areas); general security measures; barriers (particularly at high-risk areas); warning notices; prohibition of water activities, including water sports; provision of appropriate access routes and emergency equipment; fencing; inspection and maintenance of control measures; and the provision of information, instruction, and training to higher-risk groups (such as children) (Water UK, 1999). In addition, ice breaking may be carried out around the edges of frozen water to dissuade people from walking on it; however, this poses a risk to those undertaking the ice breaking (RoSPA, 2003).

Working over, on, or near water

Working over, on, or near water presents a danger that people may slip, trip, or fall into water or be swept off their feet by water leading to injuries and the risk of drowning. As with all work activities, working over, on, or near water needs to be carried out in a safe and healthy manner adopting appropriate control measures to minimize risks and mitigate the effects of any incident. General controls that may need to be adopted when work is carried out over, on, or near water include provision of appropriate platforms and gangways; safety nets and safety harnesses; illumination; first aid equipment; personal protective equipment and clothing, including personal buoyancy equipment; suitable means of access to and egress from the location; and suitable rescue equipment and procedures. In addition, it may be necessary to ensure work sites are suitably tidy and carefully consider the current and anticipated weather conditions (Construction Health and Safety, 2002).

Habitat destruction

Many of the hazards described thus far can have a detrimental effect on habitats. Lakes and reservoirs are a large and diverse habit for flora and fauna. Pollution; silting; pathogens; drought; land use; flooding; security; public access; and working over, on, or near water can act to disrupt or even devastate habitats. Therefore, habitat destruction may arguably be a side effect of another hazard or combination of hazards.

Reservoir safety hazards

In addition to the hazards outlined above, reservoirs may present further hazards. Hazards associated with reservoirs are primarily associated with the structural integrity of the dam and associated infrastructure due to leakage, soil movement/slippage, water seepage, spoiling of pointing between stone blocks, and increased or unusual vegetation growth associated with the dam or embankment. Additional hazards include blockage of spillways, silting of overflows, inoperable sluice controls, burrows into soil embankments, and intrusion of vegetation into structures. With regard to occupational hazards other than those previously discussed, issues to consider include working at height and working with electricity generation and distribution infrastructures.

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Cross-references

Acidification in Lakes
Cyanobacteria (Blue-Green Algae)
Dam Failures: Impact on Reservoir Safety Legislation in Great Britain
Dams, Classification
Ice Covered Lakes
Lake Sediments
Mass Curve and Reservoir Design
Microorganisms in Lakes and Reservoirs
Nutrient Balance, Light, and Primary Production
Reservoir Sedimentation
Water Quality in Lakes and Reservoirs

HEALTH ASPECTS OF LAKES AND RESERVOIRS

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Definition

Health aspects of Lakes and Reservoirs can refer to all the ways in which the creation, existence, and use of reservoirs and other lakes can influence human health. This entry deals with the relation of lakes and reservoirs to communicable diseases chiefly, as chemical and physical hazards are largely separate while very indirect effects through changes in income or agricultural innovations made possible by irrigation would spread the material too thinly, although they do have substantial effects.

A *reservoir* is a man-made water impoundment where the water is used in a controlled way for specific human ends. Most reservoirs are created by placing a *dam* across a stream. In some countries, and especially for small impoundments, the term *dam* is applied to the reservoir as well as the retaining wall. In South Asia the term *tank* is also used.

By *communicable diseases* we mean *infectious* diseases, which can spread directly, or through water, from the patient to other people, plus *transmissible* diseases that have an insect vector or a water snail intermediate host between the stages in the human host.

Introduction

Lakes and reservoirs have a great influence on human health, both directly and indirectly, often for the good, but also frequently leading to illness and sometimes death. Communicable, noncommunicable, and traumatic harm may all be related to lakes, whether natural or man-made. The latter are of particular importance, since by varying the way in which reservoirs are made and operated it is possible to prevent or at any rate diminish many adverse effects on health.

