3 Environmental Control of Snail Habitats

INTRODUCTION

The aim of this chapter is to describe in general terms snail habitats in natural, man-made and irrigation environments and to outline measures for their elimination or reduction. It has been assumed that public health engineers with basic training in civil engineering would be fully familiar with the technical aspects of snail control measures required in natural and man-made habitats. Accordingly, engineering design and construction methods are not given in detail but in a general and somewhat non-technical way so that public health workers, biologists and epidemiologists can gain some understanding of the engineering methods of snail control.

On the other hand, the section on irrigation habitats presents in some detail principles and practices which are not usually included in the subjects studied by public health engineers. It is hoped that this treatment will enable such individuals to understand the point of view and interests of the irrigation engineer, and thus facilitate collaboration in the institution of control measures.

Environmental control of bilharziasis must involve modifications to the environment of both the human and snail hosts of the parasite. In the case of the human hosts the object is to alter their habitats in such a way that they no longer come into contact with water infested with snails, but for the intermediate hosts it is necessary to change the ecology of the waters in which they live so that these are no longer suitable habitats. It may be possible to achieve both these objectives by a single operation, but usually the situation will be more complex and the two aspects will require different treatment. However, the present monograph is concerned with snail control, and the methods discussed here will deal with changes in the environment which are intended to reduce and control existing snail habitats and to prevent the creation of new ones.

Some knowledge of the ecological requirements of snails is needed to achieve the habitat modifications necessary to render a locality unacceptable to them. Where detailed knowledge concerning specific ecological requirements of snails is available, it is possible that small changes may be enough to make the habitat unsuitable, but where such information is not available the measures taken will probably have to be more crude and fundamental. Most of the methods of environmental control which are employed involve relatively drastic changes in the habitat. Although not complete, present knowledge of snail ecology is sufficient to guide the design of such control measures.

The problem is complicated by the fact that many of the medically important snail species have a wide tolerance for most of the physical and biological variables in their habitats, and it is therefore seldom possible under field conditions to alter any one of these factors sufficiently to effect control. Thus the optimum temperature range for many species varies between 18° and 28°C, while the lower and upper lethal temperatures are about 0° and 40°C. Although most species prefer a habitat with considerable sun-exposure, there is experimental evidence to show that some can breed in total darkness provided that food is available. The pH range tolerance is also fairly wide ; although the optimum for any particular species usually lies between 6 and 8, the lethal limits are normally beyond any practical range of artificially imposed variation. Water movement, in the sense of velocity of flow, turbulence or wave action, is a factor which is known to affect many species adversely, but limiting values for any of these effects are difficult to determine and they never apply uniformly to a whole habitat because no natural habitat is completely uniform. Even in places where the environment as a whole is unsuited to snail development, there are often small foci where the water movement is restricted and snails are able to breed. Factors such as salinity, the presence of toxic ions and pollution all merit further investigation. Some species are very sensitive to small traces of salinity, while others appear to tolerate much greater concentrations. Places are often found which appear to be excellent snail breeding-sites and yet no snails are present. Detailed analysis of water samples from such places might reveal traces of toxic ions, and this information would be of the greatest possible value in the development of new molluscicides. There is no doubt that limited amounts of organic pollution are definitely beneficial to snails, and such pollution should be prevented wherever possible. The benefit which snails derive from sewage pollution is probably both direct and indirect, for some species are able to feed directly upon faecal material, while at the same time the increased organic content of the water will encourage the growth of algae which form an important natural food of the snails. An approach to control which has often been suggested is the introduction of harmless species to act as competitors for food and egg-laying sites. There is evidence that in some circumstances the prosobranch snail *Marisa* has been successful in this respect, but many of the other suggested biological agents are ineffective. For instance, *Physa* spp., if present in a laboratory aquarium with *Bulinus*, will eventually eliminate the *Bulinus* completely, but in some parts of Egypt both *Physa* and *Bulinus* occur together naturally. As with competitors, so far little success has been gained by the introduction of predators. Here the problem is a common one in all fields of biological control. If the predator used is exclusively a snail-feeder it may effect a drastic initial reduction in the snail population but this will inevitably result in a reduction of the predator population due to food shortage, and the long-term result will probably be a periodic cycle with alternating peaks of prey and predator. If the predator is merely a facultative snail feeder it may not reduce the intermediate host population level below its minimum parasite-transmission density.

The most devastating change which can be brought about in an aquatic habitat is, of course, the removal of water. If this can be done permanently and without affecting agricultural or other requirements, it is obviously the best method of destroying the breeding-sites of aquatic snails. If, however, withdrawal of water can only be effected for short periods, as is often the case in irrigation systems, the ability of the snails to withstand desiccation will be the most important factor in the efficiency of the method. Many of the aquatic intermediate hosts of fluke diseases have remarkable powers of aestivation which enable them to survive the dry season in their natural habitats. Some species survive for six months or more without water. In a few cases there is evidence from laboratory breeding experiments that such periods of desiccation are necessary for the survival of certain species, and they will die out in laboratory culture after a few years of continuous aquatic life. It has been shown in South America that the early stages of infection with *Schistosoma mansoni* can survive in aestivating intermediate hosts and continue their development successfully after the snail has resumed its normal aquatic life.

Despite slightly discouraging aspects, environmental control of snails is the method of choice where the costs of installation and maintenance are reasonable. The reason for this is that only rarely do ecological factors act singly. More often there is a synergistic effect among a number of conditions, and these acting together can make a habitat suitable or unsuitable. Thus, it may not be necessary to alter any one factor greatly if several can be changed slightly at the same time. It is important to remember that the intermediate hosts do not occupy the whole habitat but exist only in suitable microhabitats within the larger environment; control measures should therefore be aimed at eliminating the features which create the microhabitat. One of the most usual ways of achieving this is by the destruction of the aquatic vegetation, since this removes a great deal of the substratum on which the normal algal food of the snails occurs and on which they commonly lay their eggs. It also removes a potential source of dissolved oxygen in habitats which may be deficient in this respect as well as the shelter which may be protecting the snails from the effects of water-movement.

In natural habitats the most effective measure against snails is drainage. Where this is not possible, alternative methods such as weed clearance, straightening of banks, deepening of marginal areas and prevention of sewage pollution all contribute to the reductions of snail habitats. In artificial habitats water management is a valuable asset, for rapid fluctuations in water level and flow rate have a disturbing influence on snails. Irrigation systems and reservoirs should be designed so that such operations can be performed without difficulty and the control of aquatic weeds can be easily accomplished. These approaches to environmental control are also of enormous use in molluscicidng campaigns, for they reduce the number and extent of foci to be treated and make application of the chemicals much more simple and efficient, with a consequent reduction in cost.

Environmental control is likely to be more permanent in its effects than are chemical methods. However, the cost of making permanent habitat alterations and the difficulty of obtaining the co-operation of the local people may preclude the immediate adoption of such measures. In cases where complete drainage is proposed for a natural habitat which also serves as a source of water for people, it will normally be necessary to provide an alternative water supply. If there is no human contact with the water in the first instance, it is unlikely that such a habitat is an important source of infection, and drainage is probably not justified unless the snails present are serving as a reservoir population to actual transmission sites. In many circumstances—for example, in rice-growing areas and fishponds—some of the more drastic environmental changes might destroy the possibility of using the habitat for its original purpose. Careful consideration must be given to each case; if the locality to be treated is one in which habitat modification is practicable, and if the cost of the necessary work is not likely to be much greater than of repeated mollusciciding treatment, then environmental control methods should be adopted. This approach should be given particular attention where there is a possibility that the repeated application of molluscicides without selective activity might destroy freshwater fish, thereby depriving the human population of this source of protein. Whatever methods are used, eradication of the snail host is desirable because there is, as yet, insufficient information on safe minimum population densities, and even a small residual population can rapidly re-infest a large area if control methods are relaxed.

ADVANTAGES AND LIMITATIONS OF ENVIRONMENTAL CONTROL

Introductory Remarks

It has been stated on page 64 that the types of snail habitats and transmission sites for bilharziasis are variable. In general, however, most endemic areas can be placed in one of two categories. The first of these would include the endemic foci which are located in low-lying areas where often there is an abundance of water. The extent of such areas, the lush vegetation, and difficult terrain often make the use of molluscicides impracticable. Most of the information on the methods most suitable for the elimination or control of the intermediate hosts in such areas has come from a pilot control project at Palo, Leyte, Philippines, and from Japan. In these countries, it has been shown that engineering and improved agricultural methods can be used in such foci to eliminate many colonies and reduce the total snail population by more than 95%. At the same time it has been possible to obtain greatly increased crop yields in the Philippines and to rehabilitate waste land. Snail colonies remaining after engineering control can be attacked with molluscicides.

The second broad category includes foci that occur in arid and semi-arid areas where the provision of a water supply and its equitable distribution with reference to space, time and people is an ever-present problem. It has been reported repeatedly that the irrigation of arid lands, or the conversion from basin and partial irrigation to perennial irrigation, results in an increase in the prevalence and intensity of bilharziasis. This is because the same factors which make an endemic area more satisfactory for man usually also make it more suitable for the molluscan intermediate hosts. Some areas once quite inhospitable for man and snails now have dense populations of both, and millions of cases of bilharziasis. There is some evidence that well-designed and constructed irrigation and drainage systems, properly prepared land, good water management, careful maintenance of the canals, and improved agricultural practices in a few areas in Iraq, Kenya and Ghana have at least temporarily prevented the usual extension of bilharziasis into irrigation schemes.

With this introduction to the problem, it is possible to outline the principal advantages and limitations of the measures used for the environmental control of snail habitats.

Advantages

(1) Local labour 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.

Wet areas

Environmental control measures in some high-rainfall or heavily irrigated areas may not eliminate all snail colonies, and molluscicides may have to be used (see chapter 4, page 123).

Dry areas

Since water is essential for economic development in arid areas, there is always the danger that its introduction or storage will not only encourage snail habitats but will also lead to concentration of human populations, hence increasing bilharziasis transmission. Water for man and domestic animals often must come from storage reservoirs and irrigation canals, which frequently harbour snail hosts. The use of infested water from such sources enhances the transmission of the parasite.

Whereas in wet areas environmental control measures usually result in land reclamation and increased crop yields, in dry areas such measures are limited to water storage sites and to drainage of excess irrigation water, and thus have no indirect benefits.

MEASURES APPLICABLE TO NATURAL HABITATS

Introduction

Although bilharziasis is predominantly a disease of irrigated areas, there are nevertheless many endemic regions in which natural waters provide the snails with suitable habitats. This is true in parts of South Africa, Mauritius, Tanganyika, Rhodesia, West Africa, Brazil, Saint Lucia, Puerto Rico, Venezuela and, above all, in the Philippine Islands.

Natural streams in such areas provide many of the major foci of infection, particularly where ox-bow lakes, shallows, meanders, growth of water plants, or pooling in the dry season have led to reduction in the rate of flow, and to other conditions favourable to the establishment of permanent or semi-permanent breeding colonies of the intermediate hosts. Overflow during seasons of flood, and seepage from such streams at all times, lead to the formation of marshes, swamps and pools which provide additional habitats for the snails. Human interference in the form of dam and culvert construction, of establishment of fords and crossings, and of pollution with excrement often renders the environmental conditions still more favourable to the host snails.

These situations need equal attention with those developing as a result of irrigation. When villages are situated near such streams or marshes, all the conditions necessary for the transmission of the disease from man to snail and snail to man are present. In these circumstances it is no less necessary to undertake measures for the reduction and eventual elimination of the snail habitats than under the conditions created by artificial irrigation systems.

Experience has shown that natural snail habitats are so varied that no single method can be devised which can be used for effectively eliminating or reducing all of them. Each snail colony requires individual investigation before the best approach can be decided upon. In general, however, the more radical the changes initially produced, the less maintenance is subsequently required. Radical environmental change, therefore, if it is found practicable, is apt to be the cheapest control measure in the long run.

Unfortunately, the initial cost of such measures is often high. This would be an almost intolerable economic burden if these measures resulted only in the reduction of the prevalence of bilharziasis and the funds were taken from the public health budget. Fortunately, however, the measures needed for snail control often serve other equally useful purposes. Thus several environmental control measures applicable to snails may have a profound influence on the control of malaria vectors and pest mosquitos. Moreover, such measures frequently coincide with those needed for modern agricultural practice. Water conservation and disposal, land reclamation and the proper management of fields and farms require, in many respects, the same kind of treatment of flowing and standing water and water-logged soil as does snail control when carried out by radical measures. The agricultural benefits which result, therefore, may be great enough to offset completely or, at least, in part, the cost of measures which would otherwise be prohibitively expensive. In any event the cost of radical environmental changes must be evaluated in the light of direct and indirect benefits, as well as regards the possibility of employing less expensive methods of control. It is only after a careful study of all factors concerned that a rational decision can be made.

Watersheds

In dealing with natural snail habitats, surveys and control measures should be planned on watershed units, starting from the upper reaches of the area and working down systematically. In this way, areas over which control measures have been instituted would be relatively safe from snail infestation from higher areas. Where, however, the endemic area is located in the lower regions of a very extensive watershed, control measures would have to be confined to part of the watershed, and special precautions, such as mechanical barriers or chemical treatment of a stretch of the river above the control area, need to be taken to reduce the risk of re-infestation from the upper reaches.

A thorough survey and study of the characteristics of the watershed should precede any attempt to initiate control measures. It is essential to determine the area of the watershed and its geological and topographic features, and to obtain information and data on rainfall, stream flow and land use practices. Aerial maps and observations from low-flying aircraft or helicopters would enable the engineer to gain a useful general impression of the watershed.

From topographic maps and hydrological data the engineer will be able to determine the existing water-carrying capacities of the streams and gullies, and the extent of flooded areas. Then consideration can be given to methods for improving the general drainage pattern in order to eliminate or reduce snail habitats. These methods may involve river training, channelization, cut-offs, removal of obstructions in the channels, prevention or reduction of flooding, etc.

In considering drainage as part of a snail control programme, it is only necessary to ensure that habitats are dried up sufficiently to prevent snail breeding for a period which may be several weeks. The drains required, therefore, may be smaller than those needed for agricultural or highway drainage.

Capacities for which drainage channels should be designed are determined from records of rainfall intensities and frequencies. In some endemic areas it has been found sufficient to design structures for average annual intensities. Where the drainage affects agricultural or settled land, or roads and irrigation, then the design may have to be based on five- to ten-year frequencies.

Experience has shown that where rainfall and stream-flow records are not available, as is the case in many endemic areas, it is safer to base the designs of control works on field observations, estimated capacities of existing waterways, culverts and bridges, and on information gathered from local inhabitants rather than on empirical formulae that may not apply to the local conditions.

Streams

Flowing waters differ widely in their characteristics, and therefore in their suitability as snail habitats. The intermediate hosts are often associated with a mud bottom, rich in organic matter, in those natural streams in which they occur. Clean sand, stones, and deep semi-liquid mud usually do not provide favourable conditions for these snails. It has been found convenient to place streams in three different categories, as regards their suitability for the intermediate hosts. After these categories have been discussed, the basic ecological factors in these habitats will be considered.

