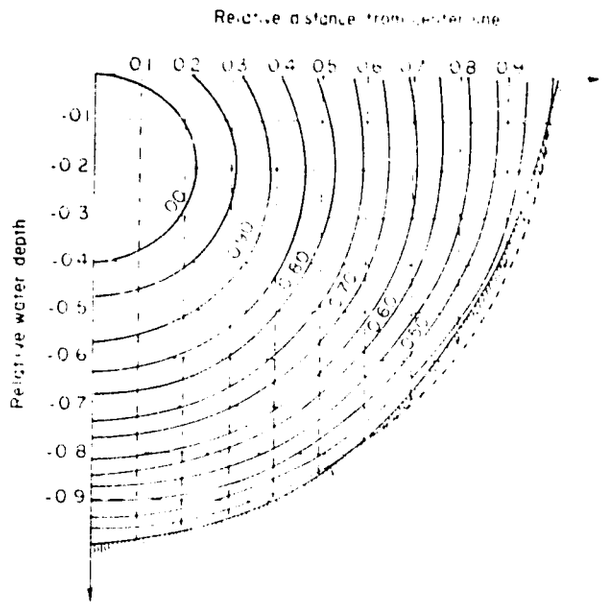


FIGURE 17
Diagram of Equal Velocity Lines

17). If the surface velocity at the canal centerline is taken as unity, then the velocity at any other coordinate of the cross section, as a decimal fraction of the centerline velocity, can be determined from the diagram. Thus peripheral velocities from the water's edge to the center point of the bottom average about 0.4 of the velocity on the water surface at the centerline. If the surface velocity at the centerline were, say, 2.5 fps, then the peripheral velocity would be about 0.4 x 2.5 or 1.0 fps.

Engineers are accustomed to working with mean (average) velocities. A common formula (Manning's) is:

$$V = \frac{1.49}{n}(R)^{2/3}(S)^{1/2}$$

where

V is the average velocity in feet per second

R is the hydraulic radius in feet; it is equal to the cross sectional water area divided by the perimeter of the wetted part of the channel

S is the longitudinal slope of the bottom of the canal expressed as a decimal

n is a surface roughness coefficient which varies with the type of channel construction.

According to De Araoz the mean velocity is 0.729 of the velocity on the water surface at the centerline. Thus the average velocity calculated by the Manning formula should be multiplied by

$$\frac{1}{0.729} \times 0.4 = 0.55$$

to obtain the peripheral velocity. Or conversely, if a desired peripheral velocity is sought, say 1.25 fps, then the Manning formula must yield

$$1.25\text{fps} \times \frac{1}{0.55} = 2.3\text{fps}$$

as the average velocity.

Inspection of the Manning formula indicates three ways to increase velocity: (1) use a smoother surface, for example concrete ($n = 0.016$) rather than earth ($n = 0.025$+) an expensive measure, (2) steepen the gradient, S, largely impractical since it must generally parallel the surface of the ground if frequent pumping is to be avoided, or (3) change the channel cross-section making it narrower and deeper. Channel cross-sections are generally designed for hydraulic efficiency (maximum discharge for a given cross-sectional area) since cost is generally proportional to cross-sectional area. To significantly increase velocity, for a given discharge, gradient, and roughness, over that obtainable with commonly used trapezoidal open channel sections requires a radical, expensive change in section, if for no other reason than that the steeper side slopes will require structural support.

The hydrodynamic aspects of dislodgement of one snail specie, *Biomphalaria glabratus*, have been studied in a hydrodynamics laboratory (Jobin and Ippen, 1964). A velocity at shell height (1.3 cm) of 33 cm/sec (1.08 fps) was shown to immobilize and 65 cm/sec (2.14 fps) to dislodge *B. glabratus* from a smooth plastic bottom. Using the method of correlating boundary velocities to mean velocities developed by De Araoz (1962), Jobin and Ippen (1964) have calculated, for a wide range of

channel geometries and discharges, the mean velocities required for control of *B. glabratus* (see Table 9). The mean velocities proposed are based on immobilization rather than dislodgement--they "are still significantly higher than values recommended from field observations and should therefore prove quite conservative in design."

TABLE 9. MEAN VELOCITIES IN TRAPEZOIDAL CHANNELS FOR CONTROL OF AUSTRALORBIS GLABRATUS

Discharge		Immobilizing Mean Velocity	
(m^3/sec)	(cfs)	(cm/sec)	(fps)
1	35	58	1.90
5	175	67	2.20
10	350	71	2.33
20	700	75	2.40
30	1000	78	2.60
50	1750	81	2.66

Source: *Jobin and Ippen* (1964).

Jobin and Ippen also furnished their snails with harnesses and trained them to pull "very light loads", leading to the fascinating finding that "the output of 2.5 million snails would be equivalent to 1 horsepower, hardly an incentive for development of this power source."

For canals excavated in certain soils, velocities high enough to discourage snails may cause damage or destruction by erosion. The determination of nonscouring, nonsilting velocities has attracted the attention of many investigators over a long period of time and a considerable mass of data and formulas, e.g., tractive force, have been accumulated. However for preliminary purposes, and for design in many cases, use may be made of the approximate values suggested by Kraatz and shown in Table 10.

The effect of water velocities on the infection of animals exposed to cercariae has been studied by Rowan and Gram (1959), Radke, *et al* (1961), and Webbe

TABLE 10. MAXIMUM VELOCITIES IN METERS PER SECOND IN EARTH CANALS

Nature of canal bed	With a Discharge in Cubic Meters per Second								
	0.5	1.0	2.0	3.0	4.0	10.0	15.0	20.0	30.0
Silt, fine sand, light sandy loam	0.37	0.39	0.41	0.43	0.45	0.47	0.49	0.50	0.52
Medium sandy ground	0.46	0.49	0.52	0.54	0.56	0.59	0.61	0.63	0.65
Light loam	0.53	0.56	0.59	0.61	0.64	0.68	0.70	0.72	0.74
Medium loam, medium loess, coarse sand	0.59	0.63	0.67	0.69	0.72	0.75	0.79	0.81	0.84
Heavy loam, light clay, close grain loess, very coarse sand	0.67	0.71	0.75	0.78	0.81	0.86	0.89	0.90	0.94
Fine shingle or gravel	0.73	0.77	0.82	0.84	0.88	0.93	0.96	0.98	1.02
Thick medium clay, medium gravel	0.82	0.87	0.92	0.95	0.99	1.05	1.09	1.11	1.16
Heavy clay (tertiary), coarse shingle or gravel	1.26	1.34	1.42	1.47	1.53	1.62	1.68	1.72	1.79

Source: Kraatz (1971)

(1966a). Webbe has also studied its effect on infection of the snail vector *Biomphalaria*. A consensus is that infection increases with increasing velocity, then decreases. The velocity of maximum infection is imprecisely known, perhaps between 1 and 3 feet per second. Some infection occurred at all levels tested. Webbe (1966a) suggests that this finding, coupled with knowledge of the peak cercaria-shedding "may be useful and of practical importance in relation to the use of infested waters for bathing and clotheswashing where no other water-supplies are available."

The role of water velocity in irrigation canals in determining their suitability as snail habitats is well-established. However its use for snail control has probably been unconscious, the serendipitous by-product of such factors as favorable topography and soils. Its expense is likely to limit its large-scale use to areas where irrigation systems with suitably high velocities would be implemented in any event. Nevertheless it should not be overlooked, especially where hydraulic head may be available. It should not be used alone but supplemented with continuing surveillance and spot application of molluscicides.

Canal Linings.

Canals are lined for many reasons: seepage control (often as much as 40 percent, see Table 11),

TABLE 11. ESTIMATED WATER LOSSES IN UNLINED CONVEYANCE SYSTEMS

Country (Project)	Water Losses in percent of total water diverted	Remarks
46 irrigation projects in the U.S.A.	3-86 (average 40)	Records from 46 irrigation projects including seepage water taken up by uncontrolled vegetation in the canals and evaporation losses of canals.

Country (Project)	Water Losses in percent of total water diverted	Remarks
West Pakistan	18-44	Seepage losses only.
West Pakistan—Indus River Basin	35	Mean figure of total conveyance losses.
Mexico	26	Less pervious soils.
	35-50	More pervious soils.
Turkey—Konya Cumra Plain	40	
U.A.R.—Nile Delta area	8-10	Low because of silting effect of Nile water.
U.A.R.—New canels in desert areas	50	
U.S.S.R.	20-35	Mains and distributaries
India, Ganges Canal	15	Main canals and drains.
	7	Distributaries.
	22	Water courses.
	44	Total seepage losses.
	Maximum 40% Average Year	Total seepage losses.
Pakistan Kushita unit of the Ganges—Kobadak Irrigation Scheme	5.7	Main canals.
	7.3	Secondary canals.
	12.0	Tertiary canals.
	25.0	Total seepage losses.
Iran Garmsar Irrigation Project	40	Main and secondary canals.

Adapted from Kraatz (FAO)

erosion control, safety, reduction of maintenance, reduction in size of complementary structures, reduction in land required for rights-of-way, appearance, public acceptance, weed control, reduction of plant transpiration losses, and reduction in total annual cost of irrigation. Benefits include more water for crops, increased

land available for cultivation, protection of low areas from seepage and water logging, and reduction in areas favorable to snails. Under certain conditions and against certain species of snails, hard-surface linings have proven extremely effective (Lanoix, 1958; WHO, 1968). The relatively high velocities possible, the relative absence of aquatic vegetation, the potential for rapid draining and drying, reduced seepage to low-lying breeding sites, and the enhanced efficacy of molluscicide application are aspects favorable to snail control and to mosquito control as well.

Canal lining may be arbitrarily classified according to the material used (see Table 22 in Annex B).

(1) paved or hard-surfaced. The most expensive, but also the most desirable. Portland cement or asphaltic concrete, brick, tile, half-pipe sections, stone, rubble, shotcrete, etc. Figure 18 is typical.

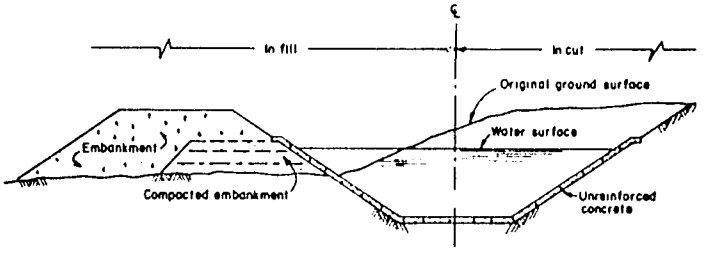


FIGURE 18
Typical Section of Concrete Canal Lining

(2) exposed membrane. Flexibility their strong point. Butyl rubber sheeting, asphalt-felt sandwiches, asphalt-coated jute. These are more subject to surface damage, weeds, and sunlight than is concrete. Butyl more successful than asphalt. See Figure 19.

(3) buried-membrane. Any water tight membrane with a long life in soil, from bentonite or clay to asphalt to plastic or rubber sheeting with consequent prolific mud growth. Readily installed. See Figure 19.

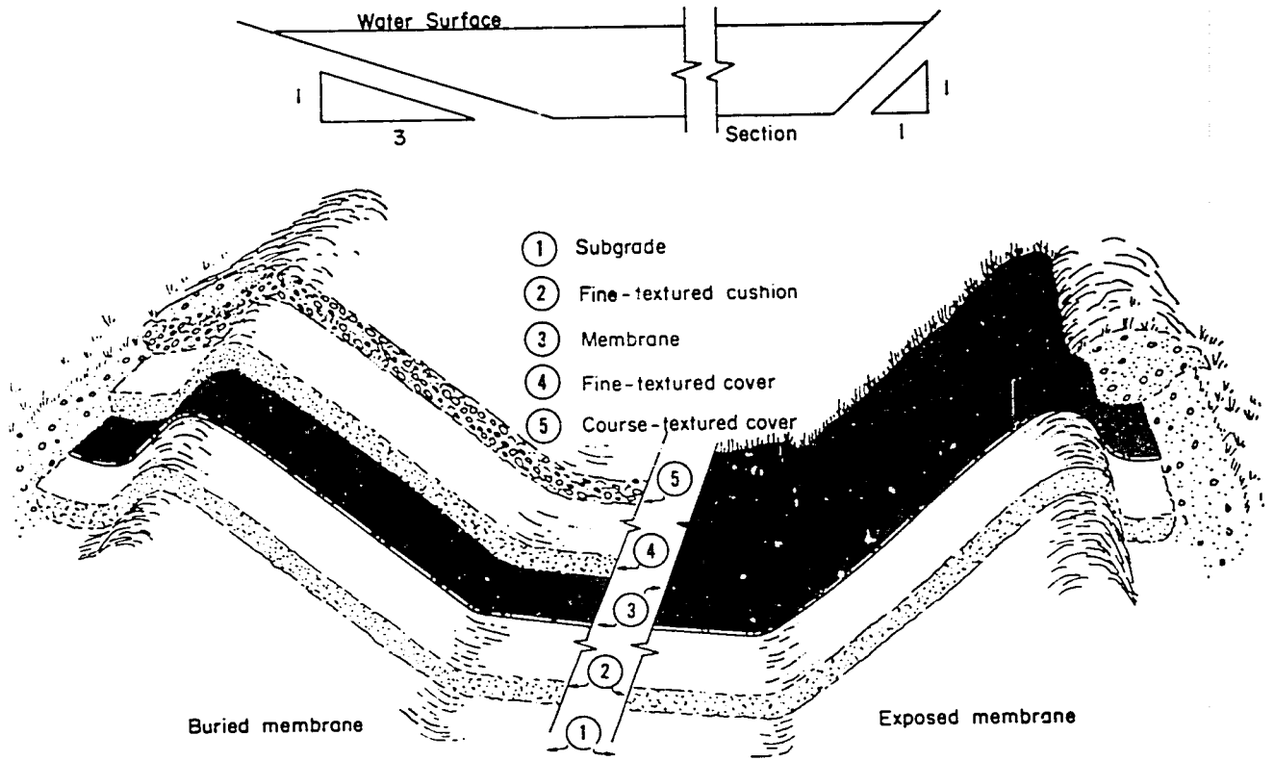


FIGURE 19
Typical Section of Exposed and Buried Membrane Lining

(4) compacted earth. Economical where suitable soils available. Maximum channel velocity of 3 fps. See Figure 20.

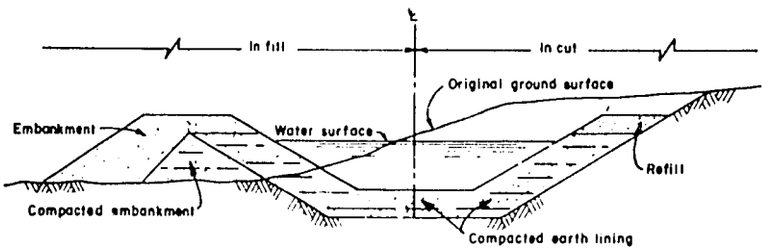


FIGURE 20
Typical Section of Thick Compacted Earth Lining

(5) earth and chemical sealants. Attractive idea with only partial success. Applied as an emulsion of water and waxes, asphalts, resins, lignins, or polymers. Thin surface, short-lived.

The cost of lining, like other construction, varies widely with location. For the purpose of comparing linings, Table 12 shows average construction costs in the western United States.

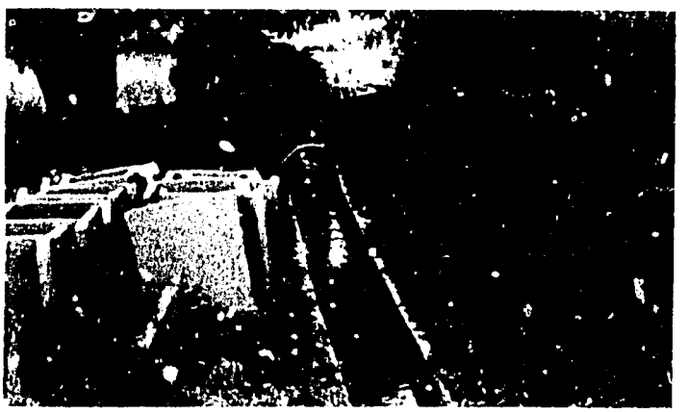


FIGURE 21
Prefabricated Concrete Lining

TABLE 12. APPROXIMATE CONSTRUCTION COSTS OF CANAL LINING

Lining	Material	Other[a]	Total
	Costs per square yard in U.S. Dollar		
Portland cement concrete, 3-inch unreinforced	1.20	1.80	3.00
Portland cement concrete, 2-inch unreinforced	.80	1.70	2.50
Asphaltic concrete, 2-inch	1.00	1.50	2.50
Asphaltic membrane, buried (BAM)	.33[b]	.77	1.10
Prefabricated plank type, exposed	1.66	.50	2.16
Asphalt-coated jute, exposed	.85	.30	1.15
Asphalt-coated jute, buried	.85	.90	1.75
Polyethylene film, 10-mil, buried	.23	.62	.85
Vinyl film, 10-mil, buried	.45	.62	1.07
Butyl sheeting, 32-mil, buried	1.25	.62	1.87
Butyl sheeting, 60-mil, exposed	2.40	.10	2.50
Earth, compacted, 3 feet			1.10
Earth, compacted, 1 foot			.50

[a] Subgrade preparation, installation, and covering, when applicable.
[b] Asphalt in place.
Source: Lauritzen (1968)

The longevity of the lining, the local interest or discount rate, and the annual operating and maintenance costs must also be considered in comparing types of lining. Consider a concrete lining with a 50 years life and a construction cost of $2.50 per square meter. At an interest rate of 10%, its annual capital cost would be [a](0.10086) (2.50) or $0.25. A polyvinyl membrane lining with a construction cost of 0.50 per square meter but a life of only 2 years would have an annual capital cost of [a](0.57619) (0.50) or $0.29. Annual operating and maintenance costs would have to be added to each figure for comparison of the total annual costs. Additional data on lining costs, longevity, seepage losses, and other important features may be found in the annex.

In comparing costs, it should be noted that the size of a canal to carry a given discharge varies inversely with the hydraulic "smoothness" of its surface. The Manning

[a] Uniform series capital recovery factor

"n" for concrete is 0.014, for buried asphalt membrane (BAM), "n" is 0.025. Thus the cross-sectional area of the BAM-lined channel will be

$$\frac{1}{0.014} \div \frac{1}{0.025} = 1.7$$

times larger than the concrete lined channel. For a typically shaped cross-section, the perimeter will be about 1.5 times greater. Thus to deliver the same water as concrete, a BAM-lined channel would require 1.5 times the lining surface, for comparison 1.5 x $1.10 = $1.65 for each $3.00's worth of concrete rather than $1.10. Table 13 below and Figure 22 are illustrative.

TABLE 13. RELATIVE CAPACITIES OF CONCRETE LINED AND UNLINED CANALS

Bottom Width (meters)	Flow Depth (meters)	Quantity (cu.m/sec) Concrete	Unlined
0.30	0.45	0.40	0.23
0.90	0.60	1.27	0.71
1.20	0.75	2.40	1.33
1.50	0.90	4.00	2.24

To supply a given discharge the surface area of the concrete lining can be reduced since the friction loss is less and the permissible velocity is greater.