The unhealthy effects of reservoirs are often primarily due to the uses to which the stored water is put. In particular, the use of water for irrigated agriculture is associated with infectious and parasitic diseases, especially in the tropics. In an irrigation scheme, large populations of workers are closely and repeatedly exposed to water contact. Diseases which occurred at the margin of reservoirs and lakes may be widespread across the whole of an irrigation scheme.

The majority of all the health hazards related to communicable disease around reservoirs and lakes are due to events taking place near the edge of the lake or in shallow areas. Reservoirs in general differ from most lakes in that they have a larger annual fluctuation of depth as the water level rises and falls under human control and in relation to various needs. Usually, the consequence is that the flow of water below the dam is more evenly distributed through the year than is the case with a natural lake overflowing. Health impacts of man-made lakes are due to both the process by which they are created and the ways in which they are subsequently operated. These are best considered separately, but it has to be remembered that resources for disease control and particularly for health care are much more readily available in the construction phase than thereafter, and the construction phase provides an opportunity to create a sound health care infrastructure which will persist for many years following the filling of the reservoir.

It is important when planning a reservoir to consider the whole catchment and the effects that its construction and operation will have upon the water throughout the catchment. Often the indirect effects of reservoir construction will be felt for a long way downstream. Where reservoir creation leads to upstream flooding of inhabited areas, adequate provision is critical for the displaced population. Historically, those people have fared very badly out of the creation of man-made lakes. Enough is known from earlier experience to avoid many of these problems, but usually there are still inadequate resources provided at the planning stage and consequently this difficult and complex operation is very detrimental to the displaced people.

Whenever a man-made lake is planned, it is essential at an early stage in the planning process to undertake a health opportunity assessment on a scale appropriate to the size of the project. Historically, such matters were not considered until relatively recently. Then the concept of an environmental impact assessment of water resources development was introduced and, mainly from evidence of schistosomiasis spread, this was developed into a health impact assessment. More recently it has been realized that not only should reservoir creation not lead to an increase in the local endemic diseases nor to outbreaks of epidemics, but also it provides an admirable opportunity to improve the health and health care facilities for the population who will be living around the lake.

This entry will focus particularly upon communicable diseases. In relation to lakes and reservoirs it is possible to classify communicable diseases by the biological nature of the causative agent, but it is more helpful to those outside the health sector to consider the different modes of transmission, because these point to the environmental modifications which can reduce transmission and which are usually the responsibility of those outside the health sector.

Water-related disease transmission

There are four main categories of transmission of water-related communicable diseases.

1. *Truly Waterborne Diseases*. These are infections where the causative organism is transmitted from one person to another by the water route. These are the concerns particularly of those providing drinking water for domestic use and where the aim will be to reduce the chance of disease being conveyed to people who drink the water. Disease transmission by this route requires both pollution of the water by a person or an infected animal and subsequent survival of the organism in the water with or without multiplication, and then for people to ingest the organisms. The classical diseases in this category are cholera and typhoid and the causes of watery diarrheas, and also *Shigella* or bacterial dysentery. As with most infections involving water bodies, transmission will largely take place at the water's edge, where pollution by excreta may occur and people collect domestic water and bathe, or near to it in shallow water offshore or wetlands near to the shore. The smaller the water body, the greater is the risk. Therefore, the risk of ingesting enough organisms to transmit the disease is relatively low in large lakes, especially

away from the shore, because of the huge dilutions involved. By contrast, small pools and ponds can very easily become polluted and if used as a source of drinking water may well pass on these organisms. Although both natural lakes and many reservoirs are used deliberately as a source of drinking water for substantial communities, the water will usually be treated before it reaches the distribution system of pipes and taps. Space does not permit an extensive discussion of water treatment. Most commonly, when pollution occurs and leads to large outbreaks of disease it is because of contamination close to or within the transmission system from the lake to the users and particularly when the water treatment works is not functioning satisfactorily. Where water is collected by individuals from poorer households around the lake there will be a risk, usually less for a large water body.