Large perennial streams (rivers)

The main body of any large perennial stream is frequently unsuitable as a snail habitat. The generally rapid flow, often accelerated to a racing torrent during the flood season; the relative freedom from pollution; the fact that there is often a heavy silt load and that the water is therefore highly turbid; the absence of aquatic vegetation; and the fact that the bed generally consists of stones, sand or alluvial clay with little or no admixture of organic matter, all tend to render it unsuitable as a snail habitat. However, a few scattered colonies may occur in protected and often inaccessible sites along the margins. The Tigris and Euphrates and their major tributaries are examples of this type of stream.

The cardinal factor, however, is the rate of flow. In gentler, slower and shallower rivers, conditions suitable for the snails may be found at many points along the course. Some rivers which are, in the main, unsuitable for snails, present limited stretches where the molluscs can establish themselves. The Nile is an example. Certain locations provide favourable conditions for snail breeding. These include the reaches above the Aswan dam where the current is gentle and pools, lagoons and marshy bays with aquatic vegetation occur along the banks, the backwater between Rhodah Island and the mainland near Cairo, and the quiet waters between the grassy islands near Embabah. Moreover, the Nile, like many such rivers, plays an important role in disseminating the snails, which are transported by its waters.

Small perennial streams

It is in the small perennial streams that favourable conditions for the establishment of permanent breeding colonies of the molluscan intermediate hosts are more usually found. These streams are more frequently infested by reason of their gentler flow, less marked changes of level, clearer water, and the more frequent occurrence of algae and aquatic vegetation which provide food and shelter for the snails.

Meandering, sluggish streams of this type in endemic areas as, for example, in the Philippines and in Brazil, are often clogged with aquatic vegetation and permanently harbour dense populations of snails. In other endemic areas, such as parts of Puerto Rico, high rainfall and varied topography are responsible for the occurrence of small, permanent streams of variable slope and flow characteristics. In such streams the snails are absent from the high gradient stretches, in which rapid flow makes conditions unfavourable to their establishment, but are often present in abundance where the gradient is low, the current is gentle and the margins irregular. Such low gradient reaches are usually associated with alluvial deposits, both on the lowland plains and in the upland valleys. Even in the steep reaches, however, snails may occur in disjunct pools, seepages and small tributaries, although they may be absent from the main stream.

In many endemic areas small snail-infected perennial streams may be found in upland regions, as relatively small tributaries of larger rivers. If such colonies exist and are allowed to remain, they tend to reduce the effectiveness of snail control measures in the lower portions of the watershed.

Intermittent streams

These streams often serve as important transmission sites, especially when they stop flowing and the river bed is dotted with disconnected pools. The rapid increase in the number of snails in the pools and the drought which compels the human population to use these same pools leads to the establishment of ideal conditions for the transmission of infection. Where the pools dry up completely, the period of transmission is shortened but snails may survive by aestivation through being buried in the mud or protected by accumulations of dead vegetation.

Fundamental ecological factors

In the study of flowing waters from the point of view of bilharziasis control, certain ecological factors are of cardinal importance. Some consideration of their nature and effect will therefore not be out of place at this point in the discussion.

Velocity of flow

The snail intermediate hosts of the schistosomes are intolerant of strong currents. Breeding colonies are not found at falls, in torrential rivers, or wherever there is a swift flow.

The intermediate hosts differ to some extent in their capacity to maintain themselves in swiftly flowing water, the deciding factor being their ability to cling to a surface. When the current velocity is such that the snails are unable to relax their hold in the slightest degree without being swept away, they are unable to move or feed, and can therefore no longer maintain themselves in the given situation.

Little is known about the relation between current velocity and snail ecology, but such information as is available indicates that the limiting velocity for most species is probably not less than 30 cm per second (or approximately 1 foot per second) as measured at the centre of a straight stream with regular margins. However, this will vary with the nature of the substratum. Snails can more easily cling to a firm rough surface, such as that of concrete or stone, than to a firm smooth surface, such as that of the glass which has been used in some laboratory experiments, or to a loose and shifting surface, such as the silt beds and earth banks of many streams. Snails with conical shells, such as the oncomelanids and bulinids, show a slightly greater resistance to the dislodging effect of swiftly flowing water than snails with flat discoidal shells, such as the planorbids.

Higher rates of flow can be withstood in streams where the current is intermittent ; the longer the intervening periods of stagnation, the higher is the rate of flow which can be borne. Moreover, more rapid flow is tolerated when the water is clear than when it is silt-laden.

From the point of view of snail control it is desirable to establish, wherever possible, such minimal average, marginal and bottom velocities as will discourage the multiplication of the snails.

Velocity of flow in open channels is affected at the surface by wave action, eddies, and, sometimes, by the effect of wind ; it is decreased at the bottom and sides by friction due to roughness ; irregularities in cross-section and alignment ; and in the body of the channel it is affected by surface tension and viscosity. In channels of variable section, such as natural streams, the distribution of velocities, though somewhat irregular, follows certain recognizable patterns. Thus, the maximum velocity in a vertical plane occurs at 5%-25% of the depth from the surface, being closer to the surface for shallower streams with rougher beds. The average velocity occurs at about 60% of the depth. It is usually taken as the mean of the velocities at 20% and 80% of the depth, and also is approximately 85% of the surface velocity (see Fig. 4, 5, page 96). The average velocity of flow in a channel can be calculated from measurements of the cross-section of the channel, the perimeter, the roughness of the surface and the longitudinal grade of the channel.

The effect of these factors on the average velocity is best expressed by Manning's formula:

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

where

V is the average velocity in feet per second

R is the hydraulic radius in feet; it is equal to the 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.

The following are typical values of n:[1]

Nature of surface	*Value of* n
Concrete-lined channels	0.016
Cement-rubble surface	0.025
Dry-rubble surface	0.033
Earth canals, straight	0.022
Earth canals, winding	0.027
Natural streams:	
clean, regular	0.030
weeds, stones	0.035
winding, pools, shoals	0.040
sluggish, weedy	0.070

Floods

Floods are usually harmful to snail populations, because of rapid flows and in some cases a marked drop in temperature which is sufficient to interrupt breeding. Moreover, the presence of a heavy silt burden reduces the amount of light penetration; hence the algae and other aquatic plants, which provide the snails with food, are affected.

The seasonal occurrence of floods has some effect on the fluctuation of snail populations, since it not only dislodges or destroys many individuals, but also interferes with, or temporarily prevents, breeding. Some individ-

[1] Adapted from King, H. W. (1954) *Handbook of hydraulics*, New York, McGraw-Hill Book Company Inc., table 76, p. 7-20.

uals in sheltered spots usually succeed in surviving the floods, and play an important role in subsequently repopulating the stream.

It must not be overlooked that flooding may lead to the creation of additional snail habitats outside the bed of the stream. Overflow may follow if floods in tributaries occur simultaneously instead of in succession, or at times when the main stream is itself in maximum flood. The resulting swamps and marshes may remain long enough to provide a large number of additional habitats. Snails to colonize these habitats are often transported to them by the flood waters.

Before embarking on any flood control schemes, it is desirable to have data respecting frequency and peak discharges. In some streams floods occur regularly and can be predicted with accuracy; in others they show unpredictable irregularity.

For small streams flood control is best carried out by enlarging and improving the channel; sometimes the raising of the stream banks by levees may prove practicable.

Aquatic vegetation

Water plants form a desirable but not an essential feature of the habitat of the aquatic snail hosts. Bulinids appear to be slightly more dependent than planorbids upon the occurrence of aquatic vegetation, but both types of snails can subsist in its absence provided other food material is available.

Plants apparently favourable to the aquatic snails include, among many others, Nympheaceae, *Potamogeton*, *Pistia*, *Ceratophyllum* and *Myriophyllum*. Broad-leaved plants provide suitable surfaces for the deposition of eggs and for the growth of unicellular green algae which form a favourite snail food. There is no doubt that the microflora and fauna on the leaves of these plants are more important to the snails as a source of food than are the plants themselves.

Water plants also provide the snails with shelter and protection from intense sunlight and from the mechanical effects of fast current. In habitats exposed to bright sunlight, planorbids and bulinids are generally found sheltering on the underside of the leaves, where the temperature may be two or three degrees lower than in more exposed situations. Oxygen tension may also be higher, especially on the underside of leaves such as those of water-lilies which have no cuticle. The underside of leaves therefore forms a favourite microhabitat. In some cases, the translocation of oxygen to the roots of water plants provides water snails with a microhabitat having a high oxygen tension near the bottom.

Oncomelania spp. are usually found in habitats with emergent vegetation or vegetation growing closely along the bank near the water's edge, on account of their amphibious habits. Such plants shade the habitat and their transpiration cools the air and makes the habitat more favourable to snails emerging from the water. Decaying vegetation from water plants assists in the formation of a suitable substratum and provides additional food for the snails.

Pollution

Pollution by decaying organic matter is a common phenomenon in streams but is markedly more pronounced in the vicinity of human habitations, owing to the casting of animal rubbish (bones, skins, fragments of meat, carcasses, etc.) and plant rubbish (vegetable parings and discards, waste fruit, etc.) into the water. Such pollution, if not enough seriously to upset the biological oxygen demand, is definitely favourable to the occurrence of snails that transmit bilharziasis and appears to provide them with a rich source of additional food.

A moderate degree of pollution with human excrement is favourable to the establishment of large populations of snail hosts. It is not known, in most cases, whether this favourable effect is due to faeces or to urine, since the effects of these two types of excrement can normally not be differentiated, but there is some evidence to show that the pollution of streams by urine alone has a favourable effect on the snail populations. A moderate degree of pollution with animal excrement also appears to be sometimes favourable.

Other forms of human interference

In many sections of Africa south of the Sahara the construction of dams for the purpose of soil conservation and water storage has led to the formation of favourable new habitats.

For *Oncomelania* spp., the same principles apply, but the changing of water flow is on a much smaller scale. The repeated temporary damming of the small streams in order to catch fish, the presence of water-buffalo wallows, and the use of small dams to divert water to the rice-fields, are examples. These and similar diversions force the water away from any defined channel, soften the stream bed, make the flow more sluggish, and encourage the growth of semi-aquatic grasses and other plants which further impede the water flow. This vicious circle produces ideal habitats for *Oncomelania*.

Microhabitats

Reference has already been made to the existence of microhabitats in which the snails can survive and breed in streams in which the general conditions are unsuitable for their establishment. This is an important matter, since failure to detect microhabitats or to consider their possible formation may vitiate the effect of control measures.

Conclusion

It will thus be clear that, in devising environmental control measures directed against the intermediate hosts of the schistosomes in natural streams, particular attention should be paid to increasing the velocity of flow of the water, to straightening of banks and elimination of pockets and pools, to the clearance of aquatic vegetation, to the avoidance of pollution and to the elimination of microhabitats. The success of the measures taken will depend in large degree upon the extent to which these aims are achieved. The nature of the substratum will not generally be susceptible of alteration, but will provide some guide as to the possible presence of snails during the preliminary investigations.

Reduction and control of snail habitats in streams

Stream channelization

Marshy margins, seepages and small tributaries of streams in many regions provide important breeding-sites for host snails. Streams with these characteristics are always costly and difficult to treat with molluscicides. The vegetation-choked margins and the seepages along the banks tend to keep the chemical introduced upstream from penetrating many snail-infested areas. Unless they are treated separately, each tributary is a potential pocket from which surviving snails may emerge to repopulate the treated portions. As the chemical flows downstream, additional water tends to reduce the concentration to impotency. For these reasons stream channelization, not only to improve the flow characteristics, but also to facilitate effective application of molluscicides, is often necessary to eliminate or reduce snail breeding-sites. After channelization, any remaining snail colonies can usually be eliminated by mollusciciding.

Stream channelization has been used to control *O. quadrasi* in Leyte, Philippines. The following evidence indicates that it can be effective against aquatic intermediate hosts. In 1950 a section of the Latanier River extending for some distance above the Père Laval School at Ste Croix, through Port Louis, Mauritius, to the sea was channelized with concrete and rubble to prevent the breeding of mosquitos. Before this was done, the stream served as a habitat for the local intermediate host of *S. haematobium*. A survey of the schoolchildren showed that 63% had bilharziasis. In 1959 snails were found in parts of the stream above the channelized section but were not present where the mosquito breeding-sites had been eliminated by channelization. Seven years after the initial survey of the schoolchildren, and after only partial habitat elimination in the watershed, it was found that only 25% were infected. The absence of protected nooks and relatively frequent flash flooding were factors that prevented the establishment of snail colonies in the channelized reach of the stream. These observations demonstrate that, in order to be completely effective, snail control measures must extend throughout the infested portion of the watershed.

Although stream regulation is a specialized field of civil engineering, the problems encountered in the channelization of streams as a snail control measure are not particularly difficult. It is, of course, desirable that engineers entrusted with stream channelization should have adequate training, experience, facilities for field investigations and access to experimental data and reports on similar works in various parts of the world. Literature on this subject is mainly found under the heading of " river regulation ".

Field investigations consist of topographic, hydrographic and geological surveys. Topographic surveys are necessary for the determination of the physical features of the watershed such as its size, shape, drainage pattern, slope, vegetation cover, land use, tendency to erosion and any other special features. Hydrographic surveys furnish information on stream flow and facilitate the correct interpretation of rainfall data. The geological survey reveals the general land formation, soil types, and the presence of suitable materials that can be used for carrying out corrective measures.

Until recently most of our knowledge on stream-training methods was based mainly on field observations. Advances in the field of hydraulics have made possible the study of the behaviour of streams under controlled laboratory conditions. The critical application of both field and laboratory observations in the design and operation of training projects is necessary to ensure their effectiveness and to keep construction costs down to a reasonable level.

In the design of stream training projects it is necessary to select cross-sections and grades that limit the maximum tractive forces to the value that will not cause scouring of the bottom and sides of the channel. Due to considerable variation in the resistance to erosion of the stream channel, it is not easy to determine this limit with any degree of accuracy. However, observations after the completion of the work will disclose local weakness and then remedial measures may be taken.

The capacity of the stream to transport the estimated quantity of sediment is another factor which must not be overlooked. Again, due to wide fluctuations in discharge stages and sediment load, only an approximate solution is possible. The maximum quantity of sediment is usually carried by a stream at its maximum flow and the hydraulic design should be based on this value. A rough estimate of the quantity of sediment transported over a given period may be made from the flow-duration characteristics of the stream and the density of sediment at various stages of discharge.

When there is neither scouring nor deposition over a period of several years in a channel the stream is said to be in regime. The various factors that bring about such stability in streams and canals are discussed on pages 93-100.

For snail control work, stream regulation generally involves improvement of grade and stabilization, channel contraction and bank protection works. The stream bed should form a continuous gradient without depressions. At no point along its length should it be possible for water to accumulate so that snails can develop in residual pools if the stream dries out. Limited dredging may be carried out by manual labour or by use of heavy equipment including bulldozers and dragline excavators.