When erosion resistant linings (such as concrete) are used, the gradient of the bed can be increased and the side slope made steeper. The top width is reduced, which results in reduction of land area required for the canal. The right-of-way cost savings may be substantial.

Considering that a lined canal system for a given supply area need not carry the water which is lost in an unlined system, the dimensions of any lined canal system, including structures, will be smaller than for the unlined system.

The costs of lining may appear out of reach for a schistosomiasis control program. The major benefits, however, may be in reduction of seepage. It is a truism that conveyance losses alone are from ¼ to ½ of all water diverted.

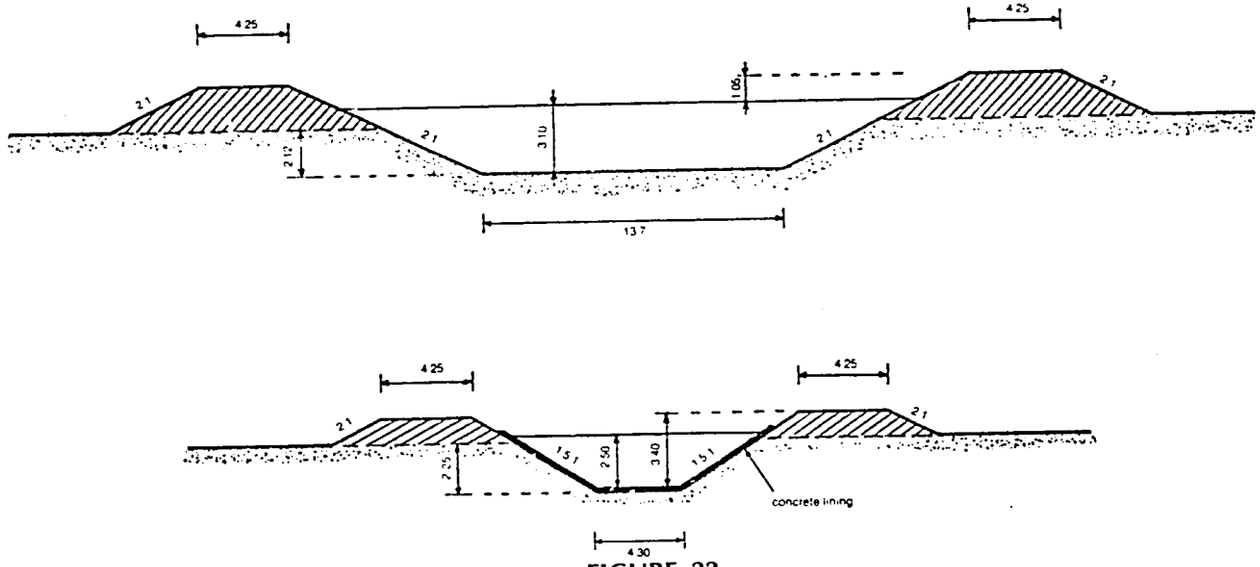


FIGURE 22

Comparison of Unlined and Concrete Lined Canal (Lengths in Meters)

The U.S. Bureau of Reclamation (1963) and the Food and Agricultural Organization of the United Nations (1971) have published helpful manuals on linings for irrigation canals.

Cover (Including Pipe).

"Of all snail control measures, the use of closed conduits is the most effective" (WHO, 1965b, p. 93). Probably the most expensive too. Covering large canals for any appreciable distance is prohibitively costly. However the use of low-pressure concrete pipe for moderate discharges (less than 10 m^3/sec or 350 ft^3/sec) is becoming increasingly more feasible. Such pipe is readily manufactured in field factories by moderately skilled labor.

Closed systems, in addition to providing an unfavorable environment for snails, have minimal transport losses due to leakage and evapo-transpiration, provide protection from pollution, are safer, have lower maintenance and operational costs, and allow more land to be irrigated than do open lateral systems. In one Egyptian province (Beni Suef) a drain covering scheme underway will add an estimated one feddan (1.04 acres) in eight of agricultural land which in addition to the environmental improvement, will adequately meet the cost of the program.

There are a number of examples where piped distribution combined with modern agricultural practices has been successful in areas endemic for schistosomiasis. The Miwani Sugar Estates, Kenya, is noteworthy (WHO, 1960a; McMullen, 1962ab).

Shape

The concept of hydraulic efficiency was previously defined in the discussion of velocity. For the most frequently used open channel section, the trapezoid—the most efficient section is a half-hexagon—the sides slope up 60° from the horizontal. For a rectangular cross-section, the most efficient section has a depth equal to half its width. These slopes, 60° and 90°, are too steep for the stability of earth canals. Side slopes commonly vary from 3 horizontal units to 1 vertical unit (3:1, or 18.4° from the horizontal) to 1:1 (45°) for highly stable materials.

The depth of water is not usually a critical element in the design of irrigation channels. In large earth canals, however, the depth is limited to protect high embankments against water pressure and to reduce the danger of an embankment failure. Consequently, depths in excess of about 10 feet (3 m) are usually avoided.

From the standpoint of snail control, canals should be provided with vertical sides and the maximum possible depth. These factors would discourage both marginal and bottom vegetation, increase vulnerability to preying fish, and reduce the penetration of light. A canal with vertical sides would of course have to be lined, and this, for the irrigation engineer, means increased costs and a totally different design. Thus, it can be seen that the points of view of engineers and malacologists are sometimes quite divergent.

Layout and Siting.

The necessity of preventing cercarial exposure of the individual and also preventing excretal contamination of the irrigation system requires that the distribution and drainage systems be carefully sited relative to residential areas. Residential sites should not give ready access to irrigation water and whenever possible should be sited in a relatively dry area away from the main intakes and channels. Layout of field channels and drains should be planned or controlled rather than left entirely to local farmers. When canals isolate villages from main roads, they should be bridged. Borrow pits and sections of old canals should be filled, drained, or otherwise eliminated as snail habitats.

For the new land to be reclaimed by water from the Aswan High Dam, ". . . whenever possible canals will be constructed at least 500 metres away from the villages, and where this cannot be done the irrigation authorities have agreed to pass the canals within the precincts of the villages and for five hundred metres on each side between perpendicular walls, rising a few metres above the level of the ground . . . there will also be no sharp curves to favor stagnation, there will be no blind ends, and . . . any disused canals will be filled in." (Ayad, in Wolstenholme, 1962, p. 377).

Protection of Access.

Several methods for protecting access to the irrigation system and thereby preventing transmission of the disease to both man and snail have been described: closed conduits, e.g., pipe; physical barriers, e.g., walls, fences, or heavy brush; distance, e.g., 500 metres between housing and canals. Some of these involve capital investment which can be reduced by confining control measures to the more likely points of infection.

Access may be protected indirectly by eliminating the need for contact with snail-infested water through provision of such facilities as bridges and culverts, public water supply, and protected facilities for bathing, washing livestock, laundering, and water recreation.

That access could be effectively protected by statute is doubtful since children are notoriously unimpressed by trespass rejoiners. Boats might be kept off the smaller canals by statutes and physical barriers conjoined. Boatmen are known to have high infection rates—52.0 percent in one area of Egypt. (Farooq, 1966a).

Drainage.

When land is irrigated, drainage problems almost always follow, particularly high ground water and development of salinity. These are controlled by drainage affected by means of open ditches or underground tile-drains. In the latter case, there is no snail growth, but the problem may be extremely serious in open drains. Such ditches often serve flat areas, so that their slopes and velocity of flow are very small. Drainage flow includes not only excess irrigation water but also normal surface run-off, the determination of which forms the basis for drainage design. Lack of drainage results in stagnant pools, wet areas, and seepages which are often good snail habitats.

While it may not be economical to line open drains completely, it is perhaps advisable to provide them at least with lined inverts (prefabricated concrete inverts, for example), which would have the advantage of concentrating small flows and of increasing water velocity.

The cost of drainage can be surprisingly low compared with the value of the land reclaimed and the benefits in terms of increased crop yields resulting from keeping the

water table within the desired distance of the root zone. In reclamation work in the Nile Delta, the cost of subsoil drainage using 4- and 6-inch (10-cm and 15-cm) diameter concrete pipes was about $70 per acre. This represented about one-tenth of the market value of the land reclaimed. However, this cost was completely offset by the saving in land which would otherwise have been required if open drains had been used. In addition, there are hardly any maintenance costs involved as compared with open drains. (WHO, 1965b, p. 113).

A possible cost breakthrough in drains may be the use of plastic pipe, locally manufactured and "plowed" into place (McJunkin and Pineo, 1970).

Low lying areas such as are found in the Egyptian delta can only be drained by means of pumping stations. The capacities of such stations need not be as great from the point of view of schistosomiasis control as for the growing of crops. Thus so long as water is drained away within two or three weeks the chances of the creation of snail habitats are practically eliminated. For crop requirements the water must be drained away over a much shorter period in order to prevent damage to crops.

An effective way of reducing the quantity of drainage water is to exercise strict water control in the irrigation canals, and to charge high rates for excess water used by irrigators (WHO, 1965b, p. 10).

Where large drains are provided to handle storm run-off or excess irrigation water, and are therefore used only occasionally, it is worth considering their drainage in turn by the installation of small diameter tile drains, or ½ round pipes, so that they can be kept dry between large discharges.

Research is showing that drainage requirements could be practically eliminated in some areas if conveyance losses were controlled and if water were applied to the land in accordance with soil and plant requirements. There are few, if any, places where this goal has been achieved, however, and, except in places where good natural drainage exists, provision for controlling ground-water elevation is still necessary (Lauritzen, 1968b).

A successful example from South Africa of a control program using only those methods outlined in this subsection is that of Pitchford (in Wolstenholme, 1962, p. 360).

Recently a survey was done on a sugar/citrus irrigation scheme nine years old and 13,000 acres in extent. All the main canals were protected by storm-water drains and fencing. This resulted in protection of all storage dams leading from the canals. All canals, whether main, subsidiary or feeder, were cement-lined. All labour was housed below the main canals and faeces were deposited in the cane where they were comparatively harmless. Drains were deep, with perpendicular banks, and were consequently comparatively inaccessible. *Biomphalaria* were present in all water types. Swimming and clothes washing were both done either in the large river which did not tend to form pools, or in the cement-lined feeder canals leading from the protected storage dams. Swimming was discouraged in these dams, mainly because they were the source of European household water. The incidence of *S. mansoni* infection in this scheme was less than 2 percent in 180 children examined from all over the area. No other antibilharziasis measures had ever been practised.

Intermittent Operation.

The possible ability of snails to survive in the absence of free water is important inasmuch as channels in well-designed irrigation systems can be dried out periodically. Species and strains of snails show great variation in resistance to desiccation. Resistance to the lethal effect of desiccation is high in the case of certain strains of snail host species that have been investigated under suitable conditions both in the laboratory and in nature. Survival out of the water for periods of from 3 to 11 months has frequently been achieved under experimental laboratory conditions (WHO, 1967, p. 10). In nature, these snails may occur in temporary pools in Africa and South American which dry up for several months during the hot season, obliging the snails to aestivate. Not all individuals survive this dry period, but a sufficient proportion do so to repopulate the habitate when it is once more filled with water.

If a single snail is introduced into a favorable habitat it is possible, owing to its exceptional reproductive capacity, to have a flourishing snail colony in about 40 days and transmission of schistosomiasis in about 60 days. Snails may be carried by canal flow, on plants, by birds, or in other ways from infested habitats hundreds of miles distant.

In unlined canals, snails are able to bury themselves or are stranded in the bottom mud and survive for several months when irrigation is suspended and the canals are dried out. This is especially true in irrigated

areas where the ground-water level is sufficiently high to keep the earth layer at the bottom of the canals in a moist and cool condition. Clay bottoms, however, do not appear favorable to certain types of snails. In concrete or similarly lined canals, snails are unable to dig in and they and their eggs are killed by desiccation and the heat of the sun.

Complete drying-out of irrigation channels, especially if carried out at frequent intervals, may not succed in destroying each individual snail, but it so interferes with the life and reproduction of colonies that they become reduced in number and, if the periods of drought are either sufficiently frequent or sufficiently prolonged, may eliminate them entirely. The latter statement is particularly true in the case of lined canals. It is for this reason that terminal distributory channels in the Tigris-Euphrates valley are almost always snail-free (WHO, 1957, p. 30). In different climatic regions, experimental research is needed to determine the most suitable frequency and periodicity of such an operation.

Maintenance.

The following measures are helpful:

(1) removal of vegetation and muds from banks and shallow margins,
(2) cleaning and re-grading canals,
(3) straightening canals,
(4) backfilling, grading and draining, or fencing borrow pits,neighboring low ground, and unused canal branches,
(5) flushing canals at periodic intervals,
(6) inspecting canal banks for seepage,
(7) inspecting canals and structures for snail lodgement sites,
(8) inspecting sluice gates, distributing chambers, float wells and other equipment for leaks and lodgement sites,
(9) inspect for improper deliveries of water, quantities and locations,
(10) inspect for general untidiness, here a pipe missing, there a leaky gate, and
(11) check for wasted water.

Control of Vegetation.

Weed Clearing. Weeds in irrigation canals and drains provide suitable habitats for snails, and, where they hamper the application of molluscicides, their removal becomes necessary. In addition, they reduce the carrying capacities of the distribution system, consume considerable quantities of water, and thus reduce the amount available to crops. Control of weeds is important, therefore, not only for snail control but also for proper functioning of irrigation schemes.

In planning irrigation schemes, adequate provision should be made for weed control. The importance of weed growth in irrigation systems can be illustrated by the case of a large irrigation scheme in Asia, completed during the 1960's, with discharge at the head equivalent to that of the Seine at Paris. Within 5 years after the system was opened, submerged aquatic weeds had cut the flow of water in the canal by 80 percent (Holm, *et al,* 1969). While such a case is rather unusual, records show that a reduction of one-third to one-half of the carrying capacity of an earth canal in from three of five years is not unusual. In the Gezira irrigation scheme in the Sudan, more than $143,500 a year is spent on mechanical weed control (WHO, 1965b).

For the control of weeds in irrigation schemes, both mechanical and chemical methods are used. They have their respective fields of application depending on local conditions, the size and characteristics of the irrigation area, types of weeds, and relative costs. Mechanical methods comprise dredging, pulling out by specially designed scrapers, burning, chaining, cutting, and mowing. Chemical methods comprise the use of selective herbicides for bank weeds and aromatic solvents for aquatic weeds. The effectiveness of chemical control depends largely on the choice of herbicide, which is governed by the type of weed, and on the method, timing and frequency of application. The number of selected herbicides is being continually extended and at least one of them, acrolein, is lethal to host snails (Ferguson, *et al,* 1965). Such a dual effect may result in substantial savings in areas where snail control has been established and molluscicides are used.

As far as snail control work is concerned, weed

removal is an important factor. With mechanical methods, snail habitats are either destroyed or seriously disturbed. However, such disturbance may also facilitate the movement of snails by floating them down irrigation canals to new areas.

Weed control operations are facilitated by the provision of places for the application of herbicides, and roads for use of mechanical equipment. In certain circumstances, provision should be made for the use of boats, both for herbicide application and for cutting of weeds. In some areas flat-bottomed boats, paddle-propelled and fitted with cutting knives, have been found practicable for this purpose. The cut weeds float downstream and are collected at convenient stations.

Additional information on weed control may be found in Annex B.

Trees.

The practice, often followed, of planting trees immediately adjacent to canals should be prohibited, for eventually the roots encroach on the canal walls and bed, providing snags and obstructions, and leaves and branches fall into the water. Maintenance thus becomes unnecessarily complicated. If trees are desired they should be planted some distance away from the canals. The shade provided by the trees is inadequate to discourage snail lodgement, at the same time preventing the sun from effectively drying out the canals on the occasions when it may be possible to empty them and allow desiccation to take place, and tempting passersby to leave their schistosome ova. The organic rubbish that often collects in the water near a lone tree may stimulate development of a large snail and cercarial population in the immediate vicinity, an unnecessary hazard to health.

Special Structures.

Special structures required for the proper functioning of an irrigation system and for the control of host snails should be made part of the irrigation scheme during the planning stage. Such structures comprise mechanical snail traps, molluscicide-dispenser sites, crossings over or under siphons, flumes, drop structures, chutes, culverts, bridges, division boxes, turn-out, checks and waste-ways. Provision should also be made for the protection of the

distribution system by means of lateral spillways, drainage inlets and drainage of natural watercourses over or under the irrigation canals. It is also desirable from the point of view of efficient operation to provide bridges to facilitate traffic movement and the transport of cleaning and maintenance equipment. For the application of molluscicides it is desirable to establish staff gauges in canals to indicate discharges at various depths (WHO, 1965b).

Storage Reservoirs

Shoreline. Water conservation and storage is essential for development of arid and semi-arid areas. These bodies of water may range in size from stock-watering ponds to mammoth regional irrigation and hydroelectric reservoirs. Located in areas endemic for schistosomiasis, they tend to increase the number of snail habitats. With human contact an increase in schistosomiasis is inevitable.

Where host snails occur, they are usually established in shallows along the shoreline. The habitat then may be rendered less suitable for snails or transmission by deepening and straightening all margins and removing vegetation, preferably before construction or during low water; shortening shoreline with dikes and fill, with particular attention to isolated ponds; where human access is unavoidable, erecting piers to transfer human contact from near the shore to an offshore area where cercariae are less numerous or frequent; construction of access roads for weed control and mollusciciding operations; and location of shoreline villages at points where maximum wave action can be expected. These actions are helpful for natural lakes also.

Intakes.

Reservoirs may serve as breeding aquaria or as traps for upstream snails. Intakes therefore should be located some distance from shore, well submerged, and provided with galvanized screens having 8 meshes per inch and protected by coarser screens. Intakes in "night reservoirs" should be avoided if possible. Snails and cercariae have been known to survive passage through hydraulic machinery.

Spillways.

Schistosomiasis occurs in some areas endemic for onchocerciasis. Spillways have become the site of abundant breeding places of *Simulium damnosum*, the vector of human onchocerciasis and dam building in Africa has caused a considerable northward shift in the area where *S. damnosum* occurs. Stepped spillways, being particularly favorable to *S. damnosum*, should not be used (Quilannac, *et al*, 1967).

Access.

The comments on access to distribution systems are equally applicable to reservoirs.

Reservoir Operation (Water Level Fluctuation)

The success of the Tennessee Valley Authority in controlling mosquito population through fluctuating water levels in its reservoirs, combined with the occasional observation of reduced snail populations in some tropical irrigation systems where water levels have fluctuated has stimulated consideration of planned fluctuation of reservoir levels as a method of snail control (Lanoix, 1958; McMullen, 1962ab).

When stranded on dry land by a falling water level, snails that transmit schistosomiasis, especially *Biomphalaria*, make little or no attempt to escape back into the habitat, although their degree of activity would enable them to do so (WHO, 1957, p. 10). They are thus exposed to the risk of death by desiccation, by the action of the heat of the sun, or by consumption by terrestrial predators (land birds, wild rodents, pigs, others), normally unable to reach them, and a large proportion of snails so exposed perish. The death-rate depends on length of exposure, rapidity with which the water level falls, presence or absence of shade, and relative humidity of the atmosphere. Prolonged exposure, rapid fall of water-level, absence of shade and low relative humidity all tend to increase the death-rate and to accelerate death. Thus rapid and regularly repeated changes of level might be a useful and practical means of controlling aquatic snail hosts in certain types of irrigation channels and reservoirs.