2. *Water Washed Transmission of Diseases*. It has been found that, for many of the diseases once thought primarily to be transmitted through drinking water, the availability of adequate water for personal cleanliness, accompanied by suitable hygiene behavior, such as the use of soap for hand-washing after defecation, can greatly reduce the incidence and severity of diarrheal diseases. It is easier for those living close to the shore of a lake or reservoir, even if they are having to use untreated water from the margin, to obtain adequate water for washing and personal use, and so to this extent the hazard of diarrheal disease and of skin infections and the blinding eye disease, trachoma, is reduced for such people. By contrast, in other respects, living very close to water may increase the risk of vector-borne diseases. It must be remembered that where villages are sited away from large water bodies it is critical to provide adequate water right to the village, preferably taken from some distance away from the shore of the lake, even if it is not possible to treat the water properly for domestic use.
3. A group of infections called *Water-Based Diseases* are of great importance in relation to lakes, and even more so in relation to reservoirs in many parts of the tropics and subtropics. These diseases are where the causative organism has a life cycle, part of which is spent inside people and part in organisms that live in the water. The most important of these are the various trematode or flatworm infections (sometimes called fluke infections), which have stages in water snails, and in particular the several forms of schistosomiasis, described below; but there are also rarer infections, which pass from people to snails, and then from the snails into what are called second intermediate hosts, usually fish, and people become infected by eating the fish inadequately cooked.
4. Water bodies act as breeding sites for *Water-Related Insect Vectors of Disease* in warm-climate countries. The mosquitoes predominate as vectors and the key diseases transmitted are arbovirus fevers and malaria (see below). The majority of mosquitoes breed preferentially in small water bodies and in shallow wetlands such as rice fields, but the edges of lakes and still more of reservoirs provide breeding habitats for several important vectors. These may be in fringing vegetation or in puddles left by falling water levels of reservoirs. A specialized group of floodwater mosquitoes have resilient eggs which can survive in sand near the high watermark for long periods, rapidly hatching when the next inundation occurs, sometimes several years later. These floodwater mosquitoes carry certain arboviruses in particular.

Other insect vectors of human disease associated with reservoirs are *Simulium* vectors of the worms which cause river blindness or onchocerciasis. They are small biting flies whose larvae, needing highly aerated water as a habitat, especially occur on dam spillways and in torrential feeder streams for the reservoir. The tsetse flies, *Glossina*, that transmit sleeping sickness (trypanosomiasis) in Africa include some species that bite in tree-shaded fringes of lakes, most notably Lake Victoria.

Some diseases that fall into categories 3 and 4 are of particular relevance and are considered in more detail.

Diseases particularly transmitted in lakes and reservoirs

Schistosomiasis

Schistosomiasis is the dominant problem associated particularly with man-made lakes, although transmission takes place also in natural lakes in parts of Africa, Latin America, and southeast Asia in particular. All the human schistosomes have a basically similar life cycle. The parasites live in the blood vessels of their human host, and lay eggs which escape in the excreta, whether urine or feces depends upon the species of *Schistosoma* involved. If the excreta pollute the water the eggs of the schistosome hatch out to set free a microscopic larva, or miracidium, which swims about for some hours. If it encounters a suitable species of water snail, this larva will penetrate the tissues of the snail and infect it. Over the next month, the parasite will develop within the body of the snail, gradually destroying many of its internal organs, and after some weeks the larval schistosomes will emerge and swim about in the water. This will happen daily for the rest of the snail's life. If people are wading in the water, the schistosome larva, or cercaria as it is called, will rapidly attach to their skin and then bore through the skin into the blood vessels beneath. The cercariae will be swept to the lungs and subsequently other organs of the body, where they will undergo development. The sexes of *Schistosoma* worms are separate, and when they mature they migrate to the blood vessels of the bladder and intestinal walls, pair, and the female will begin laying eggs on a substantial scale. *Schistosoma* worms are very long-lived and it has been found that people who have become infected and then moved away from the chance of further infection may go on passing eggs in substantial numbers for decades. Many of the *Schistosoma* eggs do not successfully escape from the host and they are the cause of much damage to the tissues of the person who is infected.