Grade correction and stabilization require the use of training walls and dikes to direct flow so as to establish favourable channels which will prevent scour and erosion. Concrete sills, mainly at scoured bends, may also be necessary. Choice of channel contraction methods depends largely on the need for re-alignment and the suitability of local materials. In some cases use of concrete, steel-sheet piling or timber has proved effective. In other cases, wire baskets filled with stones have been satisfactorily employed. Bamboo or timber cribs and fascine mattresses may also be used. In Mauritius masonry walls with cement joints have proved economical and durable. When stone or rock are not available, concrete blocks made from rather weak mixes may be used for bank protection works. In India the use of soil cement blocks has proved satisfactory. The blocks are made from a mixture of sandy soil and 5 % Portland cement. Stabilized soil blocks may also be used for short-term protection. Small streams may be enclosed in corrugated metal or concrete piping, which also reduces human access to the water and exposure to bilharziasis. Adequate training works may also be provided by rock fills or the planting of various trees such as willows and the grassing of the banks.

In stream-training work special measures are usually required at bridge, culvert and causeway sites to prevent scouring of the bank and to ensure the stability of the foundations. From the engineering point of view scouring is especially dangerous where a roadway parallels a stream. Protection of the slope against stream erosion by the use of flexible mats, retaining walls of metal or concrete, timber or steel-sheet piling may be necessary. Such localities are also dangerous from the point of view of bilharziasis transmission, since human access is easy and snail colonies may develop in the slack water on the convex side of bends.

Problems where streams pass villages

From the point of view of transmission of bilharziasis three types of problems arise where snail-infested streams pass villages in endemic areas —namely, contact, pollution and blockage. Under these circumstances, it is desirable and perhaps possible to limit human access. However, methods of preventing human contact with the infested water will not be successful unless alternative sources of safe domestic water are provided.

Bathing pools, separate from any other bodies of water, preferably cement-lined and filled with clean chlorinated water, may justify the expense of their establishment by saving the cost of treating infected children. In hot climates children bathe frequently, and unless provided with safe bathing-places they will naturally use the infested stream.

Although rarely possible, it is desirable that villages should be sited as far away as possible from infested streams. A minimum distance of 500 metres has been recommended. Where a new settlement is planned this may be done, but in other cases it may be easier to alter the channel of the stream so that it is directed away from human habitations. An alternative method of limiting human access is to flank the stream through the village and for a distance of 500 m on either side by high walls or fences. Perhaps the best method of access limitation, where engineering and budgetary considerations permit, is to enclose the stream completely within the same limits in a long culvert or underground channel.

Provision of latrines and of adequate waste disposal facilities are obviously essential measures ; but if they are to be effective the people must be induced to use them. This implies that an adequate and permanent sanitation service exists in the local health administration. It is the duty of local sanitarians to participate, together with public health officers and visiting nurses, in educating the people in health matters and in improved hygienic practices.

Discharges from public fountains and wells and effluent from public lavatories and sewage-treatment plants must not be allowed to drain into the stream or to create stagnant pools which may become snail habitats. Effective snail control in such cases may require concrete filling, subsoil drainage or absorption trenches. Where, due to the presence of large quantities of water or to topographic features, it is necessary to effect drainage by open channels, provision should be made for periodic treatment with molluscicides.

Where limitation of access as described above cannot be practised, it is important to ensure that nothing is dumped in the stream which may cause blockage which, in turn, will lead to obstruction of flow and ponding and thereby provide favourable snail habitats.

Seepages

Seepages along the margins of streams may give rise to pools or even to swamps and marshes in which the intermediate hosts find favourable conditions for breeding. In the Philippine Islands *Oncomelania* is able to maintain colonies on patches of ground kept moist by small perennial seepage flows. It is therefore important to eliminate seepages wherever possible.

Where a stream is flanked by low-lying, level ground, a considerable area of this may be affected by seepage. In such cases it is necessary to lower the water table on either side of the stream by the construction of drainage ditches or by installation of a subsurface drainage system such as French drains or perforated pipes laid in trenches filled with broken bricks or stones.

On slopes near the source of the stream and, more rarely, on lower and more level ground further down the course of the stream, seepage from springs may constitute a serious problem. Drainage in such cases will involve the construction of interception ditches by which the water can be conducted into the main stream channel without the formation of pools or marshes. It goes without saying that the drainage ditches must themselves conform to the principles laid down for the prevention of the formation of snail habitats.

The principal source of seepage along the course of many streams is the permeability of the levees or dikes constructed to confine the additional discharge during times of flood and prevent overflow. Seepage may decrease with the passage of time if the waters of the stream carry a heavy load of silt, since the fine particles tend to fill the voids in the levee ; for this, however, it is generally necessary to take some steps to reduce its permeability. Prevention or reduction may be accomplished during construction of the levee by the use of less permeable material, such as clay mixed with sand or gravel and well puddled or rammed. The same effect may be achieved by lining the levees on the water side with an impermeable layer of well-tamped clay, clay mixed with sand or gravel, or concrete. In swiftly flowing streams it may be necessary to protect the puddle from erosion by a layer of coarser material.

Plastic film, butyl sheeting and asphalt-coated fabrics can be used also to reduce the permeability of levees. These materials are less subject to blowouts than is clay. The liner should be anchored in a trench well below the bed of the stream, brought up over the embankment, anchored in the top of the embankment, and covered with at least two feet of fine-textured earth topped with gravel or other non-erosive material.

Marshes and swamps

Flood plains and low-lying marshy ground bordering rivers and streams or fringing shallow lakes are not uncommon in some endemic areas. In some cases the stream loses its defined channel and spreads out to become a swamp. Another type of marsh or swamp is that which forms in a shallow depression surrounding a spring. All of these are commonly colonized by the snails. Drainage, filling, ponding, or pumping either eliminate the breeding-sites or reduce them to a point where it is practicable to apply molluscicides.

The planning of drainage schemes must be preceded by thorough investigations of the hydrological factors, topographical features, and the soil properties of the area involved. This must be followed by the selection of the methods of construction and the types of equipment that will be needed. The drainage channels should be located in such a way as to facilitate farming operations and provide easy access to the various subdivisions. The over-all planning and budgeting for such a scheme should include the location of building sites, roads, safe water supplies and waste disposal. Provision must also be made for the maintenance of the drainage system.

In marshes of limited extent, engineering operations are relatively simple, and most of the work may be carried out by local labour with hand-operated equipment. As the water drains away, the initial trenches can be deepened to the desired level. Then after a short period of drying and consolidation of the soil, light excavators may be used to dig wider and deeper drainage channels. In the reclamation areas in Holland, a snow-plough type of ditcher has been used successfully to excavate shallow drains.

Light trenching machines for use in relatively soft ground are now available. One type weighs less than one ton, digs a trench 12 inches wide by 30 inches deep, can excavate over 100 feet per hour, has tracks that spread the weight to 518 lb/sq. foot, is only 3 feet wide, 3 feet high and 7 feet long, with a bulldozing blade 3 feet by 18 inches, and can be easily transported on a trailer. The total price, including the trailer, is approximately $3000 in the USA.

Drainage channels must be kept free from aquatic growth and may have to be treated periodically with molluscicides, since the snails which formerly inhabited the marsh probably will now be confined to them. Drainage channels are less likely to support breeding populations of molluscan hosts if the drainage flow (which, usually, is relatively small) is concentrated in lined inverts laid with a uniform gradient. This discourages the growth of rooted water plants at the bottom and makes cleaning an easy matter.

Vertical drainage wells dug into a porous substratum have also been successful in draining some isolated marshes.

For marshes of limited extent, where drainage involves relatively small quantities of water, subsoil drainage may be used to advantage. Investigations in many areas have shown that the income from the cultivation of such low-lying areas is considerable and would pay for the cost of drainage in a few years. The engineering aspects of subsoil drainage are treated in some detail on pages 110-112.

In any drainage scheme where the land is to be used for cultivation, filling and grading are essential for good crop yields and help to eliminate snail breeding-sites. While this appears to be self-evident, there are many areas where it has not been done. The material used for filling can be obtained from the levelling of higher areas, earth removed from the drainage channels or ponds, and suitable types of refuse. In coastal areas where sand is available, this can be used as fill; if covered with a foot of soil it can be used for crop production.

In places where drainage and filling are not practicable, or are only partially effective, periodic pumping from wells or channels may be a satisfactory method of drying up marshes. Where pumping is required daily or every few days, pumping stations should be established. If electric power is not available, diesel engines should be used. Where pumping is not required frequently, a truck-mounted pumping unit driven by a petrol engine could be used to cover several water-collection points.

In some localities marshes have been eliminated by constructing ponds and using the earth excavated as fill. This has somewhat the same effect as drainage channels—that is, it allows cultivation of more land, and confines the snails to limited habitats where supplemental measures can be applied. This has been used successfully in Australia and the USA to control the snail intermediate host of *Fasciola hepatica*, a trematode causing serious loss among domestic animals. It has also been effectively used in the marshy-margined, slow-flowing streams in Leyte to control *Oncomelania quadrasi*. By this method the amphibious intermediate host is eliminated from the drained marsh, and the ecological conditions in the ponds do not provide a suitable habitat for it. Unfortunately, these ponds often serve as excellent habitats for the aquatic intermediate hosts of *S. mansoni* and *S. haematobium*: even so, such ponds tend to limit the number of breeding-sites and make fertile soil available for cultivation.

Drainage and reclamation of extensive marshy areas are highly specialized and relatively expensive operations, requiring the use of a wide range of excavating and earth-moving equipment. In addition, pumps may be required to obtain satisfactory drainage after the channels have been constructed. For these reasons, large-scale drainage schemes ordinarily are impractical as a disease-control measure alone, and must be a part of a land reclamation and utilization programme to be economically feasible. Fortunately, the long-term value of such reclaimed land is often far greater than the cost of the drainage works.

Lakes and ponds

The association of the amphibious snails with lakes has never been reported. Lakes differ in their suitability as habitats for the aquatic intermediate hosts, but are often potentially or actually favourable to their establishment. No lake in an endemic area can be considered free from these snails until it has been thoroughly investigated along the whole length of its shore-line, since favourable habitats may be restricted to very limited areas. Snail control in large permanent lakes need be carried out only along stretches of the shore with which there is human contact and in adjacent areas from which snails and cercariae may be brought by the current.

Where host snails occur in lakes they are usually established in the shallows along the shore line. Only one species, *Biomphalaria choanomphala*, an intermediate host for *S. mansoni*, has been reported from deep water in Lake Victoria. Where shallow-water species are involved in transmission, the habitat may be rendered less suitable by the deepening and straightening of the margins and by clearance of all aquatic vegetation. Such work requires the use of graders or bulldozers ; and can be done best when the water level is low. Provision should be made at the same time for roads along or close to the edge of the lake to provide access for weed control and molluscicidal operations. Where the presence of swamps or dense forests make treatment from the shore difficult or impracticable, weed control and molluscicidal operations may have to be carried out from boats or barges. In this connexion, however, it has been observed that in Ghana and Southern Rhodesia snails do not thrive where vegetation along the margins of impounded waters is very dense. Such dense vegetation also limits human contact and transmission. Ultimate control can generally only be achieved by the subsequent application of molluscicides.

In arid, tropical or subtropical endemic areas many of the smaller lakes are not permanent nor sharply differentiated from marshes. Excessive evaporation under the intensely hot summer sun and, in certain areas, very low relative humidity, together with great variation in inflow of water due to fluctuation in precipitation, lead to great and rapid changes of level. Thus, a body of water which in one year or at one season may be deep and extensive, and justify the name of lake, may in another year or at another season be shallow, with emergent vegetation everywhere, and be justly regarded as a marsh. Such fluctuations of water level are not necessarily inimical to the snails since they take place slowly enough for the molluscs to adapt themselves to the changing conditions. Such marsh-lakes which frequently harbour abundant snail colonies can generally only be dealt with as part of a major land-reclamation programme.

In addition to lakes, ponds in endemic areas almost invariably offer favourable conditions for bilharzia snails and therefore require particular attention. Moreover they are often important foci of infection, since people are tempted to use them for domestic and recreational purposes and as watering points for domestic animals.

Filling-in is the most satisfactory method of control in such cases, but rarely practicable. Fencing such ponds to limit human access has been tried with success in some areas. Resort may be had to treatment with molluscicides. It goes without saying that provision of alternative, safe supplies of water for human needs is essential wherever a pond which has played an important role in the life of the local community is thus brought under control.

Soil erosion

Soil erosion in endemic areas may result in the creation of suitable snail habitats by blocking watercourses and drains, by increasing flood flows and in other ways interfering with the natural drainage of the area. Methods that have been developed recently to control soil erosion, such as improved land-use practices, not only result in considerable economic benefits but also contribute to snail control.

The provision of soil erosion control works has become important enough to require the services of specialists in the field of soils, agriculture and engineering. Where such a programme is under way, the reduction or elimination of snail habitats will be relatively easy. In regions where such is not the case, however, the engineer may have to fall back on his own resources and carry out such works as controlled drainage, filling, slope stabilization, grassing and reafforestation.

MEASURES APPLICABLE TO IRRIGATION SCHEMES

The considerable increase in the prevalence of bilharziasis which has followed the establishment of irrigation schemes in most endemic areas of Africa and Asia has been viewed with serious concern by national and international agencies concerned with public health and land development. Attempts have been made to study a number of such schemes in order to ascertain the characteristics which tend to limit the creation of snail habitats and which facilitate snail control measures. These characteristics will be discussed in the following sections in the hope that they will receive the consideration of authorities engaged in the planning of new irrigation schemes and in the improvement of existing ones.

The Planning of Irrigation Schemes

The successful development and utilization of an irrigation scheme are so intimately related to community interest and activities that the planning should be on a broad basis. Consideration should be given to the available land and water resources, climate, crops, people, health aspects and the effect of other water-use developments such as hydroelectric power, water supply, flood control, navigation, fish and wildlife, and recreation.

The detailed planning of the scheme should be based on thorough investigations of topographical features of the proposed area, soil properties, climate and hydrological factors, crops and their water requirements. It should also take into account the prevalence of human and animal diseases, vital statistics and available scientific data applicable to irrigation schemes, organization, engineering services, operation, management, and economic and marketing factors. In many schemes engineering design and construction are concerned only with the dam and main canal, leaving the distribution system in the hands of the cultivators. Inadequate preparation of the fields and faulty distribution lead to unnecessary waste of water and soil and result in low productivity. Often complex and antiquated land tenure laws and water rights further hinder the efficient distribution of water.

Water resources are limited and their development requires huge capital investment. It is therefore all the more necessary that their planning be based on sound economic considerations. Cost estimates should include recurrent as well as capital expenditure. Under recurrent expenditure full provision should be made for regular maintenance and for any special measures required for snail control, such as the cost of barriers and of treatment with molluscicides.

In some areas where snail control has been carried out for a period of several years by molluscicides alone, it has been possible to determine the annual cost of the chemical and the labour required for application. It has been found that such a programme may cost up to $3.00 per irrigated acre [1] annually. It is believed that costs of this magnitude should be considered in the planning and design of irrigation systems, especially since corrective measures can be used to reduce this figure.

The Gezira scheme in the Sudan and the Miwani scheme in Kenya may be cited as examples of well-planned and well-managed irrigation projects in areas in which bilharziasis is endemic. In the first area, reasonable snail control has been achieved by the use of molluscicides and screens at an annual cost of less than one dollar per capita of population. In the Miwani scheme, effective control of irrigation water and efficient farming practices have prevented snails from becoming established in the area.