Based on a laboratory study using *Biomphalaria glabrata*, Jobin and Michelson (1969) suggested draw-

down rates and timing to strand snails:

> ". . . during the day snails can be stranded with a vertical rate of drawdown greater than 23 cm per hour on a 5:1 slope and 0.1 cm per hour on a 100:1 slope. At night the rate of drawdown can be reduced 82 percent or even greater, as snails are thought to reverse their migration at night. In an analysis by mathematical model, a symmetrical pattern of fluctuation of water level (best suited to reservoirs on rivers of medium size) was estimated to strand snails most rapidly if the periods of fluctuation were 5 to 10 days. The asymmetrical pattern appeared to be more effective than the symmetrical for fluctuations of the same frequency. The periodic, rapid discharge from such a reservoir might also flush snails from downstream habitats."

In follow-up field studies in Puerto Rico, 10-cm (4 in) diameter siphon spillways were constructed in November 1967 on two ponds containing stable populations of *B. glabrata*. The siphons cause periodic drops (about once a month in the rainy season) in the water level of 0.5 metres (1.64) feet) in one day. By October 1968 all snails had disappeared from the ponds with siphons. In two untreated control ponds, snails continued to be present in substantial numbers.

The drawdown rate required limits this technique to small reservoirs. Such reservoirs generally employ earth dams. The requisite spillway and gates, or other mechanism, and their operation and maintenance, could be prohibitively expensive. Pipe siphons, particularly mass-produced of plastic, could be feasible. Earth dams require that the horizontal pipe across the dam be of considerable length; the resulting large volume of entrapped air creates priming problems for the siphon. For example, one of the Puerto Rican siphons described above loses 200,000 liters before priming, almost as large as the drawdown of 230,000 liters. Since the very purpose of the reservoir is conservation of water, losses of such magnitude are generally unacceptable.

Development of improved siphon designs and further field studies would seem to have merit.

Night Storage Reservoirs.

The practice of using small reservoirs for overnight collection and storage with distribution the following day is condemned by all authorities. Such reservoirs tend to have fantastic densities of snails and cercariae and

disseminate highly contaminated water over the area irrigated. Where indispensable, their number should be reduced by using larger sizes and they should be *completely* emptied during the day—no fish culture.

Environmental Sanitation

Effectiveness of Sewage Treatment. Primary sedimentation for the usual detention periods removes the "majority" (Jones, *et al*, 1947c) of *S. japonicum* eggs and 83 percent (Rowan, 1964b) of *S. mansoni*. "In practice ova of *S. japonicum* in settled sewage could be expected to pass the trickling filter and both ova and miracidia would be recoverable from the effluent." (Jones, *et al*, 1947c). Rowan (1964) found that trickling filters remove 99.7 percent of *S. mansoni* eggs. The aeration tanks of activated sludge tanks appear to be an excellent hatching medium, although most ova are removed, e.g., 99.7 percent of *S. mansoni* (Jones, *et al*, 1947c). Of 3,967 laboratory-raised *Australorbis glabrata* snails exposed to flowing effluent from trickling filter and activated sludge plants treating ova-containing wastes, not one acquired an infection of *S. mansoni* (Rowan 1964b).

Jones, *et al* (1947c), found the maximum survival time for *S. japonicum* in anerobic digesting sludge to be approximately three weeks and on sludge drying beds, fourteen days. Also that ova of *S. japonicum* are effectively removed from settled sewage by intermittent sand filtration.[a]

Sewage stabilization ponds hold great promise as an economical process for use in developing countries. Kawata and Kruse (1966) found maximum survival time of *S. mansoni* in anerobic ponds to be 10 hours but that aerobic and facultative ponds "are not likely to suppress the hatching of the eggs or significantly affect the survival of miracidia of *Schistosoma mansoni* or the vector snails." They recommend therefore the inclusion of a preliminary anerobic chamber in stabilization pond design.

Based on studies in Puerto Rico of *S. mansoni* eggs and miracidia, Rowan (1964a) recommends chlorination

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[a] Jones, *et al* did not investigate continuous sand filtration of sewage.

at a level sufficiently high to give a 15-minute residual of at least 2.5 milligrams per liter. Jones and Hummel (1947b) found that miracidia of *S. japonica* were killed within 30 minutes after chlorination with total 30-minute residuals of 0.4 milligrams per liter (0.6 for *S. mansoni)* but that *S. japonicum* ova required up to 11 milligrams per liter for 30-minute total residuals. (Also see 'chlorination" under "Water Treatment").

Aside from anerobic stabilization ponds, no conventional form of sewage treatment, without chlorination, can be said to remove *all* eggs and miracidia. There is no epidemiological evidence to predict whether one or a thousand eggs is the threshold value for transmission in a given locale. Chlorination of sewage effluent is rarely practical in developing countries. If the purpose is solely for schistosomiasis control, the money is probably better spent on molluscicides. The relatively low cost of stabilization ponds is of particular import in developing countries. Their ability to destroy schistosome eggs and miracidia is as those master tautologists, the admen, say —"an extra added bonus".

Effectiveness of Sanitation as a Control Measure

Sanitation alone is unlikely to eliminate this disease. The role of children in maintaining the schistosome life-cycle, the need for sanitation in fields as well as in homes, and the tremendous multiplication of even a single evacuation—up to 10,000,000 cercariae rule out such a solution. Sanitation *may* however help limit the frequency and severity of schistosomiasis infections and, of course, is jusified as a control measure for other equally debilitating diseases.

Public Water Supply

Storage. Since schistosome cercariae perish after 24 to 72 hours in water, storage, at least 2 days, can be used as an effective method of treatment. Storage tanks should be protected against *Aedes aegypti* in areas endemic for yellow fever.

Coagulation and Filtration.

Alum in the strongest concentrations employed for water purification does not destroy cercariae. (Jones and Brady, 1947a; Pellegrino, 1967; Witenberg and Yofe,

1938). They become entangled in the flocs but soon free themselves and swim above the sediment, Although limewater has been shown to affect cercariae, Witenberg and Yofe (1938) demonstrated that the lethal activity is mainly due to a high concentration of hydroxyl ions (pH of 11.6) never reached in water treatment plants.

Sand filters are ineffective in removing cercariae (Wittenberg and Yofe, 1938). Cercariae are removed by pre-coated diatomaceous earth filters (Jones and Brady, 1947a).

Disinfection.

The effectiveness of water chlorination has been extensively investigated. However, most of the work prior to Wittenberg and Yofe (1938) is inconsistent as virtually no experimental attention was given to pH and little to contact time. Wittenberg and Yofe reported that *S. haemotobium* and *S. mansoni* are killed within 30 minutes by one part per million (ppm) total available chlorine for a pH range of 7.5-8.9. The most recent study (Frick and Hillyer, 1966) found that minimal free available chlorine concentrations inactivating *S. mansoni* cercariae in a 30-minute contact period at 20°C were 0.3 ppm at pH 5.0, 0.6 ppm at pH 7.5, and 5.0 ppm at pH 10.0. The World Health Organization recommends 1.0 ppm chlorine residual for 30 minutes with no pH given (WHO, 1965b, p. 102).

Cercariae are destroyed by heating to 50°C (122 F) for 3 minutes. Water for washing or bathing can be effectively treated by cresol at 100 ppm (Thresh, cited in Pellegrino, 1967). Seawater with a salinity of 3 percent may be considered absolutely safe for bathing (Ingalls, 1946).

Water for Bathing, Laundering, and Recreational Use

Farooq (1966ac) has examined the personal, social, and religious habits of the population of an Egyptian province as they relate to water contacts (see Table 14). Frequency and type of water contact varies greatly by age but certain major opportunities for cercarial infection are noteworthy. For young males, virtually all contact is through bathing and playing. Urination is common during this activity. For older males, principal contact activities are washing of cattle, ablution, and wadu, the ritual wash-

TABLE 14. FREQUENCY OF OUTDOOR SOCIAL AND RELIGIOUS WATER-CONTACT ACTIVITIES BY SEX AND AGE *

Activity	Males							Female							
	No. of activities in age group (years)					Total activities		No. of activities in age group (years)					Total activities		Total activities (both sexes)
	0-4	5-9	10-14	15-24	25+	No.	%	0-4	5-9	10-14	15-24	25+	No.	%	
Washing clothes	—	—	—	—	3	3	—	—	3	31	57	63	154	10	157
Washing utensils	—	—	2	—	—	2	—	37	230	173	192	236	868	57	870
Washing animals	1	2	11	33	18	65	9	—	1	3	6	10	20	1	85
Washing vegetables	—	—	2	5	4	11	2	—	1	1	—	—	2	—	13
Bathing and playing	194	129	20	7	6	356	50	208	39	—	3	7	257	17	613
Swimming	—	12	9	—	—	21	3	—	—	—	—	—	—	—	21
Urination	5	3	—	10	16	34	5	4	—	—	—	1	5	—	39
Defaecation and urination	7	10	—	4	26	47	7	10	1	—	—	—	11	1	53
Ablution	3	—	1	8	40	52	7	2	—	—	—	—	2	—	54
Wadu	—	—	2	15	71	83	13	—	—	—	—	—	—	—	88
Taking water	—	1	1	—	4	6	1	—	14	30	70	105	219	14	225
Angling	—	13	9	—	1	23	3	—	—	—	—	—	—	—	23
Net-fishing	—	—	—	—	2	2	—	—	—	—	—	—	—	—	2
Total	210	170	57	82	191	710	100	261	239	238	328	422	1538	100	2248

* Observations by Farooq and Mallah (1966) in Egypt.

ing of all Muslims before prayers (five times daily), all at the water's edge. Young females bathe and play frequently also but the most frequent activity is washing of utensils. Utensils are washed by women, accompanied by children, standing in the water or sometimes squatting on a stone. The estimated body-surface exposure is 20 percent. Washing of clothes is done in similar fashion. To take water, done by females only, they wade into the water to wash, rinse, and fill their earthenware *ballas* or *zalas*.

Provision of protected facilities for bathing, laundering, and recreational use thus is more than a mere convenience—even if it is only a dug pond separate from the canal but kept clear of vegetation and rubbish and treated regularly with molluscicides.

Agricultural Practices

Crop Selection. The selection of crops that require less water is an obvious potential control measure. Thus, in Egypt, the prevalence of schistosomiasis is less in areas where wheat and barley are grown than where rice is grown. Crop rotation may make possible irrigation practices that could prevent snail breeding, especially *Oncomelania*.

Irrigation Practices.

Farming practices may be scheduled with some regard to seasonal fluctuations in snail breeding so that the water may be turned off at suitable intervals to interrupt this activity. Major breeding periods may occur one or more times a year, but the pattern must be known before planting, irrigation, and harvesting operations can be used to control snail populations.

The practice of planting or sowing rice in rows simplifies weed control and increases yield. The attendant cultivation tends to eliminate *Oncomelania* snails in the fields, as has been demonstrated in Leyte and Japan (WHO, 1965b).

The traditional methods of rice growing in the Far East result in the formation of habitats for snail breeding and in the transmission of schistosomiasis. Evidence now shows that rice can be grown just like many other crops without standing water in the basin. The traditional practice developed from the desire on the part of farmers

to have sufficient water stored in the rice fields as insurance against possible drought.

It was demonstrated in the Philippines that irrigation water can be turned off after an initial application of 7 cm, and then additional irrigation applied when the soil begins to show signs of drying. By proper farming practice, it was demonstrated in the Philippines that in a field where rice was grown by ponding, the number of snails average 220 per square meter. After the adoption of intermittent application of water the number of snails dropped to less than 1 per square meter and the yield in rice increased by more than 50 percent. The application of irrigation at intervals of about ten days is often adequate to bring the crop to satisfactory harvest (WHO, 1968). In Japan with the introduction of modern agricultural practices and improved irrigation, schistosomiasis is being rapidly eliminated.

The development of new pipe technology has made sprinkler irrigation more feasible in recent years. With some crops, such as potatoes and sugar beets, the application of water increases production even in areas that are well adapted to irrigation from ditches (Lauritzen, 1968b). Such irrigation would eliminate many breeding sites for snails.

Land Preparation

Land leveling contributes greatly to irrigation efficiency and reduces ponding and excess water, thus providing an opportunity to eliminate many snail and mosquito habitats.

Management

Well-managed irrigation projects both increase agricultural production and enhance vector control. Successful management requires a backdrop of adequate administrative and legal powers, and real coordination between agricultural and health authorities and specialists.

Mechanical Barriers and Screens

Where a reservoir serves as a nursery for snail propagation, screens or other barriers may be placed at entrances to diversion canals. The long-run effectiveness of such screens seems doubtful—a mesh small enough

to stop all snails, including juveniles would be so close as to create loss of head problems; would be readily clogged by suspended fines, debris, and vegetation; and would require continuous maintenance. Private discussions with irrigation and public health engineers active in endemic areas indicate that screens have not generally been successful.

Screens are, however, an established control procedure in the Gezira irrigation scheme (the Sudan) which obtains its water by gravity from the Sennar Dam where "experience with the screens in the Managil Extension has justified their use" (Rahman and ed Den, 1961) in preventing or delaying infestation of new canals.

The Gezira screens are made of iron rails and wire screen with 8 meshes to the inch (approx. 3 per cm) and the barrier and its iron angle supports are painted to prevent rust. The barrier is more or less L-shaped, with the lower sides of the "L" submerged and at an angle of 80° to the erect part. About 20 cm (0.65 ft.) of the erect part is submerged and the remaining 60 cm (1.95 ft.) is above the water. The width is 2.15 meters (7.0 ft.). It was not possible to submerge the barrier for more than 20 cm due to objections from agricultural authorities (Malek, p. 49).

Relation of Engineering to Chemical Control

It cannot be overemphasized that virtually every activity or structure designed for environmental control of snails enhances chemical control as well as making it more efficient, more effective, and less frequently necessary.

Advantages and Limitations of Environmental Control

The World Health Organization has summarized these thusly:

Advantages

(1) Local labor and materials can often be used.
(2) Under certain conditions, production is increased through utilization of waste land.
(3) Improved irrigation and agricultural methods generally reduce the number of snails and increase crop yields.
(4) Such a programme will contribute to the control of filth-borne and arthropod-transmitted diseases.

(5) Such measures reduce the area in which it is necessary to use chemicals on residual colonies.

Limitations

General

Environmental control generally requires a degree of co-operation between various public service agencies and the local inhabitants which may not be easy to attain because of conflicting interests.

In some endemic areas, economic and educational levels are not advanced to the point where the local inhabitants are capable of employing modern agricultural practices and economical water use as a means of snail control.

Environmental control may be very costly since it usually involves heavy capital expenditure, careful planning and close integration with other engineering activities.

Environmental control, although often referred to as "permanent", always involves constant expenditure for maintenance which must be considered in cost accounting.

CHEMICAL CONTROL OF SNAIL VECTORS

Introduction

Chemical control of the intermediate hosts of schistosomiasis is predicated on the assumptions that they are the weakest link in the life-cycle of the parasites and that molluscicidal compounds (chemical compounds which kill snails, i.e., molluscs) can be used to produce rapid and devastating reduction in snail populations. In practice, molluscicides have not always lived up to their promise, largely due to the diversity and extent of the habitats, the physiological differences, the habits, and the ecology of the various snail species involved. Lack of consideration of one or more of these factors may lead to the selection of the wrong compound or formulation, the use of inadequate equipment, and inefficient methods of application. Control will not be satisfactory unless an effective molluscicide comes in contact with practically all of the snails in a given habitat, often a difficult goal.

Advantages and Limitations

The most effective molluscicides will destroy schistosome cercariae and kill all, or nearly all, the snail hosts and snail eggs. Thus transmission of schistosome infection is stopped almost immediately. Unfortunately, repopulation of bodies of water usually occurs, requiring the repeated application of the chemical to achieve permanent control. However, it has been possible in certain instances to eradicate the snail hosts by the application of molluscicides. These instances have involved relatively simple physical and ecological situations in circumscribed areas. Large-scale eradication has not been achieved by chemical methods. However, the development of more effective molluscicides and more efficient methods of application gives hope that this method will become more efficient as time goes on.

Chemical control of snail hosts is usually in the hands of trained personnel. The operation is frequently under the control of one agency, the public health administration, and thus does not normally require the cooperation of other government or private organizations. However, in certain instances, other agencies have supervisory rights over water control and agricultural land involved

in the operation, and here the cooperation of these agencies is essential for efficient operation of the program. Chemical control of snail hosts does not usually involve the active cooperation of the population of the area—a cooperation essential for other schistosomiasis control procedures and often difficult to obtain.

The application of molluscicides is exclusively a measure for controlling the intermediate hosts of human and animal snail-borne disease agents. Certain other methods of schistosomiasis control contribute to the control of other diseases or the improvement of agricultural production. The cost of one measure versus that of another must be taken into consideration in planning any control program. The necessity for reapplication of molluscicides over a long period of time may prove to be too expensive, and other measures may be preferable.

Nearly all effective molluscicides are toxic in varying degrees to other organisms as well. Some must be handled with particular care. It is essential to ensure that the application of the chemical to bodies of water will not result in harm to the human or animal population. Most molluscicides are toxic to much of the aquatic fauna and some to the flora. Used in improper concentrations, they may harm cultivated crops. Thus far, there is no evidence of accumulation of any such chemicals to phytotoxic levels in the soil, although the possibility should be kept in mind.

Available Molluscicides

Molluscicides are now available that can be used successfully in the control of schistosomiasis. A strategy for their application must, however, be developed to obtain a maximum cost effectiveness. This strategy may differ for artificial water bodies (irrigation schemes, dams, etc.) and natural water bodies.

The two outstanding compounds, niclosamide (Bayluscide manufactured by Bayer) and N-tritylmorpholine (Frescon manufactured by Shell), which were developed in the past decade, are now commercially available and are currently the molluscicides of choice against aquatic snails although Yurimin is more suitable against *Oncomelania* in Japan. The properties of presently useful molluscicides are summarized in Table 14a. *Niclosomide* has the advantage that, although it kills snails, snail eggs,

and also schistosome cercariae, it is not toxic to man and has a limited biocidal effect. It is noncorrosive, reasonably persistent but not permanent, and is degraded by sunlight into harmless organic chemicals. Its disadvantages are its high cost and its lethal effect on fish and and some other aquatic animals.

Niclosomide had proved difficult to formulate except as a dispersible wettable powder that tended to settle out rapidly in dispensers. Now, however, it is available as an emulsion concentrate with 25% active ingredient. In general, this formulation has been well received and satisfactory results have been obtained with it. Although it is more expensive, it appears to be more efficient and easier to apply, and may therefore prove to be cheaper on a cost/efficiency basis.