There are five main species of *Schistosoma* that infect people. *Schistosoma haematobium* lives in the blood vessels around the bladder of the infected person, and the eggs that are laid by the worm gradually find their way from the blood vessel through into the lumen of the bladder, so that they escape when the infected person urinates. Many eggs accumulate and die in the tissues of the ureters and bladder. Fibrosis and inflammation around the eggs leads to damage to the bladder wall and ureters and also encourages the formation of urinary stones or calculi. Damage may occur to the kidneys as a result of obstruction to the flow of urine. In very heavy infections, as used to be observed particularly in Egypt, cancer of the bladder is a major complication. *S. haematobium* is found throughout much of Africa and in parts of Western Asia. It is transmitted by aquatic snails of the genus *Bulinus* with a rather low spire, some of which can aestivate in the mud of desiccated pools during the dry season.

S. mansoni has a more restricted distribution in tropical Africa and the Nile basin, also the Arabian Peninsula, South America, and the Caribbean. The aquatic intermediate host snails are flat spiral snails of the genus *Biomphalaria*. The adult worms live in the blood vessels around the large intestine, so that the eggs they lay pass through its wall and are shed in the person's feces. The pathological effects are mainly due to many eggs that do not escape being carried in the portal vein to the liver, where they get impacted and an inflammatory reaction occurs around them. Eventually the eggs are destroyed, but in some people, the fibrous tissue left behind by vast numbers of eggs eventually causes extensive and potentially fatal liver fibrosis. *Schistosoma intercalatum* in West Central Africa behaves similarly to *Schistosoma mansoni*, though its eggs resemble those of *Schistosoma haematobium*. *Schistosoma japonicum* of East Asia and parts of SE Asia has a similar pathology to *S. mansoni*, but far more eggs are laid by each female and the chance of severe disease is much greater in *S. japonicum* infections. *Schistosoma mekongi* is very similar and occurs, as its name suggests, chiefly in the Mekong Valley. *S. japonicum* has a small amphibious snail of the genus *Oncomelania* as the intermediate host, whereas *S. mekongi* has an aquatic snail, *Tricula*.

Schistosomes are par excellence the parasites associated with water resource developments. Much is known about the biology of the varied local species of intermediate host snails, so that the risks of schistosomiasis can be predicted approximately at the planning stage, but not with precision. Thus, when the Volta (Akosombo) dam in Ghana was being constructed, a schistosomiasis problem was foreseen for the lake, but the species of snail and the type of schistosomiasis were unexpected: there was a large *S. haematobium* problem imported by migrant fishermen and spread by dense *Bulinus* populations. However, the later downstream dam at Kpong, which is kept at a relatively constant water level perennially, supported snails transmitting both schistosome species. Jobin (1999) has pointed out that this is replicated in some other pairs of dams in Africa, reasoning that *Bulinus* thrives in the upper reservoir in spite of large annual fluctuations in the water level whereas *Biomphalaria* is also present in the lower reservoir which is kept at a relatively constant level. A few species of *Biomphalaria* can live in deep water and have been responsible for offshore schistosomiasis transmission.

A biologically related problem of temperate climate reservoirs involves those schistosomes with birds as their definitive hosts. Sometimes very large numbers of water snails become infected with their developmental stages and huge numbers of cercariae are shed. These are able to penetrate human skin but not to survive further, and there is an inflammatory response to the dead cercariae. This leads to outbreaks of a rash called "schistosome dermatitis" among lake bathers in the late summer in the USA, UK, and many other countries.