In other schemes where the planning and management are of a lower standard, snail control methods would be inefficient from the points of view of both cost and effectiveness. Moreover, such schemes are characterized by wasteful use of water, poor agricultural practices, low crop yields, inadequate maintenance and management, and poor health, and as a consequence these communities cannot afford the cost of snail control.

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[1] One acre is about 0.4 hectare.

Some of the more important considerations in the design and operation of the components of an irrigation scheme will be presented in the following sections.

Storage

The selection of reservoir sites should be preceded by surveys of the prevalence of human schistosomes and their intermediate hosts. Storage reservoirs usually provide suitable habitats for some species of aquatic intermediate hosts, and if these are present in the watershed they may invade the reservoir.

In other cases snails do not adapt themselves readily to the reservoir environment but may be able to migrate through it to suitable habitats in the irrigation system below the dam. Thus, *Bulinus* and *Biomphalaria* are both present in the upper reaches of the Blue Nile ; but, while the former is found in both the reservoir and the irrigation system, the latter is found only in the irrigation system. In Japan and the Philippine Islands the vectors of *S. japonicum* have not been found in reservoirs, although ecological conditions along the margins of the reservoirs seem favourable for the establishment of snail colonies.

Where evaporation losses are high, additional water has to be stored to meet the requirements of the irrigation project. This additional storage increases the length of the shore line and consequently the extent of snail breeding-sites. Evaporation losses from the Sennar Reservoir in the Sudan are estimated at 135 000 000 m^3 per year, representing one-fifth of the water diverted for irrigation. If losses of this order can be reduced, the marginal area which is suitable for the establishment of vector snails may be similarly diminished. The application of a monomolecular film of cetyl alcohol may reduce evaporation losses appreciably. Experiments by the United States Bureau of Reclamation and the Commonwealth Scientific Industrial Research Organization of Australia have demonstrated that evaporation losses can be reduced by the application of cetyl alcohol at moderate cost. At Lake Hefner in Oklahoma, having an area of 2500 acres (about 1000 hectares), 9% reduction in evaporation was achieved over a period from 7 July to 1 October 1958. The success of such application depends on wind velocity, and is very marked in areas where this seldom exceeds 15 km per hour. Efficiency would be markedly reduced in waters subject to turbulence.

Where alternative sites are available, preference should be given to areas either where snails are not present or where control measures are relatively easy. It is also sometimes possible to select areas which are relatively sheltered from strong winds and thus reduce evaporation losses. However, because of freedom from wave action, sheltered areas tend to provide more suitable snail habitats than do exposed areas, and this drawback may offset the advantages of reduced evaporation losses.

It is the practice to clear reservoir sites before inundation, and the extent of such clearing depends on the utilization to be made of the water. For irrigation purposes it is not usual to carry out as thorough a clearing as for water supply schemes, but sufficient clearing must be done to prevent damage to regulators and spillway gates from floating debris and driftwood. In addition, work should also be carried out for the purpose of facilitating snail control. In shallow areas, edges of reservoirs and vegetation usually provide suitable snail habitats, which may necessitate a number of control measures. The shore line may be shortened and steepened by the construction of dikes or by deepening and filling. Shallow pockets especially may be deepened, graded, filled or connected with the main body of water so that they do not become isolated pools when the water level drops.

Where appreciable seepage under the dam or around the abutments occurs it must be either stopped or drained away. In some cases such seepages, particularly during the first few months after construction, are important enough to warrant corrective measures from considerations of water loss alone. In small reservoirs clay and plastic linings may be used. In earth dams such as have been built in Ghana and Togo, seepage and overflow around and over the spillways and their channels provide suitable snail habitats, which may be eliminated by channelization and subsoil drainage. Often paving of the spillway channel with concrete or stone would facilitate snail control.

Water level fluctuation as a means of mosquito control has been practised with considerable success for some time. There may be instances where such a procedure would be effective and practicable for the control of aquatic snails in small reservoirs. It is possible that certain species of snails would not survive long periods of desiccation on exposed marginal areas under conditions such as are prevalent in Africa, eastern Mediterranean countries and Brazil. For water-level fluctuation fairly large outlet gates are required. Such gates will also permit lowering of the water level just before rainy seasons, and thus assist in getting rid of deposited silt, enable a grader to trim the shore line, facilitate removal of weeds and carry out any other maintenance work.

The provision of water take-off pumps and valves would considerably reduce the need for human contact with infested water in reservoirs. Fencing of small reservoirs as a means of preventing contact with, and pollution of, snail-infested water should also be considered.

Where human access to a reservoir is unavoidable, jetties might be erected so that people will not come into contact with snail-infested water near the shore, since the cercariae may be expected to be more frequent there.

Where excessive silting takes place, dams have to be constructed to store additional water, thus again creating potential snail habitats. By the institution of soil conservation practices in the watershed silting may be checked, and for the same extent of surface area greater volumes of water become available.

Diversion

Location, design and construction of diversion works play an important part in the efficient operation of irrigation schemes and in the prevention of the introduction of snails into the distribution system. The type of structure used depends on whether diversion involves an impounded reservoir, a weir or a pumping station.

For a diversion from a reservoir, intakes should be located some distance from the shore or the dam. They should be well submerged, and should be provided with galvanized screens having three meshes to the centimetre and protected by coarser screens.

Where diversion is from a low weir the chances of snails passing into the distribution system are greatly increased. It is advisable, therefore, to provide baffles as well as fine screens similar to those mentioned above. Investigations in the Gezira area have shown that about 70% of snails carried by the current are transported on trash at or near the surface of the water, and that no snails have been observed to be carried below a depth of 50 cm. This finding may be used as a guide in the design of baffles and screens in snail control work, taking into consideration the characteristics of the canal and of the flow, such as velocity and turbulence, which may affect the vertical distribution of the water-borne snails.

The canal intake structures should be located at right angles to the flow of the river. Provision should then be made, by means of baffle walls and a gate through the weir and close to the intake, to induce either a continuous or an intermittent flow in front of the intake in order to keep it free from sediment. The bottom of the intake should be a few feet above the stream bed, in order to prevent the entry of bed-load sediment. Racks should be provided to keep out trash and to protect the fine screens. The works should be located either on a straight stretch of the river or near the end of an outer concave bank, where the flow and bed-load are deflected away from the bank. Some river-training works may be necessary for stability and for the control of bed-load deposition.

Where water is diverted by pumping, care should be exercised in locating the suction pipe well away from the river bank and providing a strainer of three meshes to the centimetre. Snails have been reported to pass through centrifugal pumps unharmed, and have established thriving colonies in the distribution channels. Snails have also been found in concrete pump-wells and tanks.

The design of diversion structures should provide for the quantity of water required to meet the expected consumption, the irrigation losses and the conveyance losses under conditions of partial blockage of the trash-racks and screens.

Where silt traps are provided, the installation of baffles and screens is much facilitated. It is often more economical to prevent silt from entering canals than to remove it periodically or to provide for its transportation in suspension directly to the fields.

Distribution

Inadequate or incompetent planning of irrigation schemes is more often evident in the design, construction and operation of the distribution part of the scheme than in the design and construction of such major structures as dams and main canals.

According to the *United States Department of Agriculture Year Book, 1955* (Washington), water losses observed as recently as 1949 in an irrigation scheme in a western state were very great. The quantity of water diverted would cover the irrigated area to a depth of 3.1 m, but the depth of water actually used by plants was only 0.3 m. The losses were estimated as follows :

1.5 m of water lost in conveyance and regulation
0.5 m lost in surplus run-off
0.7 m lost in deep percolation
0.1 m lost in evaporation

Of these, conveyance, regulation and run-off losses may be reduced by improved design and construction. While this may be an extreme case, losses of the order of 60%-70% of the water diverted are common. In the State of Victoria, Australia, losses between the storage reservoir and the irrigation field are estimated at 60%, of which half is due to seepage losses from canals. In some parts of India conveyance losses amount to as much as 50% of the quantity of water diverted. Due to lack of simple means of measuring seepage, it is difficult to ascertain the true losses. However, before any corrective measures are taken, the extent of the seepage can be estimated by the method of inflow-outflow over a measured length of the canal.

Some of the important effects of seepage from irrigation canals are :

loss of water
reduced delivery to the irrigated areas
waterlogging of adjacent lands which may be rendered useless
damage to roads, bridges and other structures
an increase required in the capacity of drainage works
creation of snail habitats.

Canal linings

As far as snail control is concerned, the lining of canals does not necessarily prevent the establishment of snail colonies. Snails do not occur in the lined canals in Mauritius, but observations in Tunisia and elsewhere have shown that concrete flumes and concrete-lined canals can sometimes provide suitable habitats for snails. However, the relatively high velocities which are possible in lined canals, and the relative absence of aquatic vegetation, not only make them less attractive as snail habitats than earth canals but also facilitate rapid drainage and drying. Moreover, lining reduces seepage to low-lying areas which may otherwise become potential breeding-sites. Finally, the application of molluscicides, where advisable, is more effective and less costly in lined canals than in earth canals. Other advantages of the lining of canals, and some of the engineering aspects, are treated in the following paragraphs.

Excessive seepage losses from irrigation canals can be reduced by the use of various types of lining. However, it is first necessary to establish the economic benefits to be derived from such a step and to carry out field investigations to ascertain the most suitable type of lining to be used. In some cases it may only be necessary to line sections of the canal that run through the more permeable soils or unstable foundations. In other cases lining may be carried out in stages as water requirements increase.

In the design and construction of hard-surface linings such as concrete and bitumen, the preparation of the sub-grade is most essential in order to provide sufficient support for the lining and to avoid cracks caused by settlement. The principal types of canal linings are Portland cement concrete, bituminous concrete, bituminous membrane, plastic membrane, asbestos cement lining and clay lining. Brick may be available in some areas.

The Portland cement concrete linings are usually 5-10 cm thick and are not reinforced. Transverse joints are provided at intervals of 2-3 m. Precast concrete slabs and block sections have also been used successfully. Bituminous concrete linings are usually 5-7.5 cm thick and are placed on soil which has been treated with some chemical to prevent weed growth. The mixture contains 5%-10% by weight of bitumen. It is placed as a hot mix and packed by rolling. After compaction a sealing coat is usually applied.

In buried membrane linings excavation of the canal section is extended by about 30 cm and the sides are given a two-in-one slope (two horizontal to one vertical). Before application of the hot bitumen, the sides and bottom of the canal are sprinkled with water and a hot spray at a pressure of 3.5 kg/cm^2 is applied at the rate of 8 litres/m^2. Three coats are usually necessary to produce a thickness of 6-8 mm. The bitumen is then covered promptly with 15 cm of earth, and then another 15 cm of gravel are added to bring the cross-sections of the canal to the desired dimensions. In the USA a 50-60 penetration catalytically-blown asphaltic cement is used. In order for such linings to be serviceable, a special grade of asphalt must be used.

The use of asbestos cement sheets for canal linings has given satisfactory results in Southern Rhodesia and in Bulgaria. In Southern Rhodesia, prefabricated corrugated asbestos cement sheets with relatively flat corrugations have been used. Sheets are rolled into a parabolic shape and are specially cast to accommodate curves in the canal. The sheets are bolted, and no joint filler is used. In each case preparation of the sub-grade is important. In Bulgaria, half-round asbestos cement sections, varying in diameter from 30 to 110 cm and in thickness from 5 to 12 mm, have been successfully used.

Other buried linings, such as plastic films and butyl sheets, may be employed. Installation of these materials requires a limited amount of equipment, and a better water barrier can be assured where inexperienced help must be used.

The choice of any particular type of lining depends on local conditions, initial cost, and maintenance. These factors can only be evaluated for any particular locality by adequate investigations. For example, observations have shown that where canal velocities are low and excessive silting takes place, silt removal from lined canals may be more expensive than the removal of both silt and weeds from an unlined canal. There is also the likelihood of damage to the soft linings by livestock and equipment. Research in this field of irrigation is still under way in various parts of the world, and especially in the USA. While the various types of linings have their particular fields of application, for snail control the most suitable type is concrete.

Closed conduits

The use of closed conduits for the conveyance of water in distribution systems is rather limited due to the higher cost as compared with that of open conduits. In some cases, as in California, for instance, the low cost of making concrete pipe and the high crop returns from well-managed farms render the use of closed conduits well justified on economic grounds. The Miwani Sugar Estates in Kenya, mentioned earlier, use closed conduits to deliver water from the pump station on the river to the field canals. This practice, and the irrigation cycle used, appear to prevent snail-breeding on these estates.

In endemic areas, the use of pipes for the carrying of moderate discharges requiring pipe sizes of up to 1.5 m in diameter may be justified on the grounds of irrigation considerations alone and, at the same time may bring about the elimination of important snail breeding-sites. In some countries much larger conduits have been used, but for conditions in eastern Mediterranean countries and Africa the sizes should be limited in accordance with facilities for pre-casting concrete pipes in field factories and transporting them to the sites. Pipes for use in irrigation schemes can be readily manufactured in field factories by moderately skilled labour at reasonable cost, which, depending on local conditions, may be no higher than for concrete lining of canals.

The use of pipes results in a number of benefits which may more than offset the capital outlay. For instance, water losses due to seepage, evaporation, and transpiration by weeds are either greatly reduced or entirely eliminated. This saving of water would allow additional land to be irrigated. On account of the adoption of relatively high velocities, silting is practically prevented. The use of pipes greatly facilitates water control, reduces maintenance, makes more land available for cultivation, and facilitates transport and farming operations. In endemic areas, considerable savings in labour and molluscicides would result from the use of pipes as against open canals, since no snail control work would be required. Of all snail control measures, the use of closed conduits is the most effective.

Regulation

Effective regulation of water flow in an irrigation scheme is necessary to ensure adequate supplies to the fields ; to reduce fluctuations in demand and hence the need for large canals in the distribution system ; to prevent damage to canals and structures from overflow ; to reduce water losses ; and to enable sectors to be isolated for maintenance and repairs. This latter facilitates periodic drying-out of the habitats and is necessary for the efficient application of molluscicides (see chapter 4, page 162).

Control structures comprise gates at the main intake and distribution system, balancing reservoirs, large-capacity holding canals, fixed overflow spillways, spillways provided with gates, automatic water-level regulators, gates for isolating various sections of the canals, and various types of meters or other water-measuring devices. The most commonly used type of gate in irrigation schemes is the vertical-slide gate of various designs, depending on size. The radial gate has now largely superseded the slide gate where a large regulator is required. In some cases gates are used for metering the water deliveries. Elsewhere, specially constructed propellor-type or blade-type water-measuring devices are used, such as the Dethridge meter used extensively in Australia. More recently, various types of automatic water-level regulators have been used. These consist essentially of radial gates operated by floats, and are used for either upstream or downstream regulation in an irrigation canal.

Provision for isolating areas of an irrigation scheme, regulation of water flow, and measurement of discharge are of special importance in snail control; and for this purpose an adequate supply of gates is necessary.

Silting

Silting in irrigation canals reduces velocities and encourages the growth of aquatic weeds, and these conditions in turn contribute to making suitable snail habitats. Observations have shown that snails thrive much better in field channels where silting is excessive than in main canals where it is usually moderate. In endemic areas, therefore, the prevention or reduction in the deposition of silt in canals is of benefit not only to the functioning of an irrigation scheme, but also to a snail control programme.