The formulation was apparently quite stable following prolonged exposure to sunlight at a wide range of temperatures. The LC_{50}[a] for *Biomphalaria pfeifferi* for a five-hour exposure time varied between 0.1 and 0.15 milligram per liter (mg/l), and for *Bulinus (Physopsis) globosus* between 0.23 and 0.27 mg/l. The LC_{90} was 0.3 mg/l for *Biomphalaria pfeifferi* and 0.55 mg/l for *Bulinus (Physopsis) globosus* (figures that are three times better than those for the wettable powder). For *Biomphalaria* on St Lucia the LC_{50} for a 24-hour exposure and 48-hour recovery period ranged from 0.02-0.04 mg/l, i.e., the same range as with the wettable powder; the LC_{90} was about 0.06 mg/l. The new formulation has strong piscicidal activity.

N-Tritylmorpholine.

This compound has the advantages of being effective at an extremely low concentration and of having limited general biocidal action. Moreover, it is relatively persistent without being permanent in water. It is the most active molluscicide known, molluscicidal concentrations ranging from 0.1-0.5 mg/l for one-hour exposure, and from 0.01-0.05 mg/l for 24-hour exposures. Although the compound is not toxic to snail eggs in these conditions, recent work shows that with prolonged

[a] LC_{50} is the lethal concentration at which 50% of the snails die for a given exposure time. LC_{90} is a 90% kill, etc.

TABLE 14a. EFFECTIVE MOLLUSCICIDES AND THEIR CHARACTERISTICS

Characteristic	Niclosamide	*N*-trityl-morpholine	NaPCP	Yurlmin
Active ingredient	2'5-dichloro-4'-nitro-salicylalide ethanolamine salt	*N*-trityl-morpholine	sodium pentachlorophenate	3,5-dibromo-4-hydroxy-4'-nitroazobenzene
Physical properties				
Form of technical material	crystalline solid	crystalline solid	crystalline solid	crystalline solid
Solubility in water	230 mg/l (pH dependent)	< 1 mg/l	33%	very slight
Toxicity				
Snail LC_{50} (mg/l × h)[a]	3-8	0.5-4	20-100	4-5
Snail eggs LC_{50} (mg/l × h)[a]	2-4	240	3-30	—
Cercaria LC_{50} (mg/l)	0.3	no effect	—	—
Fish LC_{50} (mg/l)	0.05-0.3 (LC_{50})	2-4	—	0.16-0.83 (LC_{50})
Rats, acute oral, LD_{50} (mg/kg)	5000	1400	40-250	168 (mice)
Herbicidal activity	none	none	none	none
Stability (affected by)				
U.V. light	no	no	yes	no
Mud, turbidity	yes	no	no	yes
pH	optimum 6-8	yes	no	slight
Algae, plants	no	no	no	--
Storage	no	no	no	--
Handling qualities				
Safe	yes	yes	varies	yes
Simple	yes	yes	yes	yes
Formulations	70% W.P. 25% E.C.	16.5% E.C. 4% granules	75% flakes 80% pellets 80% briquettes	5% granules

Characteristic	Niclosamide	*N*-trityl-morpholine	NaPCP	Yurlmin
Field dosage				
Aquatic snails (mg/l × h)[a]	4-8	1-2	50-80	—
Amphibious snails on moist soil (g/m^2)	0.2	—	0.4-10	5

[a] The term "mg/l × h" indicates that the figures given are the product of the concentration and the number of hours of exposure.

Source: WHO (1973).

exposures it is ovicidal. Large-scale trials in several countries have demonstrated its efficacy in controlling snails both with very short exposures (4 mg/l for 15 minutes) and with prolonged applications (0.075 mg/l for 15 days). Most of the data available indicate that *Bulinus* species are less susceptible to *N-tritylmorpholine* than *Biomphalaria*. In certain circumstances it has proved possible to control snails without harming fish populations. Laboratory and field studies show that mud, vegetation, and light have little effect on the activity of N-tritylmorpholine, but hydrolysis to triphenyl carbinol with loss of activity may occur in acidic water, depending upon the initial concentrations of the compound. The rate of hydrolysis is relatively high at low pH values (7.0), but decreases logarithmically as the pH increases. Recent observations show that the compound may be absorbed by silt particles that subsequently retain molluscicidal activity for a time. The breakdown of the compound and its residues in soil and rice has been studied, and it is not considered likely to present a toxic hazard to man or animals.

N-tritylmorpholine is now available as a 16.5% weight/volume emulsion concentrate and in granules (4% active ingredient). As the concentrate can be applied by means of a drip-feed technique, it is particularly suitable for large irrigation systems where prolonged application, using continuous low dosage regimens, may be required to ensure adequate penetration. The granular formulation may prove suitable for selective mollusciciding in impounded waters. The cost of N-tritylmorpholine is competitive with that of other available compounds.

TABLE 15. ADVANTAGES AND DISADVANTAGES OF SELECTED MOLLUSCICIDES

Molluscicide	Advantages	Disadvantages
Bayluscide	Highly toxic to snails and their eggs. Safe to handle and use. Probably the cheapest chemical per unit volume of water treated. Does not upset the biota as much as some compounds.	Difficult to formulate. In certain types of habitat available formulations do not disperse effectively.
Copper sulfate (and other copper compounds)	Kills both snails and their eggs. Active at low pH. Somewhat less toxic to fish than other molluscicides. Safe to handle. (It may be possible to exploit insoluble copper compounds for use under some conditions.)	Absorbed by soil and organic material. Ineffective at a high pH. Corrosive to equipment. Of variable toxicity to snails under field conditions.
Sodium Pentachlorophenate	Kills both snails and their eggs. Excellent penetration downstream has been achieved. Widley used for other purposes and not dependent on a molluscicide "market".	Irritating and potentially dangerous to the handler. Doses required relatively high compared with new molluscicides. Activity may be reduced by bright sunlight.
Frescon	Highly toxic to snails. Toxic action against some species very rapid. Apparently safe to handle and use. Initial reports indicate no serious effects on biota. Several types of formulation possible.	Does not kill snail eggs. Removal by absorption may be a serious problem. Inactivated by a low pH.

Source: *Bulletin World Health Organization*, 33, 567-581 (1965).

Yurimin.

Yurimin is a new molluscicide (3,5-dibrome 4 hydroxy-4'-nitroazo-benzene) that has been gradually coming into practical use in Japan, where in field trials it has proved to be 16-18 times as active as sodium pentachlorophenate (NaPCP) against *Oncomelania nosophora*.

The C_{50} for *O. nosophora* for 48-hour exposure is 0.2-0.5 mg/l in immersion tests. Yurimin is almost insoluble in water, but in granule form (5% w/w) it becomes

easily miscible and, if stirred regularly during the application, will form a stable suspension.

The 5% granular formulation is used as a spray at the rate of 5 g/m². In field trials against *O. nosophora* at this rate, 80-100% snail mortality was observed. The lethal concentration is a little higher for fish than for snails. No apparent toxic hazards to man or vegetation were detected.

Hardness and suspended solids in water have little influence on the molluscicidal activity of Yurimin although the pH affects the toxicity—the compound is a more effective molluscicide in alkaline than in acidic waters. Yurimin is not affected by ultraviolet light. Like NaPCP, it uncouples oxidative phosphorylation in animal tissue. The cost of the grandular formulation of Yurimin in Japan makes it competitive with NaPCP on a cost/effectiveness basis.

Others.

Sodium pentachlorophenate and copper sulfate are still in limited use as molluscicides.

Many plants from different parts of the world have been reported to possess varying degrees of molluscicidal potency and man malian and fish toxicity. Although plant molluscicides may not be competitive with other existing synthetic molluscicides, they may be useful in the control of schistosomiasis in rural areas on a "self-help" basis. Endod (*Phytolacca dodecandra*) has been the compound most extensively investigated of this group. Its active principle is a triterpene glycoside that is highly soluble in water. It has undergone laboratory and limited field evaluations and has given encouraging results in fairly large field trials in Ethiopia.

Application of Molluscicides.

The optimum concentration-exposure time should be determined for each molluscicide. The product of the two variables is not necessarily a constant; if the exposure time is doubled, for example, the effective concentration is not necessarily halved. Further, the exposure time may be limited by the adverse effect of such factors as sunlight, silt, the chemical composition of the water, and organic matter.

The method of application is to some extent governed

by the type of formulations available. Emulsifiable liquids and soluble chemicals can be conveniently applied to flowing waters by feeding at a more or less constant rate at the head of the watercourse, and to impounded waters and swamps by spraying. Spreadable oil formulations are particularly useful in the treatment of reservoirs with heavy and dense vegetation. Wettable powders require some means of maintaining the chemical in suspension during the application period.

The use of nonovicidal molluscicides requires special consideration. One method of effective snail control is the so-called split-dose treatment. This consists of two applications spaced two to three weeks apart so that snails hatching after the first application are killed by the second. These molluscicides may also be applied monthly during the transmission season.

A third method is the prolonged application (over a period of several weeks) of a very low concentration in irrigation systems where the flow of water is continuous. This method could make the treatment of large areas possible at very low application cost, and could also be considered for single-point application in natural watercourses.

Selection of a method of application will be affected by many factors. Where the cost of the chemical is high in relation to that of labor, the use of more complex dispensing methods may be justified. The dispersal of molluscicides by aircraft is being used in one large irrigated plantation and may prove suitable for other large irrigation schemes. The exact choice of equipment will depend on the snail habitat and the molluscicide formulation chosen.

Two general strategies for snail control are at present employed: focal control and area control. Focal control may be valuable where transmission is limited to particular foci, but area control is usually the only practical approach if transmission is widespread in a watershed or irrigation system. Focal control depends upon accurate information on the transmission foci, and requires periodic molluscicidings. In the control of an area or watershed unit all snail habitats must be treated but, although initially it may be more difficult than focal control, the result is likely to be longer-lasting

and therefore more economical.

Molluscicide applications should be timed to obtain the most effective kill of snails; this is particularly important in areas with marked seasonal or environmental changes.

After the initial application, other treatments will be necessary and the timing of these will be dictated by a sound knowledge of the snail repopulation potential and the normal parasite transmission pattern. In addition, constant field assessment should be maintained to monitor the efficiency of the system.

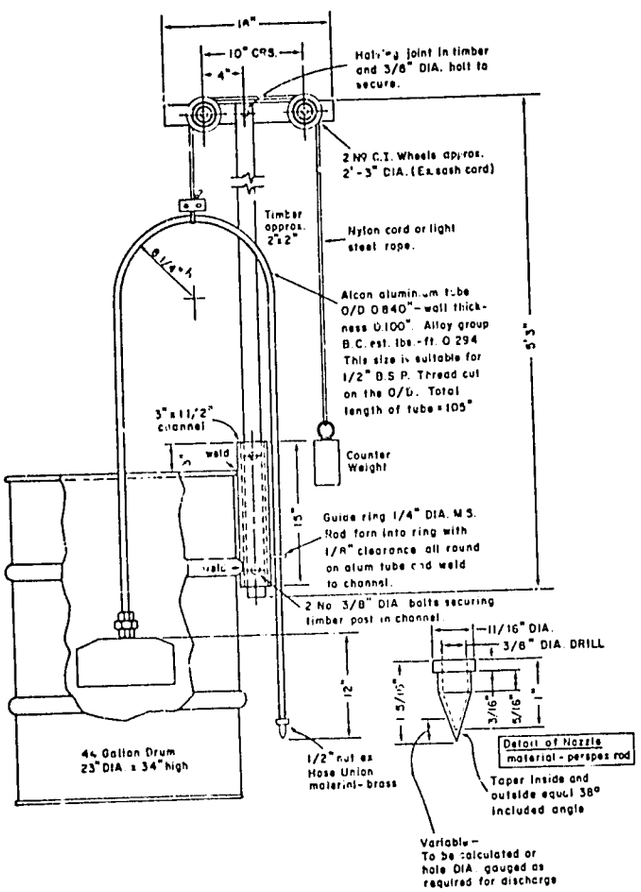
Application of Molluscicides

The purpose of the application of a molluscicide is to eliminate the intermediate hosts involved in the transmission of the infection. Since there are nearly always a few survivors from even the most vigorous control campaign, repopulation of the environment usually takes place, and molluscicidng must be repeated at intervals if control is to be realized. The cost and effectiveness of the molluscicidng program depend largely on the rate at which reproduction occurs. Therefore, in order to retard the process of repopulation, an attempt should be made to eliminate as many snail hosts within a drainage area as possible, even though many of the snail colonies may not be directly related to transmission sites.

Various methods have been employed for the application of molluscicides. Selection of the most suitable method depends on a number of factors, including the nature of the snail habitat, the type and accessibility of the body of water, the amount of labor available, and cost considerations. In certain locations, the most simple procedures, such as direct application of the chemical to flowing water, or the use of simple spray equipment, may be sufficient. Automatic devices have been developed for dispensing molluscicides, and certain equipment designed for application of insecticides has proved to be of value. Methods of application are described in detail in WHO Monograph No. 50.

Equipment used ranges from hand sprayers and dusters (see Table 19) to spray pumps to tractor sprayers to automatic dispensers especially constructed for feeding

molluscicides into flowing waters. The latter equipment is widely used in irrigation systems. Figures 26-29 are illustrative.



Source: Staff/Rhodesia

FIGURE 26

MOLLUSCICIDE DISPENSER

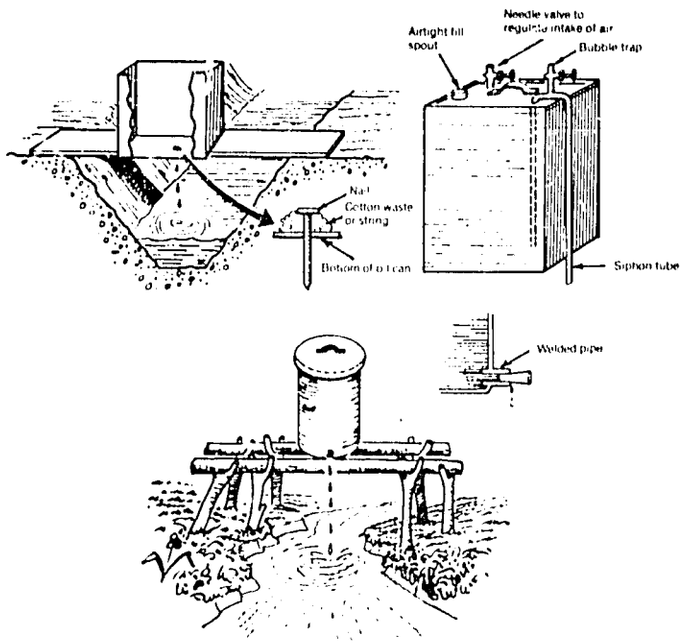
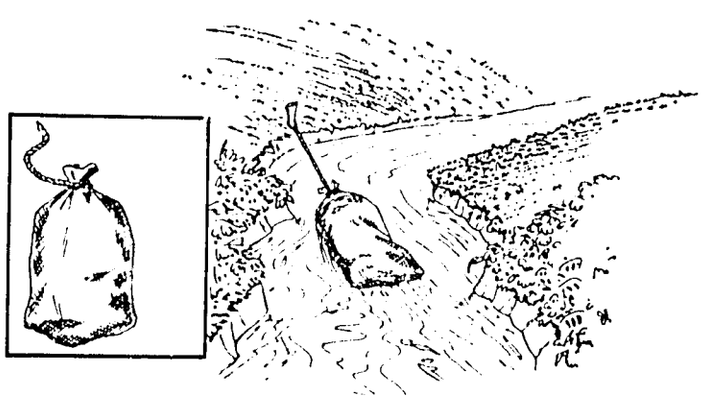


FIGURE 27

DRIP CAN METHOD



Source: U.S. Navy Medical School

FIGURE 28

ONE METHOD OF DRAGGING

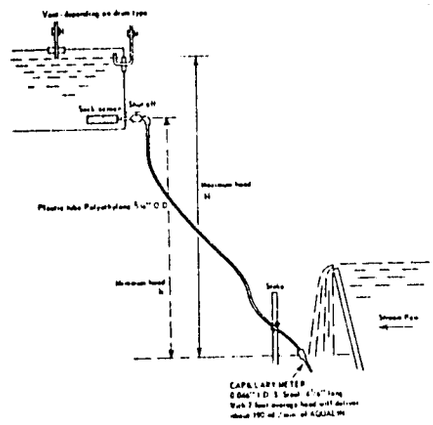


FIGURE 29

FREE GRAVITY FLOW SYSTEM

Toxicity to Man

Generally a molluscicide, to be suitable, must be relatively safe to handle, since in almost all endemic areas laborers are relatively unsophisticated and it is difficult to engender in them an understanding for the need of safe practices in the handling and use of dangerous materials. The molluscicides now widely available are reasonably safe to handle, although NaPCP in powder form is very irritating. Concentrated solutions should not be handled by common labor. This hazard can be minimized by close supervision, or the use of other formulations. However, the safety factor is only one among those that must be considered in the evaluation of a molluscicide. A dangerous compound, Aqualin, for instance, may be of sufficient value to warrant employment despite the necessity of taking special precautions in its handling and application.

ANNEXES

Annex A

CONTROL OF AQUATIC PLANTS

Introduction

The potential growth of floating, submersed and marginal aquatic plants, in tropical areas must be understood as an extremely important aspect which must be dealt with for the successful operation of flood control and water resource developments. Aquatic plant growth can harbor snail and insect vectors of diseases of humans and domesticated animals including schistosomiasis, fascioliasis, malaria and encephalitis; greatly reduce streamflow and increase potential flooding through blockage of channels and control structures; interfere with powerplant operation when excessive vegetative material collects on trashracks or enters turbine penstocks; and interfere seriously with the transport and subsequent usage of water for other purposes including irrigation. In arid areas, floating and emersed weeds accelerate water losses from storage and distribution systems through transpiration. Waterhyacinth *(Eichhornia crassipes)* for example, has been a major problem in the rivers, canals and water impoundment of the Southern United States, the Panama Canal in Central America, the Nile and Congo Rivers of Africa, and in various hydroelectric, fisheries and irrigation projects in tropical and sub-tropical areas of Asia and South America. The serious development of waterfern *(Salvinia auriculata)* on Lake Kariba between Rhodesia and Zambia is another example. The waterfern was established along the Zambezi River prior to building of the dam and was flushed downstream by periodic floods into the water impoundment area. In 1964 the area occupied by the plant reached a peak of 400 square miles. A similar problem developed in Nicaragua on Lake Apanas. Growth of water fern and waterhyacinth increased to cover an estimated 250 acres of lake surface. The reservoir (lake) became so clogged with these aquatic plants that power production was seriously limited. In the Gulf States of the United States and in other countries bordering the Gulf of Mexico, an emersed aquatic plant, Alligatorweed

(Alternanthera philoxeroides) grows profusely. The plant is highly aggressive and its unobstructed growth now blocks navigation channels, multiple water supplies, drainage and irrigation ditches.

Control by Project Design Features

Clearing of trees and brush around the perimeter of reservoirs, and deepening shallow areas will reduce marginal aquatic plant problems. Lining of main irrigation channels will substantially reduce aquatic plant growth in the irrigation system. Tops of channel banks should also be leveled and surfaced so that mechanical methods such as chaining, dragging, mowing or spraying can be easily and efficiently done. Suitable gates to permit "drawdown" of the water in irrigation channels will also facilitate control of marginal and submersed aquatic plants. It may also be economical to fence reservoir areas to permit grazing on marginal aquatic plants by cattle or sheep. Where water buffalo deteriorate the dikes of the channels, these animals should be fenced out.