Malaria

In the case of malaria, the most important vector-borne disease globally, the consequences of water resource development depend heavily on the baseline level of malaria transmission and the type of water development. The infection is transmitted by female mosquitoes of the genus *Anopheles*, which become infected by feeding on the blood of people with malaria. The parasites develop in the mosquito, migrate to its salivary glands after 1–2 weeks, and then are inoculated into other people when the mosquito feeds again. The parasites then multiply repeatedly, first in the liver and then in the human blood cells, the latter on a 2–3-day cycle so that the patient gets an intermittent fever which worsens as parasite numbers increase in the blood. In nonimmune people, death may follow from disturbance to the brain (cerebral malaria) in children and adults and from anemia in infants if they are suffering from *falciparum* malaria (of the four species of malaria that commonly infect man, this causes by far the most severe illness and is especially prevalent in Africa). At low levels of transmission prior to the development, as in many parts of India, the creation of a reservoir, and particularly one that feeds an irrigation scheme, has historically been followed by epidemic malaria. By contrast, in parts of West Africa with very heavy transmission of malaria already taking place, creation of a reservoir or irrigation scheme may greatly increase the abundance of vector mosquitoes but with little or no increase in clinical malaria. This is because the existing level of transmission is so high that children are already infected with malaria from early infancy, and acquired human immunity regulates the levels of disease observed. Indeed, in some parts of Africa the creation of irrigated rice agriculture appears to decrease the malaria level somewhat; this is sometimes known as the "paradox of the paddies" and it is not yet fully understood.

Importance of disease due to large dams

The infectious and communicable disease burden due to water resource development has been assessed for several key vector-borne diseases, primarily in relation to the larger dams and reservoirs. Malaria and schistosomiasis are greatly affected by surface water storage.

The effect will vary greatly with the baseline endemicity and local vector species, so that, for example, four times larger a percentage of schistosomiasis incidence can be ascribed to dams in South East Asia than in Africa, although the actual number of people involved is far greater in Africa south of the Sahara. Meticulous calculations have been made by Kaiser, Utzinger, and colleagues in a series of systematic reviews of the key vector-borne diseases, and the results are summarized in Table 1. Globally it appears that some 42 million people are at risk of schistosomiasis from big water storage dams, of whom 10 million are infected (Steinmann et al., 2006), while 18 million are at risk of malaria as a consequence of water storage in large dams (Keiser et al., 2005).

Environmental measures of disease control

There is sufficient knowledge to propose interventions against many pathogens and vectors but, as with most control by environmental means, interventions need to be appropriate for the local organisms and human activities and also to be maintained scrupulously, which is operationally not easy. Engineered environmental changes often need to be accompanied by changes in human behavior. Structural changes to prevent disease transmission are usually called environmental modification, while recurrent management issues such as clearing vegetation, sluicing, and regulating salinity are called environmental manipulation.

The water level of many lakes and all reservoirs tends to vary on an annual cycle. The extent of this variation, along with the slope of the shoreline and the rate of drawdown, will substantially affect populations of vector insects and intermediate host snails.

Because the vast majority of the health effects of lakes and reservoirs are determined by events close to the edge of the impoundment, its nature is of great importance. A steep shore that is unsuitable for human waterside activities, lacks vegetation and descends sharply below the water level will be most conducive to health. Where the shoreline is gently sloping and supports emergent and floating vegetation it provides a habitat for snails and mosquito larvae, especially where wave action is reduced. In Africa, fringing trees may need clearing or their lower branches removing to deter tsetse flies from biting. Human settlements should be sited away from the shore (preferably over 2 km) but water piped to them and sanitation facilities provided. In tropical areas, the aim will be to minimize contact between the people and the reservoir edges, such as by constructing jetties and cleared landing places, although, particularly among fishing communities, substantial water contact may be inevitable. Where schistosomiasis is endemic, infection may well occur, although the worm burden and so the chance of serious disease may be greatly reduced by these environmental and behavioral measures. There is now satisfactory chemotherapy available and a regular cycle, perhaps annually, of testing and treatment for schistosomiasis may be needed. Although molluscicides are available, their sustained use in lakes and reservoirs (apart from small pools and night storage ponds for irrigation) is impracticable.