The costs of silt removal from distribution systems are quite considerable. In the Gezira scheme in the Sudan, in a canal system supplying about a million acres (400 000 hectares), the cost amounts to a quarter of a million Sudanese pounds [1] a year. In Mozambique, the cost of silt removal from concrete-lined canals is also considerable, and greater than that of removal of silt from earth canals. In Egypt, too, silt-removal from canals is very costly, and as the number of irrigation canals increases it is becoming more difficult to keep up with their desilting. In Iraq considerable quantities of silt are removed yearly from canals and heaped up on the sides. After a number of years the ridges grow to such heights that it becomes cheaper to excavate a new canal than to continue removing the silt in the old canals. Silt removal from irrigation canals also creates the problem of disposal of the silt, especially where the silt consists mainly of fine sand without any fertilizing value. Another problem created by silting is the difficulty of maintaining the various regulating structures in working order.

The design of distribution systems should provide for most of the sediment that enters the main canal to be kept in suspension and to be carried through to the fields. This can only be done by the adoption of relatively steep grades, which reduce the area that can be brought under irrigation. However, such reduction in the irrigable area is often offset by the savings in the annual cost of silt removal.

Fluctuations in the discharge of irrigation canals, and variations in the quantity and size of silt introduced at the river-diversion site, make some silting unavoidable. In certain cases it may be far cheaper to reduce the quantity of silt entering a canal by the provision of silt traps than to provide steep grades to maintain it in suspension. The shutting-off of the supply to the irrigation area during periods of high silt-load, such as occur in flood time, also decreases the amount of silt entering the distribution system.

Further aspects of silting are discussed in the following section.

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[1] Sudanese £1 = ca. US $2.80.

Velocities

The effect of water velocities on the establishment of snail colonies in irrigation canals depends on a number of factors. In earth canals aquatic vegetation provides adequate shelter and anchorage for snails even though the average velocity may be of the order of 0.6 m/second.

Until recently no investigation had been made of the variation of flow in different parts of the cross-sectional area of streams and channels with particular reference to the peripheral conditions favouring the establishment of snail colonies. The following facts have now been established in respect of irrigation canals running through silty loam rich in clay and having a width of up to 4 m and a depth of up to 1.2 m :

(1) Water velocities along the periphery of the cross-section have a mean value of 0.40 of the velocity on the water surface at the centre line and may vary only within 12% of the mean value from the water edge to the centre point on the bottom.

(2) The discharge in cubic metres per second is expressed by the following formula :

$$Q = 0.549\ WHV_0$$

where

W is the width of the channel at the water surface in metres
H is the water depth at the centre line in metres
V_0 is the water velocity in metres per second, measured on the surface at the centre line.

(3) The mean water velocity, as determined by dividing the rate of flow by the area of the cross-section, is 0.729 of the velocity on the water surface at the centre line.

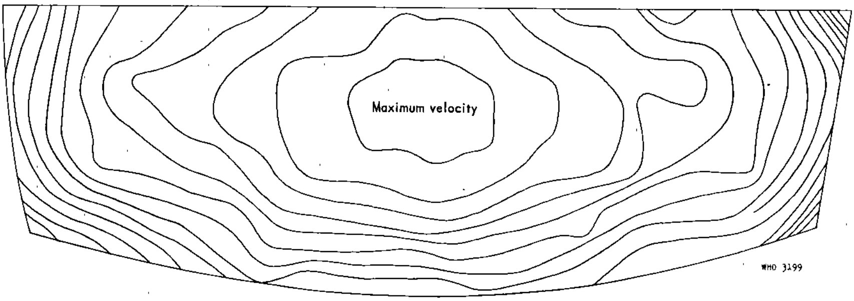
(4) The water velocity at a point on the centre line at a depth from the water surface equal to 0.755 of the total depth at the centre has the same value as the mean velocity of the water flowing throughout the channel.

Fig. 4, 5, 6 illustrate the lines of equal velocity in different types of channels.

While it is important to appreciate that the velocities in irrigation canals are not, in general, high enough to prevent snail breeding, they are nevertheless an essential factor in determining the suitability of habitats. Evidence indicates that there is a range of critical velocities for each species of snail above which anchorage is difficult or impossible ; but it must be remembered that such velocities are only effective if they reach the microhabitat. Wherever practicable, therefore, irrigation systems should be designed so that water velocities in canals are as high as the nature of the soil and configuration of the ground would permit without causing erosion. Some of the more important factors influencing choice of velocities will be considered in the following paragraphs.

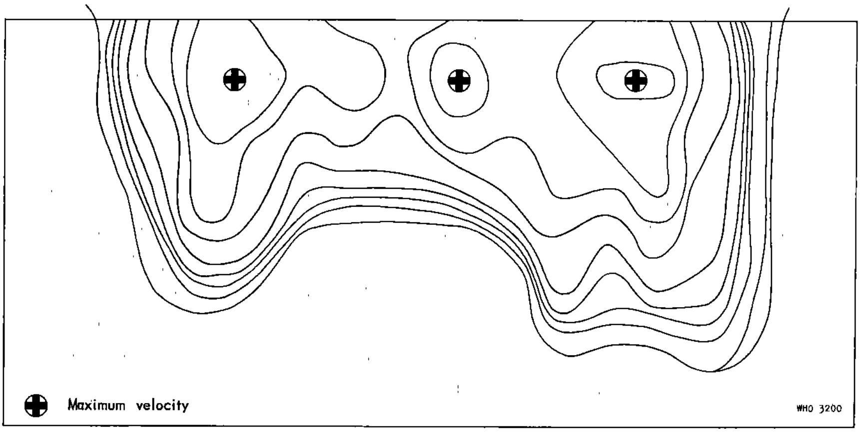
Determination of optimum velocities in an irrigation scheme depends not only on the topographical features of the area and the properties of its soil, but also on the operating conditions of the distribution system. Velocities in earth canals should be high enough to prevent silting without causing at the same time serious scouring of the bottom and sides of the canal.

FIG. 4. LINES OF EQUAL VELOCITY IN A REGULAR CHANNEL [1]



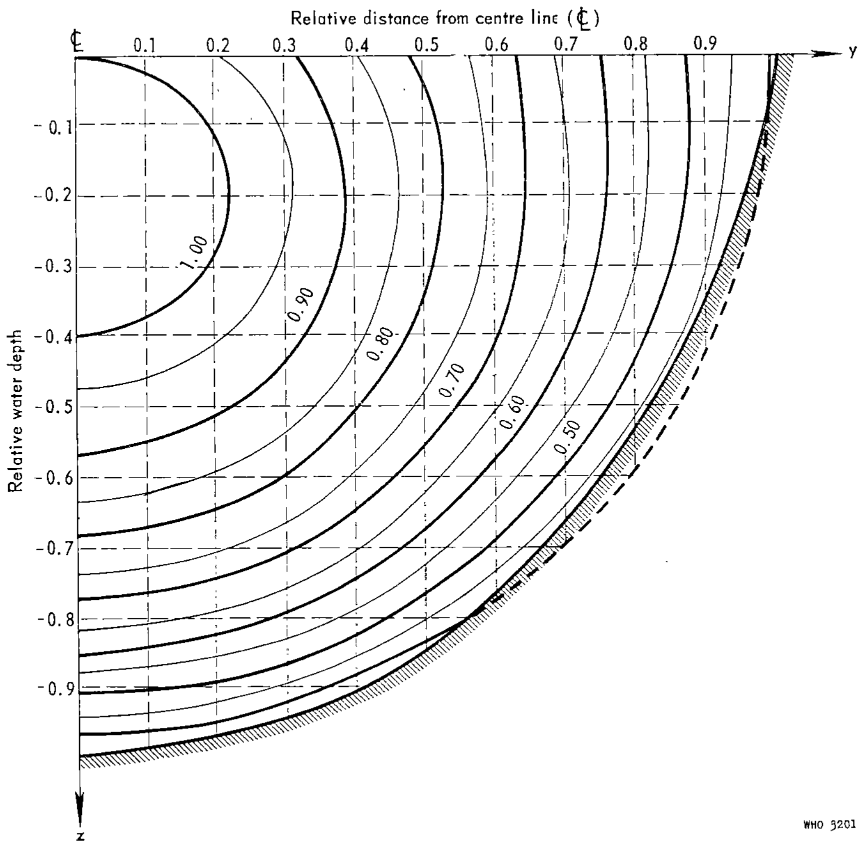
Although many attempts have been made to evaluate the various factors that determine the range of optimum velocities under a given set of conditions, it is still necessary for engineers to rely largely on their own observations and assessment of local conditions. Both silting and scouring may be expected over a period of several years, but the choice of proper velocities should result in stable canals where silting during floods would be counteracted by limited scouring during periods of normal clear-water flows.

FIG. 5. LINES OF EQUAL VELOCITY IN AN IRREGULAR CHANNEL [1]



[1] Adapted from King, H. W. (1954) *Handbook of hydraulics*, New York, McGraw-Hill Book Company Inc., pp. 9-1, 9-2.

FIG. 6. LINES OF EQUAL VELOCITY IN A TYPICAL EARTH CANAL



Observations show that in irrigation schemes silting is a far more serious problem than scouring. Whereas silting is likely to increase with the age of the canals, scouring tends to diminish due to the aging and lining of the canals with silt. Furthermore, any possible scouring that may take place during the first few years of the scheme's operation may be checked by the use of grade-reducing structures, whereas excessive silting cannot be prevented, except by means of silt traps.

The design of stable irrigation canals should be based on the latest concepts of the regime theory to guard against silting and on the tractive forces theory to prevent excessive scouring. The use of both these methods requires the determination of the properties and quantities of silt and the properties of the soil in which the canal is excavated. As a result of many years of research and field observations, the factors that determine whether a canal will suffer from scouring or silting have been evaluated with some degree of reliability. To illustrate the various methods that are now available for the design of stable canals, an example is given.

Given :

Discharge :	$Q = 100$ cu. ft/sec. (2.83 cu. m/sec.)
Sediment charge :	50-500 parts per million (p.p.m.)
Bottom of canal :	sand
Sides of canal :	slightly-cohesive to cohesive soil

Required :

Cross-section and grade for stable conditions

Solution :

A. SIMONS & ALBERTSON METHOD [1]

Perimeter : $P = 2.5\ Q^{0.51}$

$P = 2.5 \times 100^{0.51} = 26.2$ ft (7.986 m)

Average width : $W = P\ (0.75 + \frac{6.2}{80}\ 0.15) = 19.9$ ft (6.065 m)

Hydraulic radius : $R = 0.43 Q^{0.36} = 2.26$ ft (0.689 m)

Average depth : $D = 1.25\ R = 2.82$ ft (0.860 m)

Area : $= W \times D = 19.9 \times 2.82 = 56$ ft^2 (5.203 m^2)

Velocity : $V = \frac{100}{56} = 1.79$ ft/sec. (0.545 m/sec.)

Check : $A = 1.076 Q^{0.873} = 57$ ft^2 (5.296 m^2)

Grade : S

Velocity : $V = 16.0\ R^{\frac{2}{3}}\ S^{\frac{1}{3}}$

$$S^{\frac{1}{3}} = \frac{1.79}{16 \times 2.26^{\frac{2}{3}}} = 0.0647$$

$S = \mathbf{0.000269}$

B. BLENCH METHOD [2]

Note : Bottom factor : $F_b = 1.0$
Side factor : $F_s = 0.2$
Charge : C ; $a = 1/233$
Average width : W

$$W = \frac{(F_b Q)^{\frac{1}{2}}}{(F_s)} = \frac{(1 \times 100)^{\frac{1}{2}}}{(0.2)} = 22.4 \text{ ft } (6.828 \text{ m})$$

Average depth : D

$$D = \frac{(F_s Q)^{\frac{1}{3}}}{(F_b)} = \frac{(0.2 \times 100)^{\frac{1}{3}}}{1} = 2.72 \text{ ft } (0.830 \text{ m})$$

Grade : S

$$S = \frac{(F_b)^{\frac{5}{6}} (F_s)^{\frac{1}{12}} (V)^{\frac{1}{4}}}{3.63\ (1 + aC) g Q^{\frac{1}{6}}} = \mathbf{0.000213}$$

(Note : $(1 + aC)$ very close to 1)

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[1] Simons, D. B. & Albertson, M. L. (1963) *Trans. Amer. Soc. civ. Eng.*, **128**, 65.

[2] Blench, T. (1957) *Regime behavior of canals and rivers*, Washington, D. C., Butterworth.

C. Tractive force method

$Tc = WDS$

Tc is the limiting tractive force in lb/ft^2. Value recommended by Lane for 0.2 mm material is 0.052.

$0.052 = 62.5 \times 2.32 \times S$

$$S = \frac{0.052}{62.5 \times 2.82} = \mathbf{0.000295}$$

The grade to be adopted should be between 0.000213 and 0.000295, depending on local conditions, on the most suitable cross-section of the canal, and of course on the judgement and experience of the engineer. The value of Manning's "n" computed for the 0.000269 grade is 0.0236.

Investigations in the USA resulted in the determination of certain velocities that are considered safe for use in earth canals. The following velocities are given by the United States Bureau of Reclamation for average conditions (see Table 1).

TABLE 1. VELOCITIES FOR USE IN EARTH CANALS

Depth		Width		Velocity	
ft	m	ft	m	ft/sec.	m/sec.
1	0.305	2– 5	0.610 1.524	2	0.61
2	0.610	4– 9	1.219 2.743	2.22	0.68
3	0.914	7–14	2.134 4.267	2.35	0.72
4	1.219	9–20	2.743 6.096	2.43	0.74
5	1.524	12–26	3.658 7.925	2.52	0.77
6	1.829	16–34	4.877 10.363	2.6	0.79
7	2.134	18–40	5.486 12.192	2.67	0.82
8	2.438	22–45	6.706 13.716	2.75	0.84

Fortier & Scobey, after extensive investigations, have recommended the following values for maximum velocities.[1] The values are for straight canals with depths not exceeding 3 ft (0.914 m). Higher velocities may be used for deeper canals and lower velocities for tortuous canals (see Table 2).

[1] Fortier, S. & Scobey, F. C. (1926) *Trans. Amer. Soc. civ. Eng.*, **89**, 940.

TABLE 2. PERMISSIBLE VELOCITIES IN CANALS EXCAVATED THROUGH DIFFERENT SOILS

Materials excavated for canal	Velocity, feet/sec. (m/sec.) after ageing, in canals carrying		
	clear water, no detritus	water containing colloidal silts	water containing non-colloidal silts, sand, or gravel
Fine sand, non-colloidal	1.50 (0.457)	2.50 (0.762)	1.50 (0.457)
Sandy loam, non-colloidal	1.75 (0.533)	2.50 (0.762)	2.00 (0.610)
Silt loam, non-colloidal	2.00 (0.610)	3.00 (0.914)	2.00 (0.610)
Alluvial silts, non-colloidal	2.00 (0.610)	3.50 (1.066)	2.00 (0.610)
Ordinary film loam	2.50 (0.762)	3.50 (1.066)	2.25 (0.686)
Volcanic ash	2.50 (0.762)	3.50 (1.066)	2.00 (0.610)
Fine gravel	2.50 (0.762)	5.00 (1.524)	3.75 (1.142)
Stiff clay, very colloidal	3.75 (1.142)	5.00 (1.524)	3.00 (0.914)
Graded, loam to cobbles, non-colloidal	3.75 (1.142)	5.00 (1.524)	5.00 (1.524)
Alluvial silts, colloidal	3.75 (1.142)	5.00 (1.524)	3.00 (0.914)
Graded, silt to cobbles, colloidal	4.00 (1.219)	5.50 (1.676)	5.00 (1.524)
Coarse gravel, non-colloidal	4.00 (1.219)	6.00 (1.829)	6.50 (1.981)
Cobbles and shingles	5.00 (1.524)	5.50 (1.676)	6.50 (1.981)
Shales and hard-pans	6.00 (1.829)	6.00 (1.829)	5.00 (1.524)

Weed control

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, use up considerable quantities of water and thus reduce the amount available to crops. The control of weeds, therefore, is important not only for snail control but also for the proper functioning of an irrigation scheme.