Mechanical Control

Various mechanical devices are available for control of aquatic plants, including weed saws, cables, draglines, and barges or boats equipped with mowers, airjets, waterjets, etc. The advantage of mechanical control is that it involves little direct hazard to fish, wildlife or humans. However, such methods are usually inefficient and uneconomical. Usually they give only partial control and must be repeated at frequent intervals. Sometimes mechanical methods only break up or tear the weeds apart and the loosened vegetation, if not properly disposed of, may clog gates, pumps and siphons, or cause new colonies of weeds to grow downstream. Cables or booms can be used to control waterhyacinth and other floating aquatic plants by placing the boom at an angle to the streamflow, floating at the waterline to divert the vegetation to the side where it may be removed mechanically. Submersed aquatic plants can be controlled mechanically in irrigation and drainage channels by drawing down the water for two or three days. The thin-leaved submersed aquatic plants dry quickly when exposed to the air. However, some

nodes and subsoil propagules commonly survive this treatment, and it must be repeated periodically for vegetation control. Some emersed and marginal aquatic plants can be controlled by cutting the vegetative growth at drawdown so that they become submerged and killed when the water level rises again.

Chemical Control

Control of aquatic plants with herbicides is usually easier, faster and longer lasting and frequently cheaper than mechanical control. Treated plants die in place where they decay and dissipate without causing difficulties in the distribution system. Most of the new aquatic herbicides will not injure crops or fish when used correctly, but some of the older materials such as acrolein or aromatic solvents are toxic to fish. Copper sulfate is relatively inexpensive, effective, and the most extensively used algicide. Periodic treatments with copper sulfate at 10 to 14-day intervals at concentrations up to one part per million control plankton algae in non-flowing water. Concentrations up to one part per million are harmless to most species of fish; higher concentrations are toxic.

Several herbicides are used for control of rooted submersed plants and non-rooted vascular plants, including diquat, endothall, dichlobenil, fenac, silvex and 2, 4-D. These herbicides are relatively expensive and must be applied judiciously. Repeated applications are expensive and must be applied judiciously. Repeated applications of 2,4-D at 2-4 kilograms active ingredient per hectare with water carrier provides a satisfactory control for waterhyacinth and anchored floating leaf plants such as waterlily. Diquat is an effective herbicide for control of free floating species such as duckweed and waterlettuce and water fern. Rates of 1 to 1.7 kilograms per hectare are sufficient. Applications should be made as a foliar spray with surface equipment in 1650-2200 liters of water per hectare or with aircraft at 80 liters per hectare. Most broadleaved, emersed herbaceous and woody species can be controlled by single or repeated application of 2,4-D, silvex, or 2,4,5-T at 2-10 kilograms per hectare. These include alligatorweed, smartweeds and waterprimrose. Amitrole or amitrole-t at 4 to 18 kilograms per hectare will control marginal aquatic grasses, sedges and cattail.

The herbicide should be applied in 2500 liters per hectare with surface equipment and 120 liters per hectare with aircraft. A number of aquatic herbicides are listed in Table 17 according to rate and cost of treatment per 1000 cubic meters. Treatments for floating and marginal species are made in terms of surface area and submersed species in terms of the volume of water treated.

Biological Control

Techniques for control of aquatic plants with biological agents in tropical climates are relatively well developed at the laboratory level but few are or have been applied in the operational sense. Biological control of aquatic vegetation is possible by use of certain species of herbivorous fish. Nile tilapia *(Tilapia nilotica)* and congo tilapia *(Tilapia melanopleura)* are known to eat specific aquatic plants. Grass carp *(Ctenopharyngodon idella)* is known to be effective for control of aquatic vegetation. The silver carp *(Hypopthalmichthys molitrix)* is known to feed exclusively on planktonic algae and could probably be used to control algae blooms. The grass carp, the silver carp and other varieties like *Pontius* spp. and some filamentous algae feeders show promise for control of submerged aquatic weeds.

Herbicide Application Equipment and Utilization

Types. There are two types of application equipment: granular applicators for spreading granules or pelleted herbicides, and sprayers for application of liquid or wettable powder formulations with oil or water carriers.

Operation on Land.

Equipment for use on land varies from small hand operated units to large engine-driven pumping machines mounted on tractors, sleds, trailers, pickups, or trucks. This type of equipment generally has a storage tank for carrying hebicide water mixtures. It can be used to treat aquatic plants along the edge of waterways and on the adjacent banks. Land type dispersal equipment can be used best along canals and ditches that have roads built on the spoil banks or levees adjacent to these waterways.

Operation on Water.

Various types of sprayers and granular applicators can

be mounted on barges or boats for treating aquatic plants. These may have tanks for the herbicide-water mixture or for herbicide only with a hose for taking the water needed for the mixture from the lake or stream being treated. There are two disadvantages of boat mounted equipment: (1) the aquatic plant growth may be too thick for the boat to pass through freely, and (2) the water may be too shallow for boats to operate effectively. The U.S. Army Corps of Engineers has been using pumps with 10, 20 and 35 gallons per minute capacity. The smaller pumps are mounted on small shallow draft boats or rafts for spraying near the shoreline and in the upper reaches of the streams and in shallow canals and ditches. The 20 and 35 gallon per minute sprayers are mounted on 16-20 ft. work boats and are used for treating large areas of aquatic plants that occur in medium or deep water. These sprays are effective for about 60 feet from the boat. Two men make a crew, one operates the boat and the other the sprayer. They usually spray only one side at a time. In large areas the boat makes several passes through the weed infested area. However, some of the large (35 gallons per minute) sprayers are equipped with two spray hoses and treat a strip on each side of the boat. This type of operation requires three men per unit.

Aerial application.

Helicopters and light planes are used for applying herbicides to large areas of aquatic plants. A helicopter needs no runway and can fly better in low visibility than airplanes but is more expensive to operate. Drift is always a problem but can be reduced by flying in calm weather, using low-volatile chemicals, using nozzles with large openings, using water or emulsions instead of oil and using low pressures. Also, a positive shutoff valve for each nozzle will help avoid damage from dribble. A disadvantage of using aircraft is difficulty of spraying near trees, houses and other objects. The chief advantage of using helicopters and airplanes is the speed with which the treatment can be made.

TABLE 16. ADVANTAGES AND DISADVANTAGES OF VARIOUS HERBICIDES

Herbicide	Advantages	Disadvantages
AMS (Ammonium Sulfamate)	Non-flammable, non-volatile. No special handling precautions are necessary. Not hazardous to wild life.	Corrosive to metals, especially brass and copper. Drift from mist blowers is dangerous. Sterilizes the soil for several months.
Dalapon	Oral toxicity is low, but may cause skin irritation after prolonged contact.	Avoid contact with skin and eyes and inhaling spray mist.
Diquat	Non-volatile and non-flammable.	Highly toxic.
Endothall	Non-corrosive and non-flammable.	Oral toxicity to mammals is high and must be handled with care.
Silvex	More effective than 2,4,5-T on maple, redbud, saltcedar and trumpetcreeper. Safer where drift into cotton is a hazard.	Many common species are resistant to Silvex.
2,4-D	Effective control for many broad-leaved plants including some aquatic plants. Cost is lower than most herbicides.	Drift is a hazard to nearby susceptible plants.

TABLE 17. HERBICIDES AND THEIR COST AT USUAL APPLICATION RATES FOR NONCROP USES

Herbicide (common name) and Formulation [1]	Target Weeds and General Usage	Application Rates [2] (kg ai/ha)	Application Rates [2] (ppm)	Chemical Cost [3] Per Application (per ha)	Chemical Cost [3] Per Application (per 1000 cu-meters)
Acrolein	Submersed weeds—flowing water treatment		0.1		$0.17
Copper sulfate, pentahydrate salt (25% WSC) (ppm Cu)	Filamentous algae—slug treatment		1-5		$2-10
	Filamentous algae—continuous		0.01-0.02		$0.02-0.04
	Submersed weeds—continuous treatment		0.10-0.20		$0.20-0.40
Xylene	Submersed weeds—slug treatment		444-740		$42-70
Dalapon, sodium salt (74% WSP)	Annual grasses—ditchbank treatment	5-7		$11-15	
	Perennial grasses—ditchbank treatment	6-8		$13-18	
	Cattail, bamboo, reeds—ditchbank treatment	15-20		$33-44	
2,4-D amine salt (4 lb/gal WSL)	Sedges, broadleaf-weeds—ditchbank treatment	2-4		$2-4	
Diquat (2 lb/gal WSL)	Submersed weeds—static water treatment		½-1		$12-24
Endothall, potassium salt (3 lb/gal WSL)	Submersed weeds—static water treatment		1-3		$10-30

[1] Formulations: EC = emulsifiable concentrate; G = granular; WP = wettable powder; WSC = water-soluble crystals; WSL = water-soluble liquid; WSP = water-soluble powder.

[2] Rates: kg ai/ha = kilograms active ingredient or acid equivalent per hectare; ppm = parts per million active ingredient or acid equivalent in water by weight.

[3] Cost to nearest U.S. dollar.

Source: Bartley and Gangstad (1973).

TABLE 18. PLANT SPECIES AND HERBICIDES FOR CONTROL.

Plant Name	Response to Herbicide	Herbicide	Rate of Application	Remarks
Algae (*Hydrodictyon*)	S	Copper Sulfate	0.25 PPMW in soft water 1.00 PPMW in hard water	Safe for most fish except trout. Highly corrosive to iron and galvanized metal. Avoid contact with eyes, nose and mouth.
Alligatorweed (*Alternanthera philoperoides*)	I	2,4-D	8 LBS/A	Spray on foliage.
	I	Silvex (low vol. ester)	8 LBS/A	Spray on foliage.
	I	Silvex (granular)	20-30 LBS/A	Use only on rooted plants in shallow water, broadcast over weed surface.
Cattail (*Typha latifolia*)	S	Dalapon	15-20 LBS/A	Spray on foliage.
	S	Dalapon plus diesel oil emulsifiable	5-10 LBS/A	Spray on foliage.
	S	2,4-D (low vol. ester)	4-6 LBS/A in 1-20 oil water emulsion	Spray on foliage.
Coontail (*Ceratophyllum demersum*)	S	Diquat	0.25-0.5 PPMW in still water	Inject or apply on surface. Do not apply diquat to muddy water.
	S	Endothall	1.0-2. PPMW in still water	
	S	2,4-D (pellet or granular)	15-20 LBS/A	
	S	Silvex:		
		potassium salts	2-3 PPM	
		liquid	4 PPM	
		low vol. ester	2.5 PPM	

Duckweed (*Lemna minor*)	S	Diquat	0.5-1 PPMW (cation)	Spray foliage or inject in non-flowing water. Do not apply diquat to muddy water.
Eelgrass (*Vallisneria* Spp.)	S	Endothall (amine salt)	1.5 PPMW	Inject ponds or small lakes—toxic to fish.
	S	Silvex	3-4 PPM	Spray weed beds—apply when weed growth is active but below surface.
	S	Sodium Arsenite	4 PPM in soft water 8-10 PPM in hard water	Handle with extreme care. Do not use water for at least 3 days. Toxic to animals.
Elodea (*Elodea canadensis*)	S	Acrolein	4-7 PPMV	Inject under water. Toxic to fish.
	S	Endothall (amine salt)	2-4 PPM	Inject under water. Toxic to fish.
	S	Fenuron Diquat	1-2 PPMW	Inject in pond or lake, nonflowing water. Do not apply to muddy water.
Parrot Feather (*Myriophyllum brasilense*)	I	2,4-D (low vol. esters)	4-8 LBS/A	Spray on foliage.
	I	2,4-D (granular)	20 LBS/A	Broadcast over weed surface.
	S	Silvex (granular)	1-2 PPMW	Inject into small lakes or ponds.
	S	Dichlone	10-20 LBS/A	
Pond Weed (*Potamogeton* spp.)	S	Diquat	0.25-1 PPMW in still water 1-2 PPMW in slow flowing water	Do not apply diquat in muddy water.
	S	Endothall (amine salt)	1-2 PPMV in non-flowing water	Inject underwater. Toxic to fish.
			2-4 PPMV in slow flowing water	Inject underwater. Toxic to fish.

Plant Name	Response to Herbicide	Herbicide	Rate of Application	Remarks
Waterhyacinth (*Eichhornia crassipes*)	S	2,4-D (amine salt)	2-4 LBS/A	Spray on foliage.
	S	2,4-D (low vol. esters)	2-4 LBS/A	Spray on foliage using water or fuel oil.
	S	Diquat	1-1.5 LBS/A	Spray on foliage.
Waterlettuce (*Pistia stratiotes*)	S	Diquat	1-1.5 LBS/A	Spray on foliage.
Watermilfoil (*Myriophyllum spp.*)	S	2,4-D (granular)	20-30 LBS/A	Broadcast on surface.
		Diquat	0.5-1 PPMW	Spray on foliage.

S — Susceptible
I — Intermediate
R — Resistant

LBS/A — Pounds of active ingredient or acid equivalent per surface acre
PPMV — Parts per million by volume
PPMW — Parts per million by weight

Source: Nelson, Gandstad, and Seaman (1970).

TABLE 19. SOME EXAMPLES OF EQUIPMENT USED FOR APPLICATION OF MOLLUSCICIDES AND PESTICIDES

The mention of manufacturing companies or of their proprietary products does not imply that they are recommended or endorsed by the Agency for International Development.

PUMPS—High pressure, low head, engine-driven pumps, for use in raising water not exceeding 7.5 m

Manufacturer's name and address	Cat. No., type and designation	Capacity max. (l/min)	Engine (hp)	Head (m)	Weight (kg)	Estimated price ($)
F. E. Myers & Co., ASHLAND, Ohio USA	V 912 E	34	¾	46	130	175
	V 913 E	64	1	35	213	275
	V 914 E	106	2	43	332	385
	V 915 E	167	3	35	390	445
F. E. Myers & Co., ASHLAND, Ohio USA	V 931 M	15.5	½-1 Ph	70	111	170
	V 932 M	36.7	2-1 Ph	122	147	320
	V 933 M	60.6	5-3 Ph	177	345	480
	V 934 M	110.7	7½-3 Ph	168	560	675
Thuron Sprayer Manuf. Co. 12200 Denton Drive DALLAS 34, Texas USA	Eagle 20	32	18-12.5	—	30	620

LIQUID APPLICATION—(a) Compression sprayers

Manufacturer's name and address	Tank Capacity (l)	Pressure Range (kg/cm³)	Estimated price ($)
Hudson Manuf. Co. 1625 I Street N.W. WASHINGTON, D.C. 20006 USA	12-16	1.7-4	30-35
Myers & Co. ASHLAND, Ohio USA	10) 18)	1.7-4	approx. 30-35

Manufacturer's name and address	Cat. No., type and designation	Capacity max. (l/min)	Engine (hp)	Head (m)	Weight (kg)	Estimated price ($)

(b) Power sprayers

Manufacturer's name and address	Cat. No.	Tank Capacity (l)	Pressure Range (kg/m2)	Estimated price ($)
Thuron Sprayer Manuf. Co. 12200 Denton Drive DALLAS 34, Texas USA	20-T-TH	1514	56	2160
	20-T-AG	1135	35	1675
	10 T	267	35	855
	5 T	378	35	695
	10-TA	378	35	925
	20-TA-TH	1134	56	2295
J. Bean & Co. LANSING Michigan USA	6-30TR	1135	56	—
	N-6-30TR	1892	56	—
	B-6-30MT	3784	49	—

(c) Mist blowers

Manufacturer's name and address	Type	Tank Capacity (l)	Engine (hp)	Air Velocity (km/h)	Reach (m)	Weight (kg)	Estimated price ($)
J. Bean & Co. LANSING Michigan USA	Trailer mounted Rotomist 303T	1140		144			

S. Frederick Potts P.O. Box 51 CRAWFORD Mississippi USA	P24	125	7	80-320	150	140	
Buffalo Turbine Agric. Equip. Co. GOWANDA, N.Y. USA	CS Mity Mite	190 16	36 26	 high 295		100 500 10	 340

(Back packs; small mist blowers)

Solo Industries P.O. Box 128 37-41 57th St., WOODSIDE, N.Y. USA	M70B Junior	10 10		400	9-12	8	
Buffalo Turbine Agric. Equip. Co. GOWANDA, N.Y. USA	Mity Moe	1.2	1.06	150	24	6.5	120
Hudson Manuf. Co. 1625 I St., N.W. WASHINGTON D.C. 20006 USA	Bak-Pak	2.3	3.5	120		14	

Annex B

CANAL LININGS

Standardization of canal sections

To allow standardization of slipforms and other canal construction equipment standard canal sections have been introduced in several countries. Some of the recommendations worked out by the American Society of Agricultural Engineers are quoted below.[1]

The recommended standards consist of two sections with 1:1 side slopes and five with 1.5:1 side slopes. The dimensional details of these standard sections are shown in Fig. 30 and Table 20.

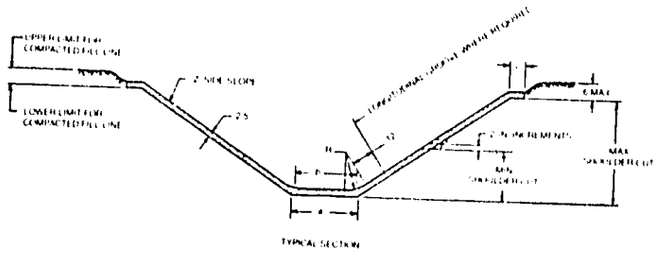


FIGURE 30

Standard trapezoidal canal section (all dimensions in inches)

TABLE 20. DIMENSIONS OF STANDARD TRAPEZOIDAL CANAL SECTIONS (all dimensions in inches)

Section	Z	a	b	c	e Min	e Max	R
A-1	1:1	14.07	12.00	4.00	15.00	30.00	9.00
A-2	1:1	26.07	24.00	4.00	15.00	30.00	18.00
B-2	1.5:1	25.51	24.00	6.00	24.00	48.00	18.00
B-3	1.5:1	37.51	36.00	6.00	27.00	54.00	18.00
B-4	1.5:1	49.51	48.00	6.00	33.00	66.00	18.00
B-5	1.5:1	61.51	60.00	6.00	36.00	72.00	18.00
B-6	1.5:1	73.51	72.00	6.00	42.00	84.00	18.00

[1] ASAE Standard S289—Concrete slip-form canal and ditch linings.

Figure 31 shows the capacity chart for these standard sections. The chart is based on Manning's formula for uniform flow in open channels using an n-value of 0.014. It is given as an aid to planners and designers in selecting dimensions.