Deliberate variation of the water level for disease control has been used for some reservoirs to control schistosomiasis and malaria. In the pre-1939 “golden age” of environmental management for vector control, just prior to the introduction of residual insecticides, particular attention was paid to varying the water level of reservoirs in a controlled way, especially in the USA, deriving from the experience of the Tennessee Valley Authority in malaria prevention on impounded waters (USPHS and TVA, 1947). The water level in medium-scale reservoirs can be rapidly lowered either by manual control of the sluice gates or by an automatic siphon device. By careful manipulation of a series of dams on the Tennessee River it was possible to raise the water level transiently to flood height, so stranding flotsam and floating vegetation that tended to harbor vector mosquito larvae. Subsequently, rapid dropping of the water level was able to strand the larvae of *Anopheles quadrimaculatus*, the local malaria

Health Aspects of Lakes and Reservoirs, Table 1 Schistosomiasis and malaria risk from water storage in large dam reservoirs

	Schistosomiases			Malaria	
WHO Region	At risk from big dams *Millions*	% of total risk from big dams *%*	Estimated infected from big dams *Millions*	Number of big dams *Number*	People at risk from big dams *Millions*
Africa S of Sahara	28.71	5.1	9.62	525	3.07
Latin America	1.22	3.4	0.06	1,449	0.48
Middle E and N Africa	2.35	1.7	0.29	812	2.46
SE Asia and W Pacific	10.09	21.7	0.23	6,405	12.33
World	**42.36**	**5.4**	**10.20**	**9,191**	**18.34**

The data are derived from Keiser et al. (2005) and Steinmann et al. (2006)

vector, and marshy areas dried out. The malaria vector bred close to the shoreline during May to September. From July, the level gradually recedes some 3 cm per week, but superimposed on this are forced fluctuations of 30 cm approximately weekly which repeatedly strand each generation of the mosquito eggs and larvae. The water regime also kept the larvae clear of emerging vegetation which provides cover for them, and helped the breeding of larvivorous fish. This highly successful approach to malaria control depended upon joint planning by engineers and vector biologists, the particular ecological characteristics of the North American malaria vectors, and the availability of water in the river to allow fluctuation of the water level. The approach has also been used against *Anopheles culicifacies* in South Asia. However, as with most environmental control methods, this is species-specific. Any attempt to use it against puddle-breeding mosquitoes in the African tropics, around reservoirs too large for rapid oscillations of level and with very shallow sloping edges, would be worse than useless: the rate of water level fall would be slow and generate extensive breeding sites for *Anopheles gambiae*, the world's most effective malaria vector, and do more harm than good.

Water level fluctuations have also been considered as a way to strand aquatic snails in Africa, but the estimated drawdown rate required, around a meter per day, is greatly in excess of what seems feasible operationally. Changes in discharge flow rates have also been recommended for *Simulium* control, but this appears speculative, unless the spillway can be dried out. More successful in one site, the origin of the White Nile from Lake Victoria, was positioning of a narrow pipe down through the dam wall so that liquids could be added to the outflow from the sluices. Insecticides were poured down at regular intervals; the turbulence reduced the insecticide particle size down to 1 μ diameter. This size of particle was raked out of the water by the feeding habits of the *Simulium* larvae which were thereby poisoned selectively. Moreover, when this came to an end after some years, it appears that the *Simulium* species that re-invaded the empty ecological niche was of a type that did not bite humans.

Where malaria vectors and other vector mosquitoes are not amenable to environmental control by water level or shoreline manipulation, or where there is residual malaria after they have been applied, other methods need to be used in addition for both prevention and prompt treatment. These include use of insecticide-treated mosquito nets if the vectors are nocturnal and rest indoors, house screening, possible residual insecticide spraying, and use of repellents, as well as sufficiently accessible dispensaries or health centers stocked with locally approved antimalarial medicines for treatment, as severe malaria is a medical emergency requiring immediate action.

Reservoir construction and early filling

There is now much published work on the health hazards of major water storage reservoirs (Stanley and Alpers, 1975; Jobin, 1999). Planning (stage 1) to construct a dam, and even the rumor that this might happen, will lead to a set of social and environmental changes with health consequences of an unplanned as well as an intended nature. The construction phase (stage 2) will greatly intensify these, as there will be immigration of workers, of those hoping to provide services for the workers, and often the beginnings of a health infrastructure. The health problems of transient labor predominate: trauma, sexually transmitted and respiratory infections, and outbreaks of locally endemic diseases if the workers are from a non-endemic area. Funds for infrastructure may enable good facilities for the longer term. The local people displaced from the inundated area almost invariably suffer from inadequate support and lack of planned movement to a suitable site. These indirect health consequences of creating water storage matter, and also provide health opportunities.