In the planning of 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 ditch 4.572 m wide by 1.219 m deep in Louisiana (USA) of which the capacity was reduced to one-tenth in only two years as a result of excessive weed growth. 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 to 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.

Weed control is a problem even in concrete-lined canals, although not to the same extent as in unlined canals. Submerged weeds grow in the deposited silt or through construction joints and cracks, while bank weeds reach down to the water level, shedding their seeds which are transported through the distribution system to cultivated fields. Further, their branches and leaves provide anchorages for the establishment of snail colonies.

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, mowing and grazing. Chemical methods comprise the use of selective herbicides such as 2,4-D, T.C.A., Dalapon and C.M.V. 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.

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.

The number of selected herbicides is being continually extended and at least one of them is lethal to host snails (see Aqualin, chapter 4, page 145). Such a double effect may result in substantial savings in areas where snail control has been established and molluscicides are used.

Weed control operations are facilitated by the provision of places for the application of herbicides, and roads for the 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.

A comprehensive account of methods is given in the Manual No. 36 of the Food and Agriculture Organization, entitled *Methods of weed control.*

Water supply

Where water supply to villages for domestic purposes, washing, recreation and gardens has to be obtained from irrigation canals, adequate provision should be made for appropriate take-off structures, protected with strainers. The water may flow by gravity to the village in a pipe to feed a ground reservoir, from which it may be pumped to elevated tanks. If gravity flow is not possible, then a pump must be installed close to the canal to feed elevated tanks in the village.

Snail breeding in such cases may take place in concrete channels, washing troughs, valve chambers and reservoirs. Effective snail control would involve surveillance, covering of the various concrete structures and filters, and the provision of a storage period of 48 hours to ensure that any cercariae that may have gained access to the water supply would perish before the water is used. As a matter of general preventive medicine practice, wherever possible water supplies should be chlorinated. A chlorine residual of 1.0 p.p.m. for 30 minutes will kill schistosome cercariae. Lower residuals are also effective for this purpose after more prolonged exposure.

Land preparation for irrigation

The levelling, grading, sub-division and layout of irrigation field ditches are very important operations requiring design and technical skill and equipment, and they are generally best handled by a constituted authority or some other organization prepared to do this type of work. When entrusted to individual farmers, such work cannot, as a rule, be properly executed, and the result will be uneven water application, water waste, formation of stagnant pools, reduced crop yields and creation of numerous potential snail habitats. Observations by the United States Bureau of Reclamation indicate that levelling alone may result in increased yields which are sometimes as much as 50%-100%. It also markedly reduces the number of snail habitats and the cost of snail control.

Furthermore, the works of a more or less permanent nature in efficient irrigation require some field preparation before every irrigation season, and maintenance of ditches and border-strip dikes. This work is greatly facilitated by the use of light mechanical equipment that can be operated by a tractor. A good example of an irrigation scheme where field preparation is efficiently practised is the Gezira scheme in the Sudan.

For sprinkler irrigation, the need for land preparation is considerably reduced. Although this type of irrigation has not been used to any extent in areas where bilharziasis is endemic, its employment would lead to reduction in the number of snail habitats and hence in the number of snails. Since field channels are not necessary and excess water is avoided, two important factors in the creation of breeding-sites for snails are eliminated.

This method of irrigation has been more widely used in the past 15 years, mainly owing to the increased availability of light-weight pipes and easily operated pumping units. The method can be applied, without causing soil erosion, to areas of limited extent which are too steep or irregular for surface irrigation, and fairly uniform application of water is possible where the design is satisfactory and reasonable care is exercised. In one irrigation scheme in Southern Rhodesia sugar cane yields were 15% higher in sprinkler-irrigated than in gravity-irrigated fields.

Some of the limiting factors of this method of irrigation are : wind interference, clogging of channels or pipe perforations by debris, the difficulty of ensuring a constant supply of water, and the need for power. Moreover, this method involves high investment cost, and skilled technicians.

The general layout of any type of farm distribution system is governed by topographical features, soil texture, methods of water application, infiltration rates, size of irrigation stream, condition of soil, and types of crops. Some of these factors vary during any one irrigation period, and the layout can only provide for average conditions. The detailed layout of the farm distribution system should take into account the supply to the various fields, the location of control structures, roads and drainage, and agricultural practice such as seeding, tillage and harvesting.

While there are variations in detail, a general pattern of distribution is discernible in many irrigation schemes. The main supply canal to the farms is located on the highest ground and is usually large and short so as to provide some balancing storage. Water flows into the various fields in more or less permanent earth ditches, having grades of about 1 to 5 per 1000, and velocities of about 0.610 m/sec. (see Table 3, page 105). These are located along the field boundaries. Temporary ditches are then used for conveying the water from the edge of the field to individual furrows or border checks. Lining of some permanent farm ditches may be advisable to reduce seepage, silting and weed growth. Materials for this purpose have been discussed on page 81. Various special control structures and devices are necessary for efficient use and even application of water. These may be either permanent, temporary or portable depending on local conditions, available funds, methods of cleaning the canals, and expected changes in farming practices. Flumes and inverted siphons and culverts are required to cross gullies and roads, railways, streams and other canals. Division boxes and turn-outs and gates to control and guide the water are required. Drop-structures are used to prevent scouring when the grade is too steep. Check-weirs are used to raise the water surface to feed some laterals.

Flow-measuring devices are most important in preventing unnecessary waste and collections of excess water. Typical examples of such devices are the Parshall flume, weirs, calibrated gates, orifices and gauges, and Dethridge meters. In the layout of the farm distribution channels, adequate provision should be made for drainage to handle excess irrigation water as well as surface run-off from rainfall.

Topographic features and types of crops usually determine the size and shape of fields and their preparation for irrigation. The more common methods of irrigation requiring specific land preparation are: border strips, basins, furrows and corrugations.

Border strips consist of fields level in the transverse direction and having a uniform slope not exceeding 1% in the longitudinal direction, varying in width from 6 m to 15 m and in length from 60 m to about 400 m, depending on soil types, land slope and depth of irrigation. The fields are divided by low ridges up to 15-20 cm high running down the slope. These prevent the sheet of water from spreading beyond the desirable width. The total infiltration may be much higher at the top of the field if, due to improper design or grading, the water is allowed to remain there much longer than on the bottom portion of the field. This method of irrigation is efficient from the point of view of water use, time and labour required. It is used mainly for close-growing crops, hay and pastures. The following example illustrates the method of designing border-strip irrigation.

Basically, the design, which involves the relationship between the intake rate, the size of stream, and area of the strip (length times width), should be such that the water will flow into the strip during the period of time required for the desired amount to enter the soil. The total volume applied must equal the desired depth of application times the area. The longitudinal slope is relatively unimportant, but must not be so steep as to cause erosion. It should be flattened at the bottom end of the strip to provide some storage, which will improve the uniformity of application along the strip. Some allowance for less than 100% uniformity in application must be made.

An example of the design of a border strip is as follows:

Flow available — 1 cubic foot per second (0.0283 cu. m/sec)

Area and size of field — 40 acres (1320 feet square) (16.187 hectares)

Average longitudinal slope — 0.5%; cross slope — 0.1%

Silt loam soil

Desired depth of water at each application — 4 inches (10.16 cm)

Assume 80% efficiency, and design for 5-inch (12.70-cm) application

Possible lengths of strips may be 1320 ft (402.34 m), 660 ft (201.17 m), 440 ft (134.11 m) or 330 ft (100.58 m)

Estimated time for a depth of 5 inches (12.70 cm) to enter the soil is 3 hours (based on some trials or experience on similar soils)

Volume of water that can be applied in 3 hours
$= 3 \times 1 \times 3600 = 10\,800$ cubic feet (305.85 cu.m)
or $3\times$ (acre inches/hour) = 3 acre inches (approx.) (3.09 cm/hectare)

For an average depth of 5 inches (12.70 cm), the required area of strip would be:

$$A = \frac{10\,800}{5/12} = 25\,920 \text{ ft } (2408 \text{ m}^2)$$

For a length of 1320 feet (402.34 m), the required width
$w = 19.6$ ft (say 20) (6.1 m).

For a length of 660 feet (201.17 m), the required width,
$w = 39.2$ ft (say 40) (12.2 m).

Table 3 shows sizes of farm ditches for various discharges.

Basin irrigation is sometimes practised where land slopes are rather flat and infiltration is slow. Low dikes are built around the field and water is turned in and allowed to soak into the soil. The size and shape of basins are determined by topography, the nature of soil and the source of water available. Where these factors are taken into account, this method of irrigation can be efficient.

TABLE 3. SIZES OF FARM DITCHES FOR VARIOUS DISCHARGES

Grade : one per thousand
Manning's Roughness Coefficient $n = 0.030$
Side slope : 1–½ horizontal
1 vertical

Formula : $V = \frac{1.49}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$

V = velocity in ft/sec.
n = roughness coefficient
R = hydraulic radius in ft
S = longitudinal grade of canal

Irrigation stream		Mean velocity		Depth of water		Bottom width	
cu . ft/sec.	litres/sec.	ft/sec.	cm/sec.	ft	cm	ft	cm
0.5	14	0.67	20.42	0.44	13.41	1.0	30.48
1.0	28	0.80	24.38	0.55	16.76	1.5	42.67
1.5	43	0.88	26.82	0.60	18.29	2.0	60.96
2.0	57	0.95	28.65	0.70	21.34	2.0	60.96
3.0	85	1.05	32.00	0.80	24.38	2.5	76.20
4.0	114	1.13	34.44	0.92	28.04	2.5	76.20
5.0	141	1.18	35.96	0.94	28.65	3.0	91.44

Furrow irrigation is most common for row crops, orchards, vineyards, cotton, corn and potatoes. In this method water flows in furrows between rows of plants and infiltrates to the roots. The land slope, soil texture, length of furrows and the depth of water application and the size of irrigation streams are important factors in controlling even application and preventing soil erosion. These factors are interrelated, as shown in Table 4. A formula developed by the US Bureau of Reclamation relates the size of maximum stream as follows :

$q = \frac{1}{45\,s}$ where q is the discharge in cu.ft/sec. and s is the slope in per cent.

For example, a slope of 2% would require a maximum stream of $\frac{1}{45 \times 2}$ which is equal to $\frac{1}{90} = 0.011$ cu. ft/sec. (0.311 litres/sec.)

The furrows are usually laid down the slope unless this is too steep, in which case they are laid at an angle in order to prevent erosive velocities (see Table 4).

Where transplanting of crops is practised, or where soil moisture is insufficient for germination in the case of sown crops, furrows are formed in advance of these operations. Where the soil moisture is sufficient for germination, furrows are formed after sowing. The spacing of furrows depends on the distance between rows of crops or fruit trees. In some cases two rows of crops are planted between furrows.

TABLE 4. LENGTHS OF FURROWS IN FEET (M) AND DISCHARGES FOR VARIOUS SOILS AND SLOPES FOR 2-INCH (5-CM) DEPTH OF WATER APPLICATION *

Soil texture **			Slope of furrow (%)	Discharge	
coarse (sandy)	medium (silt)	fine (clay)		cu. ft/sec.	litres/sec.
500 (152.4)	820 (249.9)	1 050 (320.0)	0.25	0.89	25.2
345 (103.8)	560 (170.7)	730 (222.5)	0.50	0.44	12.5
270 (82.3)	450 (137.2)	580 (176.8)	0.75	0.29	8.2
235 (71.7)	380 (115.8)	500 (152.4)	1.00	0.22	6.2
190 (57.9)	310 (94.5)	400 (121.9)	1.50	0.15	4.3
160 (48.8)	260 (79.3)	345 (105.2)	2.00	0.11	3.1
125 (38.1)	210 (64.0)	370 (112.8)	3.00	0.07	2.0
95 (29.0)	160 (48.8)	210 (64.0)	5.00	0.04	1.1

* Adapted from *U.S. Department of Agriculture Yearbook 1955.*
** Based on water retention values:
Coarse: 0.5 to 1.5 inches (1.27 to 3.81 cm) per foot (30.48 cm) depth.
Medium: 1.5 to 2 inches (3.81 to 5.08 cm) per foot (30.48 cm) depth.
Fine: 1.75 to 2.5 inches (4.45 to 6.35 cm) per foot (30.48 cm) depth.

For rather steep land slopes, close-growing crops, and soils with low infiltration capacity, small furrows called corrugations are used. Corrugations are only a few inches deep and are spaced from 18 to 36 inches (45.72 to 91.44 cm) apart. In areas where there are significant intervals between the use of the furrows and water is not allowed to stand, the snails usually do not find suitable habitats.

Application of irrigation water

This phase of irrigation practice affects not only crop yield and soil and water utilization but also the extent and cost of snail control measures that may be necessary. Yields are adversely affected by considerable variations in the depth of water application and by the loss of soil fertility through leaching and erosion. Observations have shown that young and inexperienced farmers can profit a great deal from demonstration and extension courses in this phase of irrigation.

Where flood irrigation is practised the rate at which water is applied is governed by the texture of the soil, land slope, and width of strips. Control of the size of irrigation streams can be achieved by using pipes or siphons to convey the water from the supply ditch on to the fields.

In furrow irrigation the practice of using earth dams in the supply ditch and the cutting of openings through the side of the ditch result in loss of good soil, poor water control and silting of the furrows. These can be overcome by using siphons and spiles to divert and control the water on to the furrows. Table 4 shows the sizes of streams that can be handled efficiently.

In sprinkler irrigation, the control of application is relatively simple, and over-irrigation is not likely. Rates of application can vary from 0.1 to 1.0 inch (0.254-2.54 cm) per hour, depending on the absorption capacity of the soil. The design and layout should provide for limiting the variations in the depth of application within a reasonable range, in order to avoid excessive irrigation in one part and insufficient water in another part of the field. Where necessary or desirable, irrigation at low application can be carried out at night without involving any labour.

There are a number of commercial types of sprinkler systems operating at pressures as low as 15 lb/sq. inch (1.0546 kg/sq. cm), and embracing a variety of sprinklers and perforated pipes. The choice of design will depend on local conditions, source of water and other factors.

Where the capacities of delivery canals are not sufficient to meet the irrigation requirements during daytime, the deficiency is made up by storing the night flow of the delivery canal in special storage reservoirs, usually referred to as night storage dams. This practice presents serious problems in the control of bilharziasis. In endemic areas most of these dams and canals that are used for storage become snail hatcheries and transmission sites. If, in spite of this, such storage is used in an irrigation scheme, provision must be made for control measures.

In cases where the length of the delivery canal is not great, an enlargement of the canal to supply the full irrigation requirements during daytime hours may be cheaper than the provision of a large number of night storage dams. In the Gezira scheme, night storage is provided by surcharging the minor canals by 9-18 inches (22.86-45.72 cm). There is some evidence that this practice encourages the establishment of snail colonies. Where the delivery canal is rather long, or where the quantity of water diverted must be continuous, then storage in a small number of large reservoirs may be cheaper than storage in a large number of small reservoirs.

Drainage

Importance

Lack of drainage in irrigation schemes results in the formation of stagnant pools, wet areas, and seepages which are often good snail habitats. It is therefore important that in irrigation schemes in endemic areas adequate drainage be provided if snail control is to be successful. In addition to facilitating snail control work, adequate drainage has important beneficial effects on the productivity of an irrigation scheme. There are instances of irrigation schemes that have failed to achieve the expected productivity because of lack of adequate drainage. In some places salt accumulation and waterlogging have become so serious within only a few years of the introduction of irrigation that valuable lands have been rendered useless. The reclamation of such lands may be feasible, but at considerable cost.

The following data for nine farms, compiled by the United States Department of Agriculture, show the extent of benefits resulting from drainage :

Crop production before drainage	*Crop production after drainage*
Abandoned	Alfalfa, 9 tons/acre (8165 kg)
Poor alfalfa	Sugar beets, 16 tons/acre (14 515 kg)
Barley, 2200 lbs/acre (998 kg)	Barley, 4600 lbs/acre (2086 kg)
Flax, 1120 lbs/acre (508 kg)	Flax, 1624 lbs/acre (737 kg)
Saline, bare land	Barley, 2227 lbs/acre (1010 kg)
Bare spots in field	Good production on entire field
Wheat, 1440 lbs/acre (653 kg)	Wheat, 3960 lbs/acre (1796 kg)
Ten acres no production	One acre no production
Bare spots	Uniform germination

Planning

In the planning of irrigation schemes, funds for the construction of irrigation canals are more easily allocated than are funds needed for drainage. The function of canals is readily understood, but that of drainage is often considered of minor importance. Planners and engineers are sometimes under governmental pressure to provide for the maximum area to be irrigated for a given grant, and to give little consideration to the long-term benefits of such developments. In addition to the economic losses resulting from the creation of habitats for intermediate hosts of parasites both in humans and animals, lack of adequate drainage adversely affects crop yields and seriously hampers such farm operations as tillage, land preparation, harvest, maintenance of roads and control of water.

In planning irrigation schemes it is essential to provide for adequate drainage at the outset, even though under certain conditions the implementation of this part of the development may be carried out in stages as the need arises. For example, drainage for the removal of surface run-off from rains and from excess irrigation should be provided at the outset, whereas drainage required for conditions brought about as a result of several years of irrigation practice may be provided later.

Design

The design of drainage schemes is far more difficult than the design of irrigation schemes. There are such factors as rainfall intensities and frequencies, the quantity of excess irrigation water, the length of time crops can be subjected to flooding without affecting their yield, the soil properties that control the rate of movement of water, the nature of the ground surface as it affects the movement of water overland, and, in some areas, provision for the leaching-out of salt accumulations. It must be pointed out, however, that even the approximate determination of the above factors requires a great deal of investigation and long periods of observation, and often the engineer has to fall back on his experience and judgement. Nevertheless, steady progress is being made in the various aspects of drainage design, and it is now possible to attempt such design with some confidence. Some of the more important factors will be considered in the following paragraphs.

In some countries high rainfall intensities impose a heavy load on the size of drainage to be provided. For example, the drainage system of the Kpong irrigation experimental station in Ghana has been designed for a storm intensity of seven inches (17.78 cm) per hour, and a considerable network of surface drains has been provided. While this is by no means typical of irrigation schemes in endemic areas, it illustrates the importance of providing for the drainage of surface run-off resulting from rainfall. A fairly reliable estimate of the volume of run-off, and the frequency of its occurrence, may be made from an examination and analysis of rainfall data and stream-flows. Of particular interest in irrigated areas is the limiting time during which crops may be inundated without suffering any damage, and this determines the rate at which water should be removed.

Other sources of water are excess irrigation, overflows, and seepage from dams and canals. All these vary considerably from place to place, but an estimate of their magnitude is necessary for the design of a drainage system. Some authorities state that the minimum quantity to be allowed is one-tenth of the irrigation application, and that as much again should be allowed for leaching applications. This, of course, depends on soil texture and quality of the irrigation water. Others recommend a drainage coefficient of between $^1/_4$ inch and $^1/_2$ inch (6.35 mm-12.70 mm) every 24 hours.

Having estimated the quantity of water to be drained in a given time, the layout and sizes of surface and tile drains can be determined. In many irrigation schemes drainage is effected by large open channels. Their design should take into consideration the reduction in carrying capacity which results from poor maintenance, scouring, silting, and growth of weeds. The capacities of the drains provided at Kpong, Ghana, for example, have been reduced by the tendency of the very fine-textured soil to cake and form clods.

Owing to considerable fluctuations in the quantity of water carried and the prolonged periods of very small flows, open drains provide important breeding-sites for snails. Wherever possible, such open drains should be provided with subsoil drains so that during small flows they may be completely dried out.

The problem of control by the application of molluscicides becomes even more difficult when there is not sufficient flow to carry molluscicides through the entire length of the drains. The large amount of vegetation often present also tends to prevent dispersion near the margins. In such cases molluscicides may have to be sprayed over the drains, and may necessitate weed removal.

The design of drainage channels is usually based on Manning's formula, using a coefficient of roughness of 0.025 to 0.040, and taking into consideration all the other factors discussed on pages 91-92 and 94-101.

Underground drainage is used to a limited extent in the drainage of irrigated areas where bilharziasis is endemic. It is much more widely used in the USA, and a great deal of investigation and data are now available to facilitate the design and construction of subsoil drains.

Where water quantities are small it may be cheaper to use pipe drains than open drains, as maintenance of open drains is not only costly but often neglected.

In subsoil drainage, the depth and spacing of pipes depends on the texture of the soil, and the desired level of the water table. Existing data are only empirical, and field observations have to be used as guides. For example, if the water table must not rise to a level higher than 4 ft (1.219 m) below the ground surface, open drains may have to be 8-10 ft deep (2.438 m-3.048 m), and subsoil drains 6-8 ft deep (1.829 m-2.438 m), in both cases, the depth depending on the spacing of the drains and also on whether saline ground waters have to be kept low.

The following basic information is required for the design of a subsoil drainage scheme:

(1) Soil permeability, which may be determined by field measurements of the hydraulic conductivity of the soil—as, for example, by means of the auger-hole, or piezometer methods.

(2) Drainage requirements which depend on expected run-offs from rains and irrigation applications.

(3) The determination of soil properties. It has been suggested that borings need not extend to depths greater than 10 ft (3.05 m) for tile drains, and 15 ft (4.57 m) for open drains. This, of course, depends on the soil profile stratification. If highly permeable strata are present within depths of 25 ft (7.62 m) or more, they will have an important effect on the drainability of the soil.

(4) It is essential that a very accurate topographic survey be prepared to enable the layout of the main drains and the laterals to be determined.

Having determined the probable values of hydraulic conductivity, the quantity of water to be drained in 24 hours and the minimum depth to which the water table is to be lowered, the spacing of the tile lines for a given depth may be determined approximately by the following formula [1] adopted by Donnan.

$$S = 2\sqrt{\frac{k\,(b^2 - a^2)}{q}}$$

S = spacing of tile drains in feet
k = hydraulic conductivity or rate of water movement through the soil in feet per day
q = depth in feet of water to be removed in 24 hours
b = distance in feet between the impermeable layer and the level of the water table midway between the tile lines
a = distance in feet between the impermeable layer and the centre line of the drains.

Table 5 gives the spacing of tile drains for a range of values of the hydraulic conductivity of soils, and several depths of the impermeable soil layer. The spacings are for drains laid 6 ft (1.83 m) below ground surface,

TABLE 5. SPACING OF SUBSOIL DRAINS

Hydraulic conductivity in feet and metres per day		Method of calculation						Depth to impermeable layer	
		Donnan		Visser		Hooghoudt			
(feet)	(m)	(feet)	(m)	(feet)	(m)	(feet)	(m)	(feet)	(m)
0.34	0.104	66.6	20.30	65	19.81	64	19.51	10	3.048
0.56	0.171	86	26.21	86	26.21	83	25.30		
1.16	0.360	122	37.19	122	37.19	120	36.58		
1.20	0.366	126	38.41	124	37.80	123	37.50		
1.57	0.479	146	44.50	140	42.67	141	42.98		
2.36	0.719	175	53.33	158	48.16	174	53.03		
2.70	0.823	190	57.91	170	51.82	183	55.77		
3.10	0.945	202	61.57	179	54.56	201	61.27		
3.75	1.143	222	67.67	207	63.09	221	67.36		
6.33	1.929	292	89.00	280	85.34	287	87.48		
8.52	2.597	329	100.28	335	102.11	334	101.81		
11.20	3.414	388	118.26	384	117.04	383	116.73		
13.40	4.084	425	129.54	428	130.46	420	128.02		
0.34	0.104	77.5	23.62	71	21.64	69	21.03	12	3.658
1.20	0.366	146	44.50	139	42.37	137	41.76		
3.10	0.945	231	70.41	206	62.79	225	68.58		
6.33	1.929	335	102.10	310	94.49	325	99.06		
13.40	4.084	487	148.43	475	144.78	473	144.17		
0.34	0.104	86	26.21	73.5	22.40	75	22.86	14	4.267
3.10	0.945	261	79.56	226	68.88	246	74.98		
13.40	4.084	542	165.20	510	155.45	520	158.50		
0.34	0.104	94.5	28.80	75	22.86	76	23.17	16	4.877
3.10	0.945	285	86.86	237	72.33	266	81.08		
13.40	4.084	593	180.75	566	172.52	570	173.74		

[1] This equation can apply to any unit system. For example, if S is in metres, the unit of time is in days; k must be expressed in metres per day, and q in metres per day.

a maximum height of water table between tile drains of 1 ft 6 inches (0.46 m) below ground surface, a drainage coefficient of 1/60 ft (5 mm) per 24 hours. The spacings have been checked by using Visser's nomographs and Hooghoudt's formula. Agreement between the two formulas is rather striking, and for the conditions analysed it is evident that the formula adopted by Donnan is both reliable and convenient to use.

The values of hydraulic conductivity used in this table cover a range of soil textures from silty clays to silty sands. It must be appreciated, however, that there are other factors that influence the drainage properties of a soil, and that the importance of field measurement of hydraulic conductivity cannot be overstressed.

The table also shows that the spacing of the tile lines increases with the depth of the impervious layer, which is considered as soil having a hydraulic conductivity of one-tenth of the soil above the layer.

The value of q given above was originally recommended by Hooghoudt and has been adopted by the Murrumbidgee irrigation area in Australia. Recently a value of q of 1/43 has been adopted in Holland. For a drainage coefficient of $^{1}/_{4}$ inch (6.35 mm) depth q is $^{1}/_{48}$ cu. ft/sq. ft/day, or simply ft/day (6.35 mm).

After the spacing of the tile drains has been determined, their size may be computed as follows:

The quantity of water to be drained = the rate per unit area times the length and breadth of the area.

For example, for a spacing of 200 ft (60.96 m) and a length of 2000 ft (609.6 m) the quantity will be:

$$Q = q \times 200 \times 2000$$

$$Q = \frac{1}{60} \times 200 \times 2000$$

$= 6660$ cu. ft/day (188.59 cu. m/day)

$= 0.0772$ cu. ft/sec. (0.002186 cu. m/sec.)

From hydraulic tables a 4-inch (10.16-cm) drain laid on a slope of 1 in 500 would have a capacity of 0.10 cu. ft/sec. (0.00283 cu. m/sec.).

The width of the gap between adjacent pipes determines the rate at which water enters the drain. When the width is increased from $^{1}/_{64}$ inch (0.397 mm) to $^{1}/_{8}$ inch (3.175 mm) the discharge is increased by 30%. The usual gap allowed is $^{1}/_{8}$ inch (3.175 mm), and it is protected on top by a strip of tarred paper.

Under favourable site conditions, such as in relatively stable soils, mole drains have proved both effective and inexpensive. They have their limitations, however, and failure by caving-in or by blockage from sediment and roots may limit their use after a number of years. In such cases fresh drains may have to be excavated periodically.

Costs

The cost of tile drainage is 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 the current reclamation work in the Nile Delta, the cost of subsoil drainage using 4- and 6-inch (10-cm and 15-cm) diameter concrete pipes is about $70 per acre. This represents about one-tenth of the market value of the land reclaimed. However, this cost is completely offset by the saving in land which would otherwise be required if open drains were used. In addition, there would be hardly any maintenance costs involved as compared with open drains.

Larger pipes may very well be used to replace some of the existing open drains and thus eliminate potential snail breeding-sites at no additional expense. An example of such use is the Qala drain in the Beira province, Egypt.

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-outs, 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 (see chapter 4).

Maintenance and management

Observations in many parts of Africa, Asia and the USA show that many irrigation schemes suffer from lack of adequate maintenance and efficient management. In some cases this is largely due to failure on the part of the responsible authorities or the individual farmers to make adequate provision for trained staff and recurrent maintenance expense. In other cases it is due to lack of efficient organization with adequate powers to control the irrigation works and the distribution of water. In some countries complicated water and property rights based on long traditions and customs prevent the development of efficient irrigation; as a consequence, the expected benefits from such developments are not realized and, in areas where bilharziasis is endemic, measures to check its spread are either very difficult or impracticable.

In order to reduce the extent and cost of maintenance and to ensure efficient management, irrigation schemes should be designed and constructed to as high a standard as possible. Adequate provision should be made for facilities, equipment, materials and staff to carry out regular repairs and maintenance. Where this has been done, the extent and cost of maintenance are considerably reduced. The bulk of maintenance work is in the distribution canals and drains, and involves silt removal, weed-clearing, and repairs to banks. Of smaller magnitude but of equal importance is the maintenance of control works, such as head-gates, delivery gates, bridges, culverts, screens, meters, and so on. Regular inspection and prompt repair and maintenance of this part of the irrigation system will pay in terms of increased yields, of reduction of snail populations and in the improved well-being of the people and promotion of good health. These objectives are further promoted by close collaboration between irrigation and public health authorities.

The importance of management in the successful operation of an irrigation scheme is perhaps best exemplified by the Gezira scheme in the Sudan. There it has been demonstrated that by planning and co-ordinating the interests and contributions of the various departments such as agriculture, irrigation, public works, public health, education and rural councils, a well-balanced development has been made possible. Land and water resources are used to best advantage, and a high degree of snail control has been achieved by the provision of mechanical barriers, the application of molluscicide, and adequate surveillance for focal treatment of snail habitats.