TABLE 21. COEFFICIENT OF ROUGHNESS (Manning's n) FOR UNLINED AND LINED CANALS

Surface Condition	Value of n
Unlined Canals	
Smooth natural earth canals, free from weed growth, little curvature	0.020
Small canals in good condition	0.025
Earth canals with considerable aquatic weed growth	0.030-0.035
Earth canals with thick aquatic weed growth	0.040-0.050
Rock canals	0.050-0.100
Lined Canals	
Portland cement concrete lining	0.014
Asphaltic concrete lining (machine placed)	0.014
Brick lining covered with cement plaster	0.014
Soil cement, well finished	0.015
Soil cement, rough as a gravel surface	0.016
Exposed prefabricated asphalt material	0.015
Pre-cast concrete-block lining	0.015-0.017
Brick lining, with exposed brick surface: design value:	0.0146
actual measured value of n on the same lining after gradual deterioration:	0.018
Shotcrete lining, smoothed	0.016
Shortcrete lining, average	0.017
Wooden flumes	0.016-0.020
Compacted earth linings, small canals	0.025
Compacted earth linings, large canals	0.0225-0.020

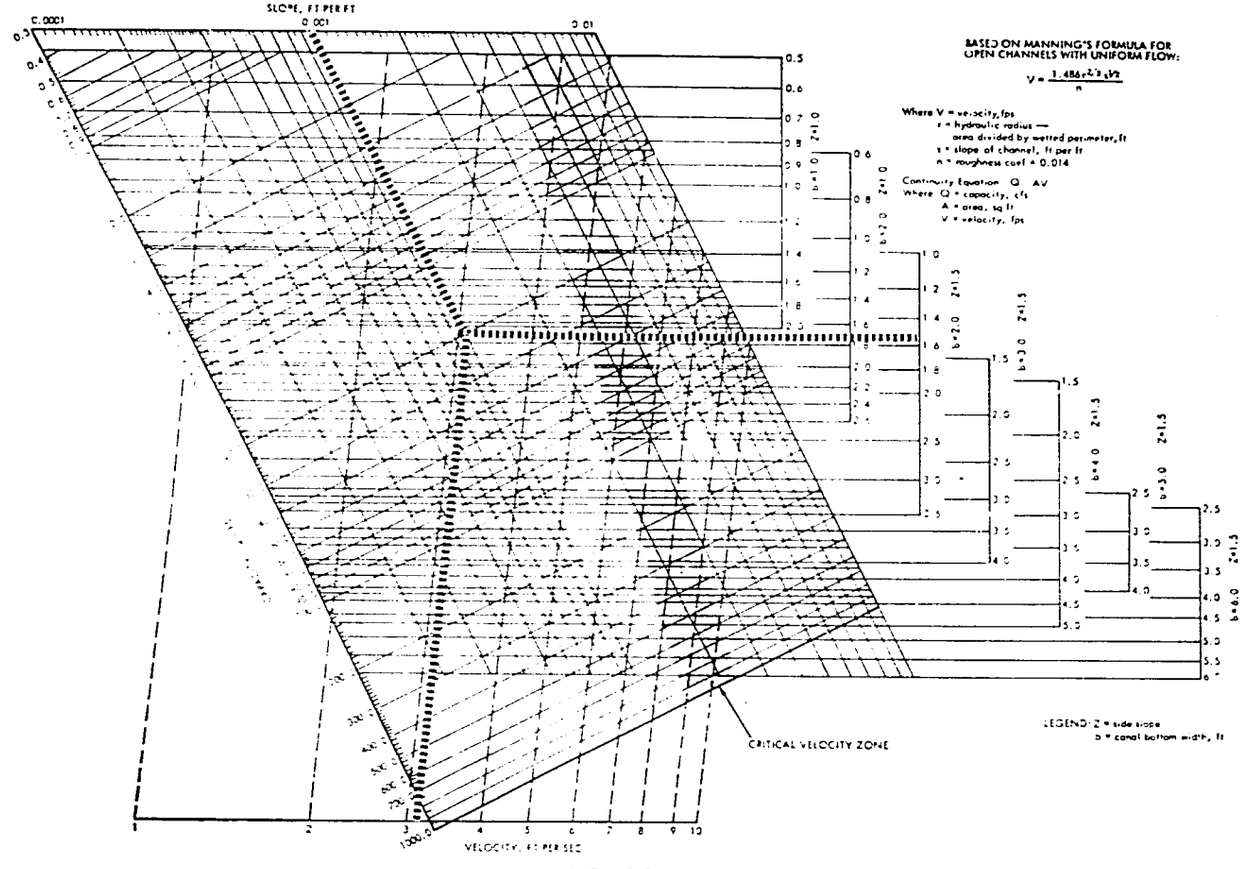


FIGURE 31
Capacity Chart for Concrete-Lined Canals

TABLE 22. IRRIGATION CANAL LININGS AND THEIR MAIN FEATURES

Type of lining and thickness	Cost per square metre $	time period referred to	Durability	Water losses in m^3 per m^2 per 24 hours	Other important features
A. Hard surface linings					
Portland cement concrete, unreinforced, 5 cm.	2.60	1955-61	Commonly estimated to last 50 years.	Below 0.03, if well constructed and maintained, but values up to 0.15 have been measured.	Suitable for all sizes of canals, all topographical, climatical and operational conditions; firm subsoil required; susceptible to swelling clays; availability of aggregates near the job is essential; construction either by hand methods or slipform.
as above, but 7.6 cm.	2.75-4.20	1955-61			
as above, but 10 cm and reinforced.	4.50	1956-58			
pneumatically applied mortar, unreinforced, 5 cm.	2.40	1945-50	As above.	0.03-0.06	As above, but no need for coarse aggregates; special equipment necessary; generally not economical for large jobs; suitable on subgrades of weathered rock.
Precast concrete blocks, 7 cm.	1.70-3.70	1947-60	About the same as above.	If joints are well sealed, about 0.03 can be achieved.	Advantageous where concrete lining is suitable, but remote precasting is more economical (lack of aggregates at site, transport facilities for precast material available).
Soil cement (dry mix), 13 cm.	1.90	1956-60	Largely dependent on cement content; 23 yrs. have been recorded	0.03-0.06	Although less durable than p. cement concrete, low first cost makes this an economic lining, where suitable sandy soils are available from canal excavation or nearby.
Soil cement (plastic), 7.6 cm.	1.30	1947			

Asphaltic concrete, in place, 5 cm.	2.75	1953-58	Seldom more than 15 to 20 years.	About 0.03, but will increase considerably if weed infested.	For the in-place type, availability of aggregate at site is essential; regarding the shorter life, asphalt concrete does not offer any advantage over cement concrete, except on less stable subgrades (swelling clays); offers also better resistance against certain chemical deterioration; susceptible to weed penetration.
Asphaltic concrete, prefabricated slabs, 3.8 cm.	1.80	1962			
Brick and stone	—	—	May be as high as cement concrete, if properly constructed and maintained.	Brick with cement plaster: around 0.03. Stone: relatively permeable unless carefully mortared.	Labor-intensive methods; availability of construction material at or near the site is essential.
B. *Exposed membranes*					
Asphaltic materials	—	—	Only a few irrigation seasons.	Vary widely depending on weed penetration and other mechanical damage as well as weathering.	Suitable only as temporary lining for seepage control.
Polyvinyl (0.19 mm; 8 mil)	< 0.50	pre-1963			
Resins	—	—			
Synthetic rubber (1.44 mm; 60 mil)	3.00	pre-1963	Not yet known, but not less than 10 years.	Negligible if properly jointed and maintained.	Offers permanent seepage control if protected from physical damage but is high in cost;

TABLE 22. IRRIGATION CANAL LININGS AND THEIR MAIN FEATURES

Type of lining and thickness	Cost per square metre $	Cost per square metre time period referred to	Durability	Water losses in m^3 per m^2 per 24 hours	Other important features
C. Buried membranes					Suitability of excavated soil as cover material is important for economic reasons.
Sprayed-in-place asphalt	1.30	1956-60	Depends largely on erosion resistance of cover material, maintenance (weed hazard, beaching, burrowing animals), and operation (drawdown). Records show a serviceable life of at least 15 years. Rubber-membrane is likely to last much longer.	Below 0.06.	Heater and spray equipment must move along canal; skilled personnel are required.
Prefabricated asphalt membrane	1.30	1956-60		Below 0.08.	Easily transported and placed materials but slippage of cover material, caused particularly by drawdowns has sometimes been a problem.
Polyethylene (0.24 mm; 10 mil)	1.05	1956-60		Below 0.06.	
Polyvinyl (0.24 mm; 10 mil)	1.30	1956-60		As above.	
Synthetic rubber (0.77 mm; 32 mil)	2.30	pre-1963		Below 0.03.	
Bentonite layer (4-5 cm)	1.45	1954-56		—	—

Sublining of plastic sheeting or sprayed in place asphalt under precast concrete	—	—	Determined by service life of concrete lining.	Practically watertight if properly constructed.	Very effective in preventing seepage. Concrete joints and cracks need not be sealed but eventually filled with some material to protect the underlying membrane.
D. *Earth Linings*					
Thick compacted (appr. 90 cm thick)	1.30	pre-1963	For economy evaluations 20 years have been assumed.	Below 0.08 (0.02 have been measured).	Suitable soil from canal excavation or nearby borrow area is essential for economy. Freezing-thawing and alternate wetting-drying are hazards to all compacted earth linings because they loosen the compaction and increase the permeability.
Thin compacted (30 cm and less)	< 0.70	pre-1963			
Loosely placed earth (loam, clay)	< 0.35	pre-1963	—	—	Low in first cost but with little effectiveness as to seepage control; little advantage against unlined canals; low durability.
E. *Soil sealants*					
Waterborne bentonite	0.12-0-30	1963	One or two irrigation seasons.	May average around 0.30 but varies widely.	Means of temporarily controlling seepage in unlined canals. Sealing effect is high just after treatment but may be reduced to less than half after only one or two irrigation seasons.
Resinous polymers, petroleum, asphalt emulsions and chemicals	—	—			

Type of lining and thickness	Cost per square metre $	Cost per square metre time period referred to	Durability	Water losses in m^3 per m^2 per 24 hours	Other important features
F. *Flumes + pipes*					
Concrete flumes	—	—	Appr. 50 years.	Negligible, if joints are well sealed.	Relatively independent of soil and topographic conditions; ratio of cost to carrying capacity is high; economical only when value of water is very high.
Concrete pipes (precast cast in place)	—	—	More than 50 years.	Negligibile, if joints are properly sealed.	Particularly suitable for areas with an irregular or rolling topography and intensive cultivation.
Lay flat tubing			Not yet known.	Practically nil.	As above.

Annex C

PROBLEMS OF RESERVOIR DEVELOPMENT[a]

PROBLEMS AND OPPORTUNITIES

Although reservoirs are generally planned to solve one or more primary problems, such as a need for hydroelectric power, their construction generates innumerable secondary problems, many of which have proved to be very serious. Recognizing that no two reservoirs are alike, this paper is intended to indicate which of these secondary problems might require consideration under given sets of circumstances. It is also intended to furnish guidance as to the type, planning and timing of studies needed for their solution. In so doing, it draws heavily on experience gained, particularly during the past decade, by the Food and Agriculture Organization of the United Nations and the World Health Organization.

Primary and secondary problems

Most development projects which include the creation of a large reservoir are initially conceived for a limited number of purposes. Normally these purposes include one or more of the following: generation of electricity; water storage for irrigation, industrial or domestic use; flood control; regulation of flow for navigation.

In nearly all instances the costs and benefits of the project for such primary purposes have been carefully estimated and evaluated well in advance of final planning, and the financing of the project has been based chiefly thereon.

A host of secondary problems have arisen in connection with reservoir projects, some of which may have been included in the foregoing evaluation but most of which probably have not. Representative of those which may have been included in the cost estimates are: charges for reservoir clearance; direct costs (such as new housing)

[a] Selections from a report on "Man-made lakes", prepared by Karl F. Lagler, FAO Consultant, and published by the Food and Agriculture Organization of the United Nations. All illustrations and much of the text have been deleted, and the interested reader is referred to the full text for the details. The section on public health has been omitted in its entirety because of its duplication with the present report.

associated with resettlement of displaced people; reimbursement for loss of valuable buildings and of land, forest and mineral resources due to flooding; and other direct costs that can be evaluated easily.

On the benefit side, attempts have occasionally been made to evaluate an expected increase in fishery outputs and to a less extent the possible earnings from increased tourism and recreation.

Often the few extra benefits and costs noted have not been adequately evaluated, leaving serious gaps in the over-all economic appraisal of the project. In addition, a large number of secondary problems, which are extremely difficult to quantify in terms of benefits and costs, have been overlooked or ignored. These problems include:

Over-all economic impact of the project on the region or the country;

Establishment of adequate land and water use priorities and planning through the affected basin;

Effect of resettlement on the human resources of the region or the country;

Effect of the changed enviornment on health and productivity of both man and his domestic animals, including new threats to health through the inadvertent improvement of habitats for certain diseases and aquatic vectors;

Effect on fish and wildlife resources of the new environment created by the dam;

Neglect of opportunities for improved agricultural practices, especially on seasonally inundated and exposed foreshores;

Effect of the changed environment on growth of noxious plants, especially water weeds;

Possibility that the new lake may cause earthquakes.

Secondary problems such as the foregoing are admittedly difficult to quantify, but methods are becoming available for their study. These methods are continually being improved through research and experience on existing projects.

Anticipation is the first key to the solution of the secondary problems that may arise when reservoirs are built. The second key is the timely engagement of the requisite multidisciplinary expertise at the earliest pos-

sible stage of planning, the careful co-ordination of expert findings, and, as a result, the inclusion in the cost benefit analysis of other factors in addition to those normally included in such analyses. Dam engineering with all its complexities, is a much more straightforward operation than the solution of all the ancillary social, economic and ecological problems that arise before, during and after the dam is built and fills the reservoir with water.

In spite of obvious interrelationships, the studies required to solve the secondary problems of reservoir development can be grouped conveniently by subject-matter categories:

Economic studies in the broadest sense, including multi-resource use on a regional or national basis;
Studies of sociological problems;
Studies related to land use, including land-use planning, along with agriculture, livestock and forestry production opportunities and problems;
Studies related to the aquatic environment, including fishery development, ground-water use and recharge, and water quality control;
Studies in the broad field of public health in all its aspects;
Investigations into the special problems related to aquatic nuisance plants

ECONOMIC AND SOCIAL PROBLEMS

The creation of a man-made lake has a profound effect on the way of life of local residents, particularly farmers, fishermen and traders. Human problems are no less important than engineering and economic problems, and must be investigated and solved if a productive community is to be established. Drastic changes in environment provide opportunities to alter and improve ways of life—including long-established traditions in fishing, agriculture and other forms of livelihood—as well as to improve community institutional and service structures.

However, changes in agricultural and fishery practices cannot be rushed. Nomadic habits, a subsistence economy, and such customs as shifting cultivation and casual fishing must give way to settled agriculture, systematic fishing and a cash economy. The people of the area need

guidance from experienced advisers supported by government policies and services. Particular attention should be paid to the provision of services and institutions for the communities affected.

It follows that, when man-made lakes are to be created, land tenure and sociological studies as well as the teaching of other forms of livelihood must be initiated as soon as the siting of the project is determined.

Settlement, resettlement and related considerations

Among the most pressing and potentially costly of the secondary aspects of reservoir development are those which concern the people who must be evacuated from areas to be flooded and who must subsequently be resettled. Also present, however, may be problems of settling a new population in the foreshore areas and of transferring people into the region to maximize the benefits to be derived from the new resource potential.

The problems of resettlement are much wider than the merely mechanical or logistic aspects. Not only are the technical and economic requirements of new or altered enterprises involved but the human resource—both the individual and the community—must also be helped to become adapted usefully to the new physical, social and economic environment. In resettlement, human adaptation is a particularly complex process of individual and institutional adjustments demanding time, effort, resources (physical, financial, social and technological), and considerable support and assistance. The requirements for such assistance cannot be guessed at any more precisely than can engineering specifications for a dam or irrigation works.

Systematic background investigations are needed of the rural society to be affected by the creation of a lake, along with an objective appraisal of the extent of the human resource development required by the technical and economic change foreseen. Also required are specifications for the type and timing of supporting facilities needed, the maintenance of social controls, the development of leadership, new local organizations, patterns for administrative relationships with and within the new communities and provision for succeeding generations.

Evacuation

Where a reservoir is to be constructed, the entire population and its possessions must be moved from the area to be inundated, preferably timed to avoid loss of a season's agricultural crop Such a removal is usually fraught with many stresses, and it requires resettlement into new areas that are either uninhabited or already occupied. The arrival of the transplanted people on their host community raises a different set of problems than those encountered when unoccupied areas are settled.

Population transfer

Where the man-made lake provides resources for development in excess of the manpower of the relocated and host populations, it may be advantageous to bring in additional people to make full use of the new resource potential. Such action has direct economic and social implications for the reservoir area as well as for the areas from which the population will be drawn.

Food and health

It may be necessary to supply food on an exceptional scale until a resettled or transferred population has re-established its productive capacity, and to provide supplementary health control measures for man and livestock where they are moved to a different environment. Food aid in such instances has been provided by the World Food Programme, and other forms of help (farming tools, fish nets etc.) have been granted by the FAO Freedom from Hunger Campaign.

Some of the most serious health effects may be mental, resulting from people being uprooted from a familiar environment around which their way of life was organized. This environment was not merely of relevance in a physical sense but also had an important social and psychological meaning. When people have to be resettled into a markedly different physical and social environment in combination with the economic and technical changes required, social conflicts and tensions may result, leading for example, to the exploitation of the weak by the strong. Serious psychological stresses and social tensions can result unless adequate and appropriate provision is made for the adjustment of the set-

tlers. The new environment acquires personal significance for the settlers through their participation in such activities as the selection of home sites, the planning and construction of housing and other facilities, and in the formation of community organizations.

Settlement area

Potential areas for irrigation around a man-made lake are usually limited by physical factors, such as the contour of the land. Whether for irrigation or for dry-land farming, however, investigations must be made to determine the most suitable areas for irrigation or other development and of the methods to be used.

Public works and housing

Resettlement may entail new buildings for housing, schools, community and health centres, recreation and public offices (police, administration), along with storage, primary processing and market facilities, roads and other transport facilities, domestic water supplies, and waste removal and sanitary installations. Depending on the circumstances, it may be possible to compare the economic implications of the choices for resettlement in large villages or towns, small villages or individual farms.

Although the task of clearing land for dwellings, cultivation and recreational activities may be undertaken to a varying extent by the farmers themselves, costs are inevitably entailed that are logically chargeable to reservoir construction. The expenditure for such work is often relatively high and may continue for several years. Experience gained from earlier projects is of help in discovering the most economical system. For example, the incentive to clear land provided to individuals through food aid, perhaps with the help of the World Food Programme, may be more effective than cash advances.

Rural structure

The construction of a man-made lake often offers a convenient opportunity for the introduction of badly needed economic and social structures. Such structures may involve the system of land tenure, individual or communal ownership, co-operatives, credit institutions or a redistribution of land to form economic farm units,

all of which may not only directly affect human relationships but also have a major influence on the economy. Faulty social and agrarian patterns can stultify progress; in contrast, well-adapted patterns can greatly help economic development. Socio-economic studies are required to determine the feasibility of a project and its likely rate of implementation by the local community.

Management assistance and related activities

One of the most effective forms of assistance for new settlers around man-made lakes is to provide guidance that will maximize production and earnings from fisheries or from foreshore agriculture per unit of area, investment or labour. As a result, for many, their resettlement would not only be to a new and hopefully more acceptable habitat but also to higher production levels and to improved standards of living. Both farm and fishery management assistance include plans for technically and economically valid enterprise structures, taking into consideration existing obstacles—whether technical institutional social, economic or financial—to improved production. Such assistance should also show how to overcome existing shortcomings at the local, regional or national level with a view to facilitating settlement.