The early period after filling the reservoir (stage 3) may see complex biological changes such as rotting forests, explosions of insects, fish, fishermen, and shoreline vegetation with vector habitats being created, leading to outbreaks of schistosomiasis and malaria (in areas of previously low transmission), with gradual progression to a steady state (stage 4) which may or may not include a higher level of health hazards than before. Stages 1–3 comprise a key period or "Chronotone" lying between the original state of the landscape and the final relatively steady state of the mature dam and reservoir (Bradley, 2004). The terminology is by analogy with the term ecotone, which is the area in space that lies between two types of ecosystem whereas the chronotone is an equivalent interval in time rather than space. It includes the structures, water and adjacent land, the ecology, settlement, use and social conditions. Many of the changes that occur during the chronotone are predictable, and others not, so there is a need both to plan the management of expected health hazards and to monitor the situation. It is a key time to invest effort in order to reap long-term reductions in health hazards. While this is also true of small impoundments, the strategy needed is different from that appropriate for large reservoirs. For a big dam, such as that for the Volta Lake, Ghana, the chronotone may last for around two decades.

Small reservoirs

Methods to reduce the health hazards of large reservoirs are well studied, even if often ignored, but those for small dams are less clear, requiring choice appropriate to the locally relevant pathogens and further research attention.

Small multipurpose reservoirs, "tanks" and "dams" are probably collectively more important for health than are large dams, making up in numbers what they lose in capacity. In part of Northern Nigeria there were over 700 in a limited area. Worldwide, in 2001 it was estimated that there were 40,000 large dams and over 800,000 small reservoirs (Keiser et al., 2005), although the last figure is probably a substantial underestimate. Multiple small reservoirs pose different problems from big dams. Formal control over them is weak, and is exerted at local level by local government and community pressure. The users need to be convinced if health measures are to be implemented and maintained. The various health risk issues have to be balanced against the different uses to which the water will be put. General rules are less applicable and flexible local inputs are needed. Resources are, however, much more limited and many small dams pose major health hazards.

Measures to control the health hazards of small dams are site-specific, but may include avoiding the need to enter the water, by provision of pumps, cattle troughs (but with adequately drained surrounds), sites for laundry and canoe landing stages. These will reduce schistosomiasis risk. Fencing may be used to prevent access of livestock and consequent pollution, and steep edges to the pool deter emergent vegetation and reduce mosquito breeding (although they may create a drowning risk to children unless fenced), while stocking with appropriate small fish may reduce mosquitoes further. The floating fern *Azolla* will also deter mosquito breeding (especially of anophelines) once surface coverage exceeds 90%, which may or may not be acceptable to users. It is difficult to prevent all pollution of surface waters and some form of post-storage treatment is, if possible, needed for drinking water. In the tropics, sanitation is best directed toward pathogen reduction, rather than relying on water treatment to achieve this.

Conclusion

Several broad principles should govern the approach to health issues in developing impoundments of water, whether small or large. These include considering health issues at all stages of the project, from initial plans and design right through to operation and management.

Early advice should be sought from public health experts, particularly those who have worked in the area of the proposed reservoir for many years, both medical biologists and communicable disease epidemiologists. In the case of a large development, an expert epidemiological team will need to make a health opportunity assessment. The issues should be addressed from a co-ordinated but interdisciplinary viewpoint, at all stages.

Research has been concentrated on health hazards of large dams, but in spite of some excellent local studies, work on smaller water storage reservoirs is relatively neglected. More work is needed on these problems, not only in relation to health but also into linked aspects of agriculture, livestock watering, and conservation.

Whatever the scale of water storage, planning for health hazard reduction needs to be undertaken well before the development and construction of new storage. The chronotone, or period of rapid change around the development that is crucial for effective long-term action, is a period of great opportunity to improve health.

The literature on reservoirs and disease transmission is chiefly from the last three decades of the twentieth century when many large dams were built, especially in the tropics, and the two best books are Stanley and Alpers (1975) and Jobin (1999), the former for its broad scope and Jobin for detail on selected areas from a control viewpoint. The water-related disease classification is to be found in White et al. (1972). Keiser and Utzinger's papers have the best estimates of the effects of water development on malaria and schistosomiasis. Birley's (1991) guidelines can be downloaded from the WHO website, as can Bradley and Bos (2010) from the SIWI website.

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HYDRODYNAMICS AND CIRCULATION OF FJORDS

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Introduction

Fjords are narrow and deep inlets, carved by glacial processes, with a sill in the mouth. They are typically strongly stratified, often with three clearly distinguishable water masses. The surface water has often reduced salinity due to local freshwater supply. The stratification of the intermediary water, between the surface water and the basin water, continuously mirrors the ever-changing stratification of the coastal water outside the mouth but with some phase delay. The basin, below the sill level, contains the basin water which is the densest water that occurs above sill level in the coastal area, i.e., outside the fjord. Water masses and some physical processes and modes of circulation in fjords are indicated in Figure 1.

Currents in a fjord are generally forced both inside and outside the fjord. The local wind in the fjord forces surface currents that are approximately in the wind direction and with a speed that is a few percent of the wind speed. The wind drift converges toward the shores whereby baroclinic horizontal circulation, often encompassing the upper layers of the whole fjord, is generated. The wind also drives vertical mixing of the surface layer and if there is local freshwater supply to the fjord, wind mixing will sustain so-called estuarine circulation leading to outflow of brackish surface water and inflow of seawater. Remotely forced circulation will proceed in a fjord even under calm conditions. One differentiates between baroclinic circulation that varies vertically and barotropic circulation with uniform velocity in the whole water column. Remotely forced circulations are driven by horizontal pressure gradients, due to differences in vertical stratification and sea level, respectively, between the fjord and the area outside the fjord.

In this entry, currents due to various modes of circulation are discussed with focus on fundamental dynamic balances and simple formulas that can be used to make first-order estimates of the flow through the mouth and also within fjords. The water exchange with the coastal water is coupled to various modes of forcing and the following externally forced processes and circulation modes are discussed here.

- Intermediary circulation forced by density variations outside the fjord (Section Intermediary Circulation Forced by Density Variations in the Coastal Water)
- Barotropic tidal circulation forced by sea level variations outside the fjord (Section Barotropic Tidally Driven Circulation)
- Estuarine circulation forced by local wind mixing and freshwater supply (Section Estuarine Circulation)
- Generation of internal tides and jets at sills
- Vertical mixing in fjord basins, ultimately powered by tides and the local wind (Section Vertical Mixing in Fjord Basins)
- Exchange of basin water (below sill level) forced by turbulent mixing (Section Exchange of Basin Water).
- In addition there is also internally forced wind drift and wind-driven fjord-scale circulation and surface and internal seiches (Section Wind Drift and Related Phenomena).
- Application of hydrodynamics to fish farming (Section Hydrodynamics of Fjords Applied to Fish Farming).
- A short summary concludes the entry (Section Summary).

The aim of this entry is to give an overview of the hydrodynamics of fjords including general modes of circulation with emphasis on basic dynamics. Excellent reviews of the physics of fjords have been written by Gade and Edwards (1979) who concentrated on deepwater renewal, by Farmer and Freeland (1983) who covered several aspects and recently by Inall and Gillibrand (2010) who covered recent contributions to the physics of fjords, and Cottier et al. (2010) who reviewed the physical oceanography of Artic fjords.

Stratification changes in small fjords due to water exchange and mixing

The waters of many fjords may be treated as 1D because horizontal gradients are much smaller than vertical. The 1D vertical advection–diffusion equation for salinity (temperature, etc.) is then an appropriate starting point for descriptions of large-scale circulation. Consider a horizontal slice (slab) of a fjord centered at the depth z - (Figure 2). The slice has thickness dz, horizontal surface area A(z), volume V(z) = A(z)dz, and salinity S = S(z). Inflow/outflow through the fjord mouth introduces a flow q = q(z) into and out of the fjord which in turn introduces vertical advection of velocity w(z) through the

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