The impact of river flow regulation and manipulation on the invertebrate hosts of malaria, bilharzia and liver fluke disease

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The effects of stream flow manipulation on the invertebrate hosts of malaria, bilharzia and liver fluke disease.

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Executive Summary

Introduction

The regulation of rivers is known to cause a number of changes to the function and form of rivers. According to Davies and Day (1998), the river continuum concept describes the river as a single longitudinal ecosystem with component variables that act as drivers eliciting responses from other variables (response variables). The flow regime in a river is one such 'driver variable'. Regulation of the flow in a river alters the nature of this important driver, and thus alters the responses elicited in the more reactive variables (for example geomorphic form of the river channel, range of in-stream habitats or biota assemblages).

Almost every major river in South Africa has been regulated to a certain degree, largely to meet the growing needs of development (Davies et al., 1993 – as reported in the State of the Environment report 2007). This report aims to assess the current state of knowledge concerning the relationship between river flow regulation and its effects, and the population dynamics of the invertebrate hosts of malaria, schistosomiasis (bilharzia) and fascioliasis (liver fluke disease) in South African rivers. The habitat requirements of these invertebrates will be central to this discussion. Additionally, the concept of using the manipulation of flows to control these invertebrates and thus also the transmission of their associated diseases is addressed.

Definition and review of the invertebrate hosts and routes of parasitic transmission in the natural environment.

Malaria

Four species of malaria parasite occur around the world.

- *Plasmodium falciparum*
- *P. ovale*
- *P. malariae*
- *P. vivax*

Plasmodium falciparum is the most common in South Africa and is also the most pathogenic. All four of these parasites can be transmitted by 28 of the approximately 200 species of *Anopheles* mosquitoes found around the world. The most important species for malaria transmission in South Africa are *Anopheles funestus* and *Anopheles arabiensis*. The distribution of *An. funestus* has been reduced significantly by spraying of insecticides, leaving *An. arabiensis* as the most important malaria vector in South Africa.

Anopheles arabiensis is an opportunistic breeder which uses different habitat types in summer and in winter (le Sueur, 1991). During winter they use overflow and seepage irrigation water and the vegetated margins of larger water bodies, where submerged plants protect the larvae from predators. During summer, they use temporary rain-filled, sunlit pools that are typically un-vegetated and can be man-made such as vehicle wheel tracks or cattle hoof prints.

Anopheles funestus breeds in larger, more permanent water bodies with emergent vegetation such as swamp margins and streams. Research in Kenya suggests that they are found breeding mainly in stable stream pools (Mwangangi et al*.,* 2007).

Schistosomiasis (bilharzia)

Worldwide, 30 species of schistosome (blood flukes) parasitize mammals, and an even larger number parasitize water fowl. Seven of these are known to parasitize people, of which two species commonly infect people in South Africa, *Schistosoma haematobium* which causes urinary bilharzia, and *S. mansoni* which causes intestinal or rectal bilharzia. Both of these parasites' life cycles involve two hosts, a warm blooded vertebrate final host (humans) and an invertebrate intermediate host which is an aquatic snail. Most, if not all of the schistosome parasites of birds are known to penetrate human skin, but they do not develop further and when they die, they cause a rash known as 'swimmers itch'.

In South Africa, *S. haematobium* has two intermediate snail hosts, *Bulinus africanus* and the closely related *Bulinus globosus*. *S. mansoni* uses *Biomphalaria pfeifferi* as its snail host. Transmission of these parasites can take place in any water body where these snails occur and with which people have contact.

Schistosome eggs are released into the water from the human host through urine (*S. haematobium*) or through faeces (*S. mansoni*). The eggs hatch and the motile miracidium seeks out and penetrates its snail intermediate host. Inside the snail, asexual division takes place resulting in the production of cercariae, which leave the snail at the rate of hundreds per day in a diurnal rhythm designed to coincide with the swimming activities of children. The cercariae penetrate the human host through the skin and make their way to the liver where they mature into adult worms. They then pair up and make their way to the vessels draining their final target organs where they begin to produce eggs (*S. haematobium* – bladder, *S. mansoni* – lower intestine or rectum).

The invertebrate hosts of *S. haematobium* are generally found in permanent, slow moving water bodies. *Bulinus africanus* is found over much of the eastern half of the country as far south as the Kromme river in Humansdorp, while *B. globosus* is limited to the extreme eastern parts of Limpopo and Mpumalanga provinces and to a small area of north-eastern KwaZulu- Natal. Both species are vulnerable to desiccation and their intrinsic rate of increase is considered relatively low (De Kock et al., 2005) but is strongly linked to temperature. Indeed temperature and water body type or flow rate appear to be the major factors determining the distribution of the *Bulinus* group.