Management assistance at farm or fishery unit level is particularly valuable in the early stages of a lake project, as, for example, where lake fishing or irrigation is new to a country or region, and where there is little knowledge either among the fishermen, farmers or the extension staff as to how to operate under the new conditions. Research, advisory and training services can be costly, and it may take a long time before fishing and farming can be brought to reasonable efficiency. Obviously, the opportunities, needs and costs for improvement in farming and fishing techniques must be recognized and planned well in advance of construction operations.

Credit

In developing countries most schemes for resettlement, including the improvement of fishing or farming, require a progressive approach, probably including more credit on better terms than was formerly available. In particular, where farmers are compelled to move

because of the submergence of their lands, exceptionally generous credit measures may be justified and, if so, this would have to be taken into account in the economic appraisal of the project. The same is true for fishermen in their shift from river to lake fisheries, which usually requires investment in different gear and boats.

Marketing products and developing co-operatives

Evaluation of production potential, including agriculture, fisheries, electricity and industry, encompasses marketing, both as to internal and external demand, and method. Market prospects have a determining influence on the pattern of investment to be recommended. With irrigation schemes involving heavy investment in terms of costs per hectare to be irrigated, it may be expedient to concentrate on the production and sale of high-value commodities to justify the costs; this may require creation of an internal market able to absorb increased quantities of the new product. Equal care has to be taken in selecting a specific crop for export by making sure that it is not already in over-production in the world. One way of promoting specific cropping patterns and of helping small fishermen or foreshore farmers to ensure advantageous disposal of their products may be to create marketing co-operatives which guarantee to take end products at predetermined minimum price levels. Assistance is required for the establishment and management of such co-operatives. Production co-operatives may also be needed for the supply of essential inputs, including seed, fertilizer and machinery for farmers, and nets, boats and motors for fishermen.

Clearing the bottom of the proposed lake

A decision as to whether or not to clear trees and brush from the area which will form the bottom of the lake for navigational, public health or fishery reasons involves cost-benefit assessments and should be a part of the earliest planning for a reservoir. Experience at both Lake Volta (no clearing) and Lakes Kariba and Kainji (partial clearing) affords examples of the economic and practical consequences of different treatments of the lake floor. If clearing is to be done, it is necessary to determine purposes, areas, costs, timing and value of reclaimable timber, as well as methods of clearance and

of disposal of the useless remains of trees and brush.

AGRICULTURE AND LIVESTOCK PRODUCTION

Foreshore agriculture and livestock production

The alternately exposed and inundated shores of large man-made lakes have opportunities of unusual promise for the cultivation of short-term crops and as managed forage areas for livestock. The uses to be assigned will depend on topography and soil type as well as on crop suitability determined by previous experiments. Topography and soil type are particularly significant features for estimating potential production, among other things because of the relation of slope and soil composition to water retention during the seasonal drawdowns of the reservoir.

Early planning stages of reservoirs may advantageously incorporate analyses to disclose the qualities of potential drawdown areas, perhaps by aerial photography and photogrammetry coupled with representative soil studies on different degrees of slope. Sometimes crop experiments can be started on suitable sites in advance of initial flooding; often there will be available considerable local experience on short-term crops derived from the flood plain agriculture of the river to be drowned by the reservoir. The creation of a new foreshore habitat for agriculture can offer a good opportunity for the introduction of high-yielding crop strains.

Livestock production in the foreshore areas may be helped by the availability of aquatic plants which can be harvested from the water and useful from the standpoint of public health and recreational convenience, as it may help to control the nuisance caused by overgrowth of aquatic plants. However, there is only a limited amount of information currently available concerning the practicability and the value of using the aquatic plants for animal feed.

Where land slopes gently away from a river course that will be flooded by an impoundment, vast reaches of shallow water may develop. A disadvantage of shallow-water zones is their tendency to increase the area of inundated land which becomes covered with an aquatic or swamp-type vegetation. In such areas, vectors of livestock diseases, in particular the snail vectors of liver

fluke, can undergo an explosive expansion in population. Such vector hazards can be identified by early study of the topography of the land that may be flooded and the distribution of vectors and diseases of the river system.

There may also be a tendency to overgraze around new areas of standing water, especially where no other sources of water are readily available for livestock. The situation can be alleviated by controlling the access of livestock to the water; however, in many circumstances this method is uneconomic.

A build-up in livestock population can also cause pollution of the water resource, and this may be important when water is required for drinking purposes, either by the animals or by man.

Finally, mention may be made of the possibility of increasing animal-protein feed as a by-product of developing the fishing industry in a new man-made lake. This may be commercially significant only where the supply of fish offal or trash fish or both is substantial.

Irrigation from lateral dams

Not infrequently, a man-made lake must be protected from excessive siltation and loss of holding capacity by the construction of auxiliary lateral dams or control structures in tributaries known to carry heavy silt loads. In some instances it may be feasible to construct flood or controlled irrigation schemes in a nearby area, but at a lower level than such lateral dams. By this means, the silt may be spread beneficially over potential croplands and increase fertility instead of being harmfully deposited in the lake. The water stored by lateral dams may also be useful due to the drawdown of water in the main lake. Aquacultural use of water in or from auxiliary impoundments is also possible, sometimes jointly with agricultural use, as in rice-paddy fish culture which simultaneously produces crops of rice and fish.

Pumped irrigation

By pumping from a man-land lake, it may be possible to bring under irrigation considerable bordering areas. Such areas could include foreshores that are seasonally exposed by the drawdown of the reservoir, or adjacent land at higher elevations. A careful cost/benefit analysis should precede any large investment in pumps and con-

duits. Pumping installations might be from floating rafts or at the land end of canals or tunnels originating in the lake. Clearly, it would be necessary to investigate whether it would be more beneficial to use water for irrigation above or below the main dam; still further consideration would be necessary for schemes with a hydroelectric component. Should extraction from the reservoir for irrigation be large, it might affect the design of the dam and, in particular that of the spillway. Economic appraisal at an early stage of planning would be needed to evaluate all aspects of pumped irrigation, especially in the relationships to the over-all secondary uses to which the water might be put and to its effect on public health.

Reduction of inundation zone and use of gravity irrigation

Where the edges of a man-made lake are likely to spread in shallow sheets of water over wide areas of a gently sloping plain, the amount of inundation may be advantageously reduced and controlled by the construction of dikes or bunds. In addition to protecting the lands shoreward of dikes from unwelcome inundation, there will also be a decrease in evaporation loss from the surface of the lake. Keeping the reservoir from spreading into shallow areas may also be of benefit to public health and help to control the spread of aquatic plants. The possible elimination of needed fish-spawning or nursery grounds must, however, also be considered. In favorable circumstances polders may be created below the highest level of the lake, and these may be irrigated by gravity; drainage problems might arise but could be alleviated, as the low-level stage of the lake should be well below the base of such polders.

Drainage of swamps

Where swamps will be unavoidably created by the construction of a man-made lake, such areas can often be identified in advance. Swamps may originate from inadvertent damming of ground water or flooding with surface water. Whatever their origin, they may induce undesirably high evapotranspiration losses. But, with care, steps can be taken in advance for the control of such swamps.

Prior evaluation of swamp drainage for land reclamation will require a multidisciplinary approach. The land

may be valuable for agriculture and livestock; and drainage may benefit public health by destroying the habitat for aquatic disease vectors, such as malaria mosquitoes and schistosomiasis snails. There may, however, be overriding values against drainage, such as reduction of the ground-water level, destruction of fish and wildlife habitat, elimination of subsistence and tourist fishing and hunting grounds, and unfavorable desiccation of forest sites.

FORESTRY AND FOREST PRODUCT INDUSTRIES

The opportunities and problems involved in deriving benefits from, or providing benefits for, forestry have been almost consistently overlooked when man-made lakes have been planned. If forestry is considered at all, it is generally in relation to its effects on the efficiency of the water storage and distribution system. Nevertheless, the over-all relationship should be regarded from two points of view—the effect of forestry on the lake and the effect of the lake on forestry.

Effect of forestry on a man-made lake

Forests have both a protective and a productive function in their environment. In their protective role, they may influence the changes in the environmental conditions brought about by a large impoundment, particularly through the soil and water conservation functions of forest establishment and management. The productive aspect is generally complementary to this and can improve not only the over-all economics of a project but also adjust land-use balances within the local economy covered by it.

Upstream catchment zone

In contrast to artificial plantations composed mainly of single species, existing indigenous forests commonly form more stable ecological communities and may therefore be more effective in protecting unstable catchment soils. However, under appropriate management, both types of forest can form an effective catchment cover. Generally the forest can also perform a significant economic role by providing immediate cash returns, employment for local or resettled communities, and material required for domestic use and for construction.

If existing forests on the up-stream catchment are to be utilized for wood production, the manner in which logging and road construction is carried out can have important effects on both stream-flow and water quality. If adequate regeneration is slow, operations involving large-scale clearing or burning can be followed by increased flood peaks and sediment loads. The extensive use of insecticides and herbicides in forestry, as in agriculture, can have serious repercussions down-stream. If, however, the possible dangers are realized, adequate precautions can be taken to permit economical forest exploitation without down-stream damage.

Afforestation or reforestation can often provide the means for the rehabilitation of large bare areas in up-stream catchments resulting either from natural causes or from mismanagement, such as overgrazing. The reduction of soil erosion and the improved infiltration and water retention capacity of forest soils, combined with the eventual provision of commercial wood crops, can both directly and indirectly raise the general level of catchment protection. Again, protection-oriented management systems will need to be applied in the harvesting of the wood crop, so that the primary objective of the afforestation programme is not impaired.

In areas of unstable soil, where flash floods occur, streambanks are a major source of erosion sediment. Afforestation or the improvement of existing forest stands adjacent to watercourses can often be combined with engineering works to provide successful stabilization measures.

In addition to the direct effect on the lake itself, afforestation or the reservation of existing forest stands may provide village woodlots as local sources of fuel and construction wood. The planting of trees for shade and recreational shelter in new town sites can also be considered an important function of forestry in the man-made lake environemt.

Shoreline zone

Forests can be managed or established so as to provide very effective filter strips between the high-water level of the lake and the remainder of the catchment. In this way it is possible to insulate to some degree the reservoir itself from the worst effects of such factors as overgrazing,

high human population density, and substrate movement, and thus to improve lake shore stability. Where a shoreline is in an extremely arid area, the establishment of such shelter belts may be difficult, but irrigation water pumped from the lake may overcome the difficulty.

Trees transpire large amounts of water owing to their extensive root systems and their dark foliage which may absorb greater amounts of solar energy than the light-coloured surfaces. Whereas this comparatively high transpiration rate varies with the local climate, a forest is likely to remove more moisture from the soil than a less tall form of cover, such as grass. Thus, where drainage is important, tree planting may be advantageous, but where soil moisture must be conserved, a less dense, shallow-rooted plant cover may be required. Of course, the protective function of forest cover must always be weighed against its water-using function, and may frequently be of overriding importance.

Effects of a man-made lake on forestry

The effects of the creation of a man-made lake on forestry are either direct and physical or indirect. Direct effects are represented by changes in the water table, including the drowning of trees, and possibilities for irrigated forest production. Indirect effects include improved transportation and labour resources which can make economically possible the afforestation of an area otherwise too inaccessible or lacking available manpower.

One of the first results of constructing reservoirs is that trees must often be drowned. Riverine forests which are casualties during the filling of new reservoirs sometimes contain valuable timber, such as species of Khaya in Africa. Early planning can lead to the salvage of such merchantable timber prior to flooding, with possible related benefits to navigation, public health, fisheries and aquatic weed control.

Up-stream

In the up-stream catchment, the direct effects of the lake on forestry are likely to be insignificant, but the indirect effects may be quite considerable. Of particular importance could be:

Bringing inaccessable areas within range for commercial utilization through improved communication;

Lowering timber transportation costs by floating or rafting;

Extending the supply zone for large-scale wood-using industries.

The availability of low-cost hydroelectric power and large quantities of water may also assist in the development forest and wood product industries which may otherwise be impossible, even though the forest resource is large.

Around the lake

Following impoundment, the altered ground-water pattern in the vicinity of the shoreline may simplify the establishment of plantations or the management of existing forests. However, some problems will inevitably be associated with the fluctuating level of the lake and hence of the water table. Within a middle strip around the lake conditions may be ideal for tree growth, whereas near to the lake the soil may be too wet, and farther away it may be too dry. If the soil moisture in the middle strip changes drastically with changes in the lake level, finding a suitably tolerant tree species may be impossible. If the fluctuation in lake level can be minimized, forest production can be greatly improved. Most trees that tolerate periodic flooding are less tolerant of stagnant than of flowing water, and for this reason a reservoir margin may be a less suitable site for indigenous species than the former river margin.

When establishing forest plantations, either for the benefit of the man-made lake system itself or to exploit the environmental changes brought about by the lake, the introduction of species new to the area will certainly be considered. It is essential that large-scale planting should be preceded by small-scale trials of species or varieties. In attempting to make the right choice of species for planting, an ounce of local experience is worth a pound of expertise under different ecological conditions. But a grain of properly controlled experimentation is usually better than either. Careful soil survey and differentiation of the assorted sites available for planting should go hand in hand with species trials. The creation of a man-made lake is therefore not likely to be followed in a short time by a large-scale change in species composition of forests in the area.

INDUSTRIAL AND SUBSISTENCE FISHERIES

The potential fisheries of a new man-made lake are of three kinds: industrial (commercial), subsistence and recreational. Together they constitute one of the earliest and most easily gained returns from a man-made lake. The first two are considered here; recreational or sport fishing will be taken up under the heading of tourism. There is no problem of conflict among these three types of fishing in large man-made lakes that is without solution if adequately studied. For example, although it has sometime been alleged that the quality of sport fishing may be adversely affected by commercial fishing, under proper management systems the two types can be complementary and can greatly increase the net economic benefit derived from the fishery resource.

As with most other secondary aspects of reservoir construction, the disciplines of fisheries and related hydrobiology should be represented at the earliest stages of planning. Fishery expertise will be required to evaluate the effect of the engineering works and the proposed land and water uses (especially the projected water régimes) on the living aquatic resources and to avoid costly losses of aquatic production.

Fairly lengthy pre-impoundment research and study are required to make predictions of future fishery potential for economic assessment and planning. The components of such investigations are:

Species composition and relative abundance of stocks of the riverine fish population, both down-stream and up-stream from the proposed dam site;

Soil types and their extent and distribution in the basin, especially in relation to the spawning grounds;

Location and characteristics of tributary streams, including character and amount of silt load;

Areas and rate of siltation;

Extent and volume of water available for fish production, including water-level régime and flushing rate;

Nutrient impact from run-off and tributaries;

Thermal and chemical stratification probabilities;

Current and historic yields by species in the riverine fishery.

Combining this local information with experience recorded elsewhere, including testing the validity of

similar estimates of production, will enable a fishery scientist to make predictions of future fishery yields. Alternative predictions based on alternative forms of engineering work will assist in making the best decisions as to the location and design of the dam. Design features that might be affected would include:

Vertical location of draw-off structures, such as penstock (sluice gate) openings;

Need for, and character of fish passes or devises for controlling the movement of fish;

Best water régimes for the fishery component of an economically optimized multiple water use scheme.

Early predictions regarding the aquatic resources that may bear on engineering works and on land and water-use planning are many. Detailed discussion follows on some of the most important of these.

Planning for optimal development

The fishery of a new reservoir can develop fortuitously or it can be developed on the basis of an orderly economic and scientifically conceived programme. If the development is allowed to be haphazard, net yield is likely to be far below the maximum sustainable, and overexploitation of at least some key stocks is likely to take place. Furthermore, fishermen are likely to become entrenched in inefficient methods of fishing and catch disposal from which it may be extremely difficult to disengage them.

If, prior to impoundment, valid predictions are made as to the character and natural development of the fish stocks, and if the optimal manpower and investment schedule in different kinds of fishing is carefully planned, along with an adequate scheme for disposal of the catch for goods or cash, then an orderly development may result. As part of this development, a system of catch statistics to give yield and value by species in relation to fishing cost and effort must be instituted as the primary indicator of the adequacy of the plan of fishery development. These statistics are also the basis for early identification of overfishing or underfishing of species stocks, and are therefore a first key to rational management of the resource.

It often becomes evident early in the planning of fishery development programmes that the fishermen

themselves are in need of education and re-equipment. A vigorous fishery extension programme can meet this need but, to be successful, it should go into operation at a very early stage of planning so as to offset the shock caused by the sudden appearance of a new man-made lake.

Additional planning for optimal fishery development will include:

Appraisal of relevant aids to navigation and marine safety requirements;

Provision of systems for landing, handling, storing, processing, transporting and marketing the aquatic produce, possibly through fishermen's co-operatives;

Organization of a fishery trade school;

Development of an advisory system on the investment of venture capital in the fishery;

Financing as required, by means of bank loans, of both the fishermen and the fishing industry. Supporting services that may need to be developed include the supply of fishing gear, boats and ancillary goods and repairs.

The whole plan for the orderly development of the fishery resource depends on early and vigorous interaction for planning among fishery scientists and technologists, resource economists and engineers.

Changes in fish fauna from river to reservoir

In an impoundment made by damming a river, its natural stocks of fishes result from the stocks previously present in that river. Although it is possible to alter the composition of the species stocks later, the initial fishery is most often dependent on natural stocks; only rarely have fish been eliminated from a river system by the use of poisons prior to damming and an effort made to establish from the outset, by intentional stocking, a fish population of the desired species composition.

Assuming a mixed species population in a river before impoundment, can the contributions of these species to the reservoir population be predicted? The answer is yes, to a limited but continually improving degree of accuracy. The better the knowledge of the ecological requirements of the species, the more accurate can be the prediction. Especially important components of this knowledge, for prediction purposes, are reproductive requirements—for example, the character of spawning

grounds and the means for access to them, food and feeding habits, and temperature, oxygen and current requirements.

In a riverine fish population one may expect a range of species requirements extending from quiet water to moving water. Thus some species will inevitably be encouraged by impoundment and others discouraged. Similarly, riverine populations are often low in predominantly plankton-feeding fishes while in a lacustrine situation there is often a very substantial population of plankton feeders. This fact reflects the prevalent difference in available microscopic plant and animal life (plankters) in the two habitats, and represents a direction of ecological change that comes with impoundment—change that can be very significant for fish production. In a reservoir made by damming a river, therefore, not all of the newly created habitats may be fully utilized by the expanding populations of native riverine fishes. For example, in Lake Kariba, Zambia, the open water was little used and led to the experimental introduction of a small freshwater herring, *Linothrissa miodon*, from Lake Tanganyika. Such introductions, of course, may be dramatically successful or catastrophic for the over-all fishery. They must be preceded by intensive research.

Throughout its depth, temperature of even a large river is quite uniform although unstable, since it fluctuates with daily changes in air temperature. Upon impoundment, the temperature, except in headwater and surface zones, becomes relatively stabilized and in the depths may change greatly only with the seasons. The change from riverine thermal conditions to those of the impoundment will affect both the abundance and the distribution of the various fish species differenetly, sometimes predictably.

In flowing river water there is normally saturation of dissolved oxygen from surface to bottom, However, at least seasonally in many impoundments, this gas may be in saturated solution only in the surface waters and be so deficient in stagnated depths that fish cannot survive there. Where this occurs, that section of the impoundment must be discounted, at least seasonally, for fish production. Such an adverse effect may be compounded by the development of hydrogen sulphide from organic decomposition in stagnated depths. This gas is injurious

to aquatic life and its presence in water can also cause damage to hydroelectric turbines. Since adverse chemical stratification is associated with thermal stratification, it can be partially overcome by the positioning of the water outlets in the dam.

Possibilities for improvement during construction

Advantageous opportunities exist for the improvement of fish habitat and of fishing grounds prior to the first flooding of a man-made lake. Part of the advantage is that some of these improvements can be made only with difficulty or not at all once the reservoir is permanently filled. Only seasonally exposed areas can easily be altered once the reservoir fills. This means that fishery experts should study the possibilities of fish habitat improvement at the earliest planning and feasibility assessment stages of proposed man-made lakes.

Illustrative of habitat improvement procedures that may be evaluated for applicability is the installation of spawning grounds for preferred species. The application of this procedure requires prior knowledge of substrate spawning requirements and of the greatest extent and depth distribution under water of the suitable substrate. Where it is lacking at the proper depths, desired substrate may be exposed by stripping off an overlay of topsoil.

Devices that concentrate fish for capture, such as piles of native brush, may be anchored on barren lake bottoms. Their location may be marked with buoys that will rise with the flooding water to guide fishermen to the sites and aid navigation among them. Such devices may be particularly useful where desert grounds are flooded, and also valuable for concentrating fish near centres where people are likely to be concentrated and desirous of subsistence or recreational fishing.

The improvement of fishing grounds has often taken the form of the removal of obstructions which would limit the efficient operation of likely types of fishing gear. A common means of such improvement has been to remove trees and brush prior to initial flooding in areas of permanent inundation. This derives from the strong resistance to deterioration of wood permanently submerged in fresh water. Loss and damage to gear such as gill nets, long lines and trawls can certainly be reduced by clearing. Nevertheless, clearing also means that

sheltering cover and foraging grounds for fish are removed. Because of these conflicting concerns, clearing proposals require early and individual evaluation for each new impoundment.

Evaluation must also include recognition that transportation and public health needs are to be taken into consideration at this time.

Dams as physical barriers to fish movement

A river system plays a vital role in the life cycle of migratory species of fish — it is a route up or down which spawners reach their spawning grounds, and fish in their young life history stages reach their feeding grounds. For such species an abstruction like a simple dam can spell doom. For, not only may the dam prevent migration up-stream, but fish migrating down-stream may not survive the effects of passage through the turbines, or, if led into irrigation ditches, they may be stranded and die.

If a fishery scientist is called in to advise early enough in the planning and feasibility studies on a dam, some unwanted direct effects of the dam as a barrier may be overcome, often at surprisingly low additional cost. In such instances the fishery expert may determine the need, feasibility and characteristics of appropriate fish-passing devices and fish-guidance structures. Thus, in carefully planned and executed dam systems, uneconomic barriers to migratory fish stocks may be minimized if not contempletely overcome.

Among the means of passing fish in both directions over dams and for related guidance systems that may be combined into sound economic investments are: fishways; fishlocks; fish lifts or elevators; systems of trapping at the dam and transport around it; guidance devices for fish to entry of fish passes and traps, or away from danger points such as inlets to irrigation ditches or penstocks.

The success of any such installation depends on the extent of knowledge of the physiology and behaviour of the species concerned. Often it will be necessary to undertake original and detailed field and laboratory studies, including experiments with models of proposed fish-passing or fish-quidance structures. From this point of view alone it is therefore of extreme importance that

fishery experts be involved in the earliest stages of planning for dams across rivers.

Effects of altered water régime

Dams alter water flow characteristics down-stream and thus may affect aquatic stocks in many different ways including water velocity and volume of discharge, water chemistry, temperature and turbidity, and the stream's ability to purify its waters. There may also be alterations in the amount of living space for fish, including the extent of spawning, nursery and feeding grounds. In the estuarine tidal zone, a chemical change of potentially vast significance may be effected in salinity, probably in the form of an over-all net increase due to reduction of stream discharge. Any reduction in the net annual discharge also lowers the capacity of a stream for self-purification, especially as regards reduction in capacity for oxidation of transported organic material and reduction in the beneficial effects of flushing.

These effects and changes obviously include elements of danger vis-à-vis the maintenance of aquatic production. For example, reduction in living space means decreased production and the increased vulnerability of fish to predators and fishermen. Wide and sudden fluctuations in daily discharges through dams also reduce potential for aquatic production and place stress on indigenous species stocks. In extreme situations, the down-stream watercourse is alternately wet and dry each day and aquatic production is terminated. A further example occurs when oxygenless water or water laden with noxious substances passing through a dam may eliminate the desired aquatic productivity for some distance down-stream. As a specific example of such changes, by 1967 it had already been noted that adverse effects of the still uncompleted high dam on the River Nile near Aswan were manifest in the estuarine fisheries of the delta and were even detectable in the eastern Mediterranean.

Many potential adverse effects of altered water flow can be offset by careful planning. This planning calls for interaction between engineers and fishery scientists, with the result that any planned flow regulation may involve little or no compromise of the primary objective in creating the reservoir and may add significantly to the economic soundness of the whole scheme by eliminating

any loss in fishery potential.

Effects of flooding and siltation

A common feature of man-made lakes is that historic spawning grounds for certain fishes are drowned. These grounds may be the riffles of streams, or quiet, backwater areas of specific depth, bottom and cover types that took a long time to evolve. In either instance the effects may be very damaging to certain species, since successful reproduction is of first importance to ultimate yield in a fishery. To a limited degree, the effects of such drowning are identifiable; countermeasures may be justifiable for key species and may be accomplished at least in part by habitat alteration prior to first flooding. Such habitat improvement may take the form of moving earth to provide alternative spawning grounds as the reservoir rises initially and subsequently rises and falls. Water level control during spawning season can offset the drowning of spawning grounds and alleviate the possibly even worse effect of the alternate drowning and stranding of nest sites. This is particularly important for such fishes as basses and sunfishes of the family *Centarchidae*, of various species of tilapia, and of many kinds of catfish.

Equally damaging can be the smothering of spawning ground or nests by deposits of silt, where the main stream and tributaries enter impoundments and also in waters adjacent to agricultural land or along windward shores where there is ersosion by wave cutting. In order to guard against the potential threat of siltation to acquatic production, early and integrated planning is required of engineers, agriculturists, fishery scientists and soil conservationists.

Harmful introduction of exotic species

Sometimes the elevation of water levels or the construction of canals to cross natural drainage divides may result in the unwanted spread of certain acquatic plants and animals into areas not native to them. The outcome of such incidental introductions can be so serious that fishery, plant protection and public health scientists should be involved early in any such engineering planning. Intentional introduction of exotic aquatic plants, fishes and other animals should be undertaken only after extensive research.

Possibilities for aquaculture

The construction of a reservoir for water supply is the classical prelude to the development of a fish cultural enterprise down-stream from the dam. Early planning considerations for man-made lakes may advantageously include aquaculture in the over-all scheme for water use. One of the economic attractions of aquaculture is that it is essentially a nonconsumptive use of water in contrast to irrigation agriculture which is very highly consumptive. Further more, per unit of land, aquacultural yields can under some circumstances far exceed those from agricultural production in terms of economic and protein returns.

A wide variety of plants and animals may be propagated in small ponds supplied with reservoir water; the variety is so great that market preferences can usually be readily supplied. Such plants include several kinds of water cress, water lettuce and water chestnut. Among the animals, most popular and productive are different species of fish; shrimp along with other crustaceans and shellfish; frogs, crocodiles and turtles are also among the prime potential of aquacultural produce. In some circumstances fish can be cultivated simultaneouly with rice, the fish being a bonus crop and the rice yield being increased substantially by the presence of the fish. Some irrigation canals are readily adaptable to fish or aquatic plant propagation.

Although ponds or channels that can be supplied by gravity from a reservoir may be best for aquacultural purposes, the practicability of developing locally intensive forms of aquaculture within the arms of the reservoir basin or on its banks should not be overlooked at the planning stage. In some instances it may be feasible to lift water from the reservoir to supply ponds located above the normal high-water levels.

Experience to date indicates there is little likelihood that ponds for fish culture in the vicinity of reservoirs can ever be justified for purposes of planting native fishes in the reservoir for stock maintenance purposes. If, however, it appears likely that planting an artificially reared fish of a preferred species may compensate for its loss of spawning grounds due to impoundment, a feasibility study may well be undertaken. The provision of cultural facilities for exotics desired for later

introduction should be considered during the planning stage, and also the possibility for establishing facilities for artificial rearing from which owners of small, sometimes domestic, ponds or rice paddies can secure the proper fish of the correct size for stocking their own water. Among the fish suggested to stock such water might even be Gambusia, for control of malaria mosquitoes.

WILDLIFE, RECREATION AND TOURISM

Man-made lakes, ecologically cataclysmic though they may be, often afford unusual opportunities for economic gain of wildlife resources and outdoor recreational facilities. Altering ecology as they do, and often isolating islands or long peninsulas, such new lakes also offer an opportunity for the conservation of open spaces and natural beauty, and the preservation of natural areas for study and enjoyment. In addition, forests within these areas may often be managed for multiple use including wildlife within conservation areas is sometimes desirable from a management point of view; at the same time, it provides an immediate economic return in meat and skins and ensures future returns from hunting, viewing and photographing wildlife.

Unless there is planning, feasibility analysis and implementation of proposed wildlife and recreation development at an early stage, economic losses may be incurred in the management and investment planning for wildlife, recreation and tourism for any man-made lake. To be noted in planning, the rescue of specimens of rare or valuable species of wildlife from drowning has not generally been justified from a strictly wildlife management point of view.

A programme for the conservation and development of wildlife resources in the vicinity of a new man-made lake might range widely from conservation planning for the immediate basin of the reservoir to the establishment of small natural reserves within the area, even on certain small islands that may come into being in the lake. Conservation planning for the entire basin may take the character of a watchdog operation to press for good conservation concepts in all the forms of land and water use--concepts that are often overlooked when early economic development alone is the prime moving force.

Aspects that should be taken into account at the planning stage for conservation are discussed in the following four paragraphs.

How, by planning, can different uses such as tourism, recreation and wildlife utilization be developed, co-ordinated and integrated with other aspects of the management of the new lake or the entire drainage basin of which the lake is a part? Planners should identify the existing resource and the potential for its development; in particular, national parks, game reserves and other game and forest managements areas that may be devoted to various recreational uses, such as camping, hunting for game and wildfowl, fishing, boating, swimming and water skiing.

Creation of a new lake will destroy some natural areas and create others, but early planning can ensure that maximum advantage is taken of opportunities to create new wildlife habitat in order to compensate for that which is lost; for example, auxiliary dikes may serve jointly for irrigation agriculture, aquaculture, and wildlife habitat maintenance.

Infrastructure for recreation and tourism development, such as tourist roads, harbours of refuge, marinas and tourist accommodation, should be constructed with over-all lake development in mind, and sited so as to preserve and take advantage of features of natural beauty.

The interpretation of natural areas and archaeological sites for visitors and the education of local residents in conservation are important parts of wildlife, tourism and recreation development programmes, and should be examined at an early stage in over-all planning.

All these considerations require the early formulation of policies for wildlife, recreation and tourism, the designation of an appropriate administration, and enactment of suitable legislation.

NAVIGATION AND WATER SAFETY

Although provision of cheap water transport often appears among the primary considerations in the construction of man-made lakes—as in those of the Tennessee Valley Authority (which is concerned with the Tennessee River drainage basin in the United States of America) or Lake Kainji on the River Niger in Nigeria

—aids to navigation and the codification and enforcement of water safety regulations are often considered of secondary importance. Early planning can help to overcome some of the problems.

For example, it may frequently be advisable to add to the costs of any projected man-made lake the expense to be incurred in removing dangerous obstructions to navigation. Included here might be:

Levelling of rocky outcrops;

Removal of trees, at least down to a safe level for navigation;

Preparation of hydrographic navigational maps and of radar charts for blind-weather travel;

Maintenance of information communication services on marine weather and lake elevation, and for use in distress;

Training and equipment of marine safety and rescue police services.

Transportation is inevitable on large man-made lakes whether or not it has been a primary purpose in construction. Consequently, feasibility studies of the whole project must include the costs of instituting and policing marine safety regulations and services. Earliest concern will often be over the lack of suitability of native riverine craft for use on a new area of water which may virtually be an inland sea. Special concern may well arise over water taxis and ferryboats. This should lead to the codification of regulations for design, capacity and requisite on-board safety equipment for all vessels, and to the establishment of rules of road and vessel-handling procedures. Enforcement will involve both the training of officers and the education of boat crews and the general public.

It may be wise to consider at an early stage the possibility of a watercraft licensing system before tragedies occur and unwise investments are made in faulty hulls with inadequate equipment. Licensing provides a means for vessel inspection and certification, and for offsetting the costs of these and other policing services. Some income from this source and taxation systems for cargo landings at major ports may support, at least in part, the costs of port and navigational aid maintenance.

Another cost to be anticipated is the provision of

docking facilities, not only for efficient loading and off-loading, but also to keep stevedores and passengers out of the water where waterborne diseases are present. Experience has shown that such facilities are likely to be needed at road-ends around the reservoir and that the need will exist as soon as the reservoir starts to fill. If ramp devices are to be a part of the dock facilities, it is easier to construct them before the reservoir fills for the first time, although their location may be best defined by the first high water.

WATER QUALITY CONTROL

Man has proved himself to be unusually adept at fouling the surface waters of the earth. Even such extensive water areas as the Great Lakes of North America, segments of the oceans, and the world's largest rivers now show damage from pollution. Early thinking and planning relative to man-made lakes should include consideration of the water quality through the enactment of appropriate legislation, monitoring and enforcement, if they do not already exist.

Included in the uses of water quality standards are erosion control to minimize turbidity and siltation as withholding from the water of nutrient materials that may have unwanted side effects. The inflow of nutrient materials can stimulate the growth of waterweeds, including algae; common sources of such nutrients are drainage from fertilized agricultural land, domestic sewage and certain industries such as food canneries or processing plants. Domestic sewage effluents are also hazardous to public health.

Pesticides can have dangerous side effects and early plans for regulating their use in the basin should be carefully formulated. The following are examples of pesticides that may be used in or around man-make lakes in many parts of the world: herbicides for the control of nuisance aquatic plants; Molluscicides for the control of snail hosts of bilharzia (schistosomiasis); insecticides for the control of the insect vector *(Simulium)* of river blindness (onchocerciasis), mosquito vectors of malaria, the tsetse fly vector of sleeping sickness in man and cattle, and for the control of agricultural and forest insect pests.

Fish poisons may also be involved owing to local

methods of fishing. All such chemicals and others, some of which may derive from industrial effluents, may have undersirable side effects on man or on the aquatic ecosystem; some can limit or destroy the capacity of water for fish production. The development of methods of direct government control of the use of toxicants in the reservoir ecoystem is therefore an important part of reservoir planning.

Early thinking on water quality control in new man-made lakes will find technical leadership in the fields of soil conservation, forestry, public health and fishery limnology.

AQUATIC NUISANCE PLANTS

By means of careful and early planning and action it is possible to avoid some of the hazards offered by aquatic plants to public health, fisheries and navigation in man-made lakes. Such lakes can be expected to provide good growing conditions for many kinds of plants, some valuable or relatively harmless, or both, others actively dangerous. If the problems posed by aquatic nuisance plants are to be avoided or, if necessary, solved, their early assessment is essential to preparation for a man-made lake.

Preliminary survey

Early planning or advice regarding a proposed man-made lake should include competent information on aquatic weeds. The first task would be to survey carefully the drainage area of the future lake for problem plants. If potentially dangerous plants are discovered in the upland drainage basis, but not in the future lake area itself, it may be possible to build barriers to arrest their spread into the future reservoir.

Quarantine

If the lake and its associated areas are free from certain dangerous plants which exist in nearby drainage basins or countries, then stringent quarantine precautions may be justified to reduce the risk of accidental or deliberate importation.

Measures to minimize risks from noxious plants

Removal of partially submerged trees

Where the crowns of many trees will extend above the

water to provide shelter and support for aquatic plant communities, the application of herbicides may be extremely difficult and even impracticable. Considerations regarding the clearance of the future reservoir bottom should include the effect of both aquatic plant establishment and its control.

Lake installations

Those planning installations for a new reservoir should consider the possibilities of heavy aquatic plant infestation. A dam with an open spillway, for example, may enable large quantities of plant material to be discharged easily from the lake in time of flood, as on the Rio Lempa in El Salvador. In contrast, a spillway overflowing into a tunnel may run the risk of being blocked, as on Lake Apanas in Nicaragua.

Swamps

Extensive shallow-water areas may not only be wasteful of water due to evapotranspiration but may also provide habitats favorable to aquatic weeds—areas which, because of size, may be expensive or impracticable to treat. Keeping the lake out of such areas and, as far as possible, into areas with steeply falling banks can help to control littoral weeds. Steep banks, furthermore, may augment turbulence during storms and so break up floating masses of weeds. However, shoals may be important for fishes as spawning, nursery or feeding grounds and need also to be evaluated on this basis as well as for their public health implications.

Planning to control aquatic plant invasion

Conventional spraying methods

If it has been determined that an invasion of troublesome plants can be expected in a reservoir, a control plan should be prepared and costed which, if considered feasible, could be implemented when needed.

The plan should include ecological control and, perhaps, chemical control. Provision should be made for spraying equipment (land, water and airborne) and for supplies of the necessary herbicides. Cadre crews for the control operation may have to be trained in the recognition of plants, in preparing and handling herbicides, and in the operation and maintenance of the herbicidal

distribution equipment.

An effective control plan would include a campaign of constant vigilance, continuing indefinitely, to attack any developing infestation at its earliest stage. Budgeting for a steady campaign to keep invading plants at a low level of infestation may prove to be wiser than waiting until the problem becomes overwhelming.

Biological control

The possibility of biological control—by habitat manipulation or by animals, fish, insects or diseases—is always attractive. Unfortunately, there are few examples of its successful operation. However, research into all methods of biological control is useful, and information on the latest possibilities should always be sought.

Losses caused by waterweeds

Evapotranspiration

Engineers frequently are unaware of the extent to which invading plants cause losses to stored water. If problem plants are present in quantity, local experiments to measure evapotranspiration would give an indication of the potential total water losses from these plants. The value of the lost water then becomes the basis for assessment of the costs of control.

Fish and fishing

Aquatic weeds compete with fish for living space. However, they also provide shelter and forage grounds, including an increased area for the production of food organisms. Sometimes the shelter they afford is so effective that some fishes become overcrowded and grow very slowly. Dense plant growths may interfere with fishing. Careful local evaluation is needed.

Utilization of aquatic plants

The question of whether or not aquatic plants can be utilized locally may be worthy of study. The most obvious use is as animal feed.

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