Irrigation requirements in the Gezira area are carefully assessed for each zone, compiled and passed on to the engineers at the Sennar dam, and the correct discharge is allowed down the main canal. In the Murrumbidgee irrigation scheme in Australia, water requirements are made known to the field supervisors on 48 hours' notice, and this also facilitates the allotment of water to the various users.

Training of field supervisors in extension service courses would help in the general adoption of scientific methods in irrigation practice. FAO has been active in organizing seminars for this purpose. Such training should precede the commissioning of any irrigation scheme in order to enable the farmers to adopt the proper methods and practices. In some countries metering of irrigation water has proved an effective means of reducing losses. In such cases the farmers pay a fixed amount for the right to have water on their land, and another amount based on the total volume of water used. It has been pointed out that payment for water may result in smaller quantities being used for irrigation than are required for maximum crop yield. However, taking the over-all view it would seem that for best use of water resources some form of metering and payment for water used is necessary.

Organizations or agencies responsible for the operation of an irrigation system can do this successfully only if granted adequate administrative powers by the Government. The Gezira Board is a good example of an agency with such powers. Under such conditions protection and promotion of public health become important functions in an irrigation scheme. In Iraq the Irrigation and Embankments Law of 1923 empowers irrigation engineers with control of distribution. However, difficulty is caused by inherited water rights which are often based on quantities disproportionate to the areas served. Under the 1923 law engineers can fix dimensions of channels, limit pump capacity, and, if necessary, requisition labour for maintenance. The law provides for the imposition of fines upon conviction by a District Magistrate. Under this law provision is also made to regulate the building and maintenance of flood embankments.

Improvement of Existing Irrigation Systems

Opportunities for major improvements in the basic features of existing irrigation schemes with the objects of increasing their efficiency and facilitating snail control are in general rather limited. However, such opportunities should be explored and attempts should be made to carry out whatever modifications or improvements seem practicable both physically and financially. Before corrective measures can be considered surveys should be conducted to locate both actual and potential snail breeding-areas.

In most existing schemes there is room for improvement and intensification of the maintenance of the canals, drains, structures and regulators. Regular clearing, weeding and desilting of the canals and restoration of their original cross-sections are not only necessary to maintain full supply to the farms, but are also justified on economic grounds when the useful life of the scheme is taken into consideration.

Some reduction in the number of snail habitats along the shores of storage reservoirs can be effected by the methods outlined on pages 87-89.

As the silt-carrying capacities of existing canals cannot be increased, attempts should be made to reduce the amount of silt entering the system by the installation of sand traps and desilting basins at the head of the main canal.

Improvement in the distribution system may involve relocation of limited sections of the canals, provision of structures for canal crossings, of flumes, of concrete or masonry lining of unstable sections, and measures to reduce excessive seepage. Snail habitats at regulator bays and watering-places may be reduced or eliminated by the revetment of the canal banks and by the provision of concrete aprons.

Main head gates may need either repair and adjustment or complete renewal. Often due to lack of adequate maintenance, corrosion of the gates and lifting gear is severe, and their operation becomes either difficult or unsatisfactory.

The installation of screens at the head of the main canals would prevent most of the drifting snails from being carried into the distribution system.

The overtopping of canal banks may be prevented by the construction of overflow spillways at selected sites.

The need for drainage is usually obvious in most irrigation schemes. Unsatisfactory agricultural practices and lack of maintenance result in gradual reduction in the carrying capacities of the drains. Additional drainage may be required to take away seepage from irrigation canals, and for this purpose tile drains may be used to advantage, as the quantities of water are usually small. In some cases pumping may be necessary, and where this is done the water may be returned to the distribution system and used for irrigation. Drainage may also be required where the ground water table has risen too close to the surface after long periods of irrigation.

In some schemes supply canals terminate in dead-ends which are usually enlarged to form pools for watering purposes. These should be drained completely or provided with gates that will facilitate their periodic drying and thus prevent the establishment of snail colonies.

Good management of existing irrigation schemes can greatly increase their economic benefits and also facilitate snail control. Vigorous and enlightened efforts should be made to train farmers to discard inefficient practices such as night storage in canals for daytime irrigation, and to adopt practices in the selection of crops and methods of cultivation and irrigation that will result in higher productivity. Observations have shown that water management is one of the most important factors in sound agricultural production, and that it has the added advantage of checking the establishment of snail colonies. A great deal can be achieved by proper organization and by training of staff to ensure that water is well used and that the amount of excess is kept down to a minimum.

Improvements in engineering structures, and in the operation and management of existing irrigation schemes make snail control practicable from the points of view of both effectiveness and cost. Additional details will be found in the following section.

Agricultural Practice

Soil properties and water requirements

An accurate knowledge of the properties of the soil and the water requirements of the crops to be irrigated is necessary for the success of an irrigation scheme. Soil properties under given climatic conditions will largely determine the kinds of crops that may be grown and methods of field preparation and water application, and these in turn will determine the extent of snail control work which will be necessary.

The determination of soil properties such as depth, composition, structure and texture enable the planner to leave out areas of poor soil which may be used for engineering works such as canals, control structures, roads, housing, etc. Where water is limited, only the best areas are considered for bringing under irrigation. Composition of soil determines its potential fertility, capacity to promote crop growth and fertilizer requirements. Structure and texture determine the properties of the soil as they affect tilth, water movement and retention, extent of root zone, field capacity and wilting-point.

The water-holding capacities of soils depend on their texture, condition and the presence of organic matter. Coarse soils hold less water than fine soils; the following values are given as a rough guide:

Type of soil	*Depth of available water in inches (mm) per foot depth of soil*	
Sandy soil	1/4 inch	6.35 mm
Sandy loam	3/4 inch	19.05 mm
Fine sandy loam	1 1/4 inch	31.75 mm
Silt and clay loams	2 1/2-3 inch	63.5-76.2 mm

Recent research into water requirements of crops has led to the concept of potential evapo-transpiration which is defined by C. W. Thornthwaite as " the amount of water which will return to the atmosphere from a surface completely covered with vegetation when there is in the soil sufficient moisture for the full use of the vegetation at all times ". [1]

Blaney [2] has developed a method of estimating water requirements of crops based on mean monthly temperatures and daylight hours (see Table 6, overleaf). It is interesting to note that such factors as humidity, wind prevalence and marked daily variations in temperature are neglected in this relationship. This method has been used in the USA and in other parts of the world with remarkable success, and water requirements determined in this way have been confirmed by experience in Madagascar, Egypt and

[1] Quoted in Dickson, B. T. (1956) *The future of arid lands*, Washington, D.C., American Association for the Advancement of Science.

[2] Blaney, H. F. (1955) *Water*. In : *The Yearbook of Agriculture 1955*, Washington, D.C., US Department of Agriculture.

elsewhere. A knowledge of the proper value of K for the region and crops to be grown is essential.

The basic formula is

$U = KF$, where

U is the depth of water in inches required during the growing season of the particular crop

K is an empirical coefficient derived from field measurements of water requirements

F is the sum of the products of the monthly daytime hours expressed as a percentage of the yearly daytime hours and the mean monthly temperature.

Thus, considering the water requirements of corn (maize), let it be assumed that the growing period is from 1 May to 1 September and that the latitude of the locality is 30° north. From available field data $K = 0.80$.

TABLE 6. WATER REQUIREMENTS OF CORN CROPS BASED ON MEAN MONTHLY TEMPERATURES AND DAYLIGHT HOURS

	May	June	July	August
(1) Per cent daytime hours (p)	9.53	9.49	9.67	9.22
(2) Mean temperature (°F) (t)	70	75	78	78
(3) Product of (1) and (2) (f)	6.68	7.12	7.52	7.2
(4) Monthly requirement in inches and in cm ($u = 0.80 \times f$)	5.32 13.54 cm	5.7 14.48 cm	6.0 15.24 cm	5.75 14.61 cm
Seasonal irrigation requirement $= \Sigma u = U = 22.77$ inches (57.87 cm)				

Once the water requirements for optimum yield are determined, it is possible to control and regulate irrigation heads within close limits, making due allowance for rainfall, and thus prevent unnecessary waste of water which results in poor yields and in the creation of snail habitats.

Water requirements are computed from values of consumptive-use coefficients, which may be estimated from observations of irrigation farm practices or may be determined at agricultural experimental stations.

For crops grown in arid or semi-arid areas of the USA, Blaney gives the following seasonal values of the coefficient K:

Alfalfa	0.85	Deciduous trees.	0.70
Corn	0.80	Potatoes	0.75
Grass hay and pasture . .	0.75	Rice	1.20
Cotton	0.65	Vegetables	0.60
Citrus trees	0.60		

It is interesting to note that coefficients determined in Egypt for the following crops are:

Wheat	0.71	Barley	0.75
Corn	0.75	Millet	0.71
Cotton	0.73		

From the water requirements for each crop in the respective areas, the total net quantity of irrigation water is estimated. To this figure are added the quantity of expected losses in the distribution system and the quantity lost in the conveyance of water. The sum total is the quantity which must be diverted into the irrigation area.

The next step is the preparation of fields to be irrigated, and the drawing-up of a schedule of irrigation. The amount and frequency will depend on local conditions, soil properties, annual rainfall and kinds of crops. In general, irrigation in any one farm may start when the moisture available is halfway between the wilting point and field capacity, and may be completed before soil moisture drops to a quarter of this value.

This method of approach makes possible the best use of land and water resources ; at the same time, by preventing unnecessary excess water in the area, it facilitates snail control measures.

Crop selection

In areas where bilharziasis is endemic selection of crops, rotation and farming practices can play an important part in a control programme. If preference is given in the selection of crops to varieties not requiring a large amount of water, control or elimination of snail habitats is greatly facilitated. Thus, in Egypt, the prevalence of bilharziasis is less in areas where wheat and barley are grown than where rice is grown. Crop rotation makes possible irrigation practices that could prevent snail breeding, especially of the amphibious species. For example, in areas where *Oncomelania* is prevalent such crop rotations can be used to control or even eradicate them. For the control of aquatic snails, crop rotation is only effective where the distribution system is so designed that channels supplying uncropped fields may also be dried out. The sequence in which crops are grown affects tillage, seeding, weed control equipment, fertility, erosion, cultural practices and profitable land use.

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 obtain the control of 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.

Because of the high water requirements and methods of cultivation, rice-growing is a major problem in any snail control programme. It is therefore essential that attempts be made to cultivate varieties requiring relatively less water. One type developed in Egypt in a five-year programme by the Food and Agriculture Organization of the United Nations (FAO) and now called NAHDA, gave the lowest reduction in yield when subjected to reduced water applications. As a result of this work the growing of this variety increased from 38% of the total production in 1955 to 85% in 1957. While the extent to which reduced water application may facilitate snail control operations is not clearly known, it may be safe to expect that it will be of some benefit.

Further research in Egypt led to the selection of varieties, methods of cultivation and application of fertilizers that resulted in an increase in yield from 3.67 tons paddy per hectare in 1953 to 5.61 tons paddy per hectare in 1957. Rice in Egypt is irrigated for four days at intervals of four days. When the period of irrigation was changed to six days with a twelve-day interval the yield of the NAHDA variety was reduced by 14.8%, whereas for other varieties the reduction in yield rose to 25%. This loss in yield should, however, be considered in relation to the benefits that may result from the effect of such practices on snail control.

Results of experiments in Japan show that under certain conditions water application for rice-growing can be reduced by as much as 50% without affecting yield. The method recommended is as follows : water is applied to maintain the soil moisture at about 75% of field capacity from the period of transplanting to the beginning of heading ; then the application is increased sufficiently to maintain a depth of water in the paddy field of 2-3 cm for 30 days ; finally the application is cut back so as to maintain the moisture content at 75% of field capacity until just before harvesting. A reduction in the water application can prove an effective means of preventing snail breeding in rice fields, drains and canals, if it is consistent with good rice culture.

Of course, in the final analysis the effectiveness of any of these experimental results as snail control measures depends on their acceptance and use by the entire farming community.

MEASURES APPLICABLE TO OTHER MAN-MADE HABITATS

General

Engineering operations associated with the construction of public works, utilities, industrial activities and mines often involve excavations, fills and hydraulic structures which may provide additional breeding-places for host snails. Such places include roadside ditches, borrow-pits, quarries, gullies, obstructed drainage channels, bridges, culverts, causeways. Even the laying of a water supply pipe may create potential breeding-sites. In one case the excavation of the trench on each side of a bridge and excavation for pipe supports caused surface erosion, and leakage from an air valve and pipe joints supplied the necessary water for snail colonies to be established.

All these potential snail breeding-sites result from careless engineering practices, and their elimination can be effected by the responsible government agencies. The importance of such habitats in the transmission of bilharziasis has been amply demonstrated by careful investigations in Iraq, Iran and elsewhere. They provide suitable breeding-areas for vector snails, they attract human pollution, and provide opportunities for human contact with infested water.

The elimination of these snail habitats by engineering methods does not involve a great deal of work or expense. Where water bodies cannot be eliminated by these methods, snail control may be effected by treatment with a molluscicide.

Borrow-pits

Borrow-pits which are no longer used for mining clay or storing water may be eliminated by filling, grading and drainage. Where such methods are not practicable the pits may be dried out by periodic pumping during the snail breeding-season. Fencing of the pits may prove an effective means of preventing human contact. Where borrow-pits are used as water reservoirs, fencing and the provision of a satisfactory means of drawing water, such as a pump, are necessary to prevent transmission.

Stream Crossings

In endemic areas stream crossings present important transmission sites, whether the crossing is a ford or a bridge. They are of special importance when located near centres of population or schools. Methods of control here should be aimed at prevention of snail breeding and of human contact with the water.

At fords the provision of a foot-bridge and fenced approaches would go a long way towards reducing human contact with the stream. In South Africa this has been much assisted by the fencing of critical reaches and of the foot-bridges used as crossings.

Causeways often create snail breeding-pools either above or below the crossing. They also serve as washing and bathing sites for nearby villagers. Pools upstream of the causeway may be drained by the provision of pipes of sufficient size to take the normal flow of the stream and thus prevent water from flowing over the causeway. Pools downstream of the causeway may be eliminated by the construction of concrete or masonry aprons.

Where culverts are used for stream crossing, scouring is difficult to prevent, and pools are often formed either above or below the crossing.

Sometimes the inverts are either too high or too low, and to eliminate the pools the culvert may have to be reconstructed so that the invert lies at the normal stream grade. Where the culverts are too high, it may be more convenient and cheaper to lay pipes at the correct level to take the normal or low flows. Where the culvert is placed too low, it is necessary to raise it or to fill the portion below the channel grade with concrete or grouted masonry, and provide additional waterway. Unless steps are taken to eliminate such habitats, other methods of control must be considered.

At bridge sites scouring of the banks and stream bed creates pools in which vector snails may breed. As such sites are much frequented by nearby villagers the opportunities for transmission are considerable. In such cases control measures would have to provide for alternative sources of water supply for domestic and recreational purposes.

Miscellaneous

Important snail habitats are sometimes created by the blockage of water courses or roadside ditches by dumping soil from excavations, by silt and flood debris, by weeds and by caving-in of the banks. In some areas abandoned rice fields and unkept ponds provide suitable breeding-sites. In a snail control programme provision should be made for applying measures in such situations ; regular inspection and maintenance and the use of molluscicides should be considered.