Biomphalaria pfeifferi, the intermediate snail host of *S. mansoni*, is also generally found in still or slow moving permanent water bodies. This species is particularly vulnerable to desiccation and thus is unlikely to be found in temporary rain filled habitats. Its distribution is similar to that of *B. africanus*, but does not extend further south than Port St Johns. Like the *Bulinus* species, this snail's distribution is mostly influenced by water body type and temperature.

Fascioliasis (liver fluke disease)

Fascioliasis is caused by two species of trematode – *Fasciola hepatica* and *F. gigantica*. Very little is known about the epidemiology of fascioliasis in South Africa, though the vast majority of infections are in fact in wild animals and livestock. Infections of humans are extremely rare in South Africa.

Both species use freshwater snails as intermediate hosts. *Fasciola hepatica* uses *Lymnaea truncatula*, and *F. gigantica* uses *Lymnaea natalensis*. The invader species *L. columella* may also play a role in the transmission of the parasites, but this is unproven in South Africa.

Lymnaea truncatula is an amphibious species, found characteristically on damp mud around temporary habitats such as swamps, bogs, irrigation ditches and drains. Its preference for cooler humid areas means it is most abundant in high lying areas such as Lesotho and northern parts of the Eastern Cape. It can reportedly aestivate up to 12 months (Kendall, 1965).

Lymnaea natalensis is widespread across South Africa, and unlike *L. truncatula*, is completely aquatic. It is thus mostly found in permanent larger bodies of water. Temperature appears to have less of an effect on the distribution of this species, and water body type appears to be the most important determining factor.

Important habitats

Water body type appears to play an important role in determining suitability of a particular habitat for the invertebrate hosts of the three diseases. This includes the rate of flow. Since mosquito larvae are unable to resist flow, adults particularly seek out still water in which to breed. Snails are also vulnerable to higher flow velocities and Appleton (1978) identified current velocity as the abiotic factor most influential in determining the distribution of host snails in flowing waters, with snails unable to resist flows of greater than approximately 0.3 ms^{-1}. Several other authors have expressed similar views regarding the limiting effect of stronger currents (De Kock et al*.,* 2004; Brown, 1994; O'Keefe, 1985)

Temperature also plays a large part in determining habitat suitability. Temperature is documented as being one of the most important factors influencing A*nopheles* mosquito distribution (Coetzee et al., 2000). Water temperature plays an important role in determining the fecundity of snails, and with the exception of *L. natalensis*, all species reviewed appear to be temperature sensitive. Temperature also plays a role in the development of the parasites within the snail, a fact which may limit the transmission of the disease in cooler parts of the country during colder months (Moodley et al., 2003).

Aquatic vegetation also appears to play a role in determining habitat suitability, though this is likely linked to providing shaded refuges away from predators, food availability and protection from excessive current speeds.

Present interventions affecting invertebrate hosts life cycles

Interventions which have led to the expansion of the distributions of invertebrate hosts of the three diseases have been investigated. There is little doubt that the most important intervention in this category is the impoundment of rivers. Through retaining water, vast areas of suitable standing water habitat are created, and improved access to water bodies increases human contact with water which, in turn, increases the risk of transmission.

Five case studies were examined where dams either caused an increase in the transmission of disease through the creation of additional habitat, or where dams were used to interrupt the parasite transmission through controlling the invertebrate host.

The Bargi dam in India, the Diama and Manantali Dams in the Senegal river basin and the Akosombo dam in Ghana are all illustrations of a dam's potential to create new invertebrate host habitat, and to increase the potential for disease transmission. Two case studies, one in Sri Lanka (Konradsen et al., 1998) and one in Tanzania (Fritsch, 1993) are illustrations of the use of flow manipulation from dams in an attempt to control the populations of invertebrate hosts.

The following factors are drawn from the literature as being important in establishing the links between invertebrate hosts and rivers.

1. Volume and rate of flow.
   For malaria mosquitoes, flow rate is definitely important, especially if they use rivers as breeding habitat (*An. arabiensis* typically use stagnant water bodies). Those that do use rivers seek out quiet back waters where flow is almost non-existent. Snails are susceptible to flows greater than 0.3 ms^{-1}, and are likely to be washed away if faced with currents greater than this (Appleton, 1975). Additionally, stronger currents are thought to reduce breeding success as snails expend more energy attempting to resist dislodgement (Loreau et al., 1987). Flow regulation may thus limit the influence of natural population limiting events such as floods.
2. Vegetation
   Aquatic vegetation may be important in the life cycle of malaria mosquitoes since it has been shown that *An. arabiensis* will breed in larger water bodies if suitable refugia such as beds of *Potamogeton crispus* are available (le Sueur, 1991). *An funestus* has been shown to breed in vegetated back waters of streams and swamps. The case study of the Akosombo dam has shown that an increase in aquatic vegetation brought about by the cessation of scouring floods may well play a part in facilitating an increase in the abundance of bilharzia host snails.
3. Temperature
   Temperature has been shown to play a strong role in the distribution of both mosquitoes and most species of freshwater snail. Temperature of water bodies can be influenced by the regulation of flow both through allowing greater in-stream heating, and through the release of water from impoundments with a temperature different from the naturally determined temperature. The temperature of the water is likely to influence the population dynamics of snails.

Flow related control feasibility

The feasibility of undertaking flow manipulation as part of invertebrate host control should be assessed in terms of which water bodies are in fact possible candidates for flow manipulation. It is proposed that only rivers which flow through disease endemic areas, and that are regulated by large dams are feasible candidates for this form of control. Large dams are defined as impoundments with a capacity that is greater than 10 million m^3. Large dams are preferred since it is assumed that they will have the infrastructure to release or retain calculated volumes of water at will, and will have the capacity to store these volumes. It is also assumed that larger dams will be managed more effectively than smaller dams, and that the implementation of flow manipulation will be a more realistic proposition in these dams.

128 candidate dams were selected from the DWAF dam safety database, and these were used to select sections of river in which flow manipulation control may be possible. This resulted in 4766 km of river being selected as candidate rivers.

Using a buffer distance of 5 km (based on the possible flight distance of *Anopheles* mosquitoes (Menach et al., 2005; Ghebreyesus et al., 1999), and an assumed distance children are willing to walk to swim in a river), a population group was identified which represented people at risk from diseases originating in candidate rivers. In the case of Malaria, this group represented approximately 40% of the people living in malaria endemic areas. In the case of bilharzia, this group represented approximately 18% of people living in bilharzia endemic areas.

Cost of the diseases to South Africa

The costs associated with these diseases in South Africa are difficult to estimate. Very few studies have been conducted, and most concern particular areas. Several international studies do shed light on the issue. Direct costs and indirect costs associated with infections are added to the costs of preventative measures to gain an idea of the total cost to the country. Indirect costs, such as lost productivity, are especially difficult to estimate. The majority of studies around the world use a wage rate method, where the number of lost work days is multiplied by the average daily wage.

According to Tren (undated) malaria cost South Africa approximately R124.5 million in 1998 (see Table 1 below). This figure was extrapolated to 2006 using 5.3 % average inflation, and infection statistics from the Department of Health. According to this extrapolation, malaria cost South Africa R140.1 million in 2006. These costs included costs allocated for hospitalization costs, lost productivity of both the patient and care giver, mortality costs and the cost of the national indoor residual spraying campaign.

Table 1: Extrapolated figures showing estimated costs associated with malaria for 2006 (based on 5.3% inflation). 1998 data from Tren (undated)

Type of Cost	**1998 costs**	**2006 costs**
Number of malaria cases	22,690	12,098
Direct Costs		
Cost of treating and hospitalising patients	260.12	370.41
Indirect Costs		
Malaria patient lost productivity	265.15	377.58
Carer – lost productivity	8.40	11.97
Mortality costs	1,870.36	2,663.39
Cases outside malarial areas	73.30	104.38
Infection related costs (cost per case)	**2,477.33**	**3,527.72**
National infection related costs (cost per case * no of cases)	56,210,697.00	42,678,391.61
National preventative costs (malaria control programme)	68,424,164.00	97,436,009.54
TOTAL Cost to Country	**124,634,861.00**	**140,114,401.14**

Unlike malaria, bilharzia is not a notifiable disease, and so infection statistics are not available. Moodley et al. (2003) (reported in Appleton, 2006) estimate that 2.5 million people are infected with bilharzia at any one time. This figure was used in conjunction with treatment and loss of productivity costs estimated by Mander in Cox et al. (2003) and Mander et al. (2003) to estimate the total cost of the disease to the country as being made up of an estimated once off, national treatment (chemotherapy) cost of approximately R363 million, and a further value of between R250 million and R275 million reflecting lost productivity every year. It should be noted though that this figure is entirely hypothetical, since many infected individuals do not seek treatment, and the long term productivity loss costs carried by these individuals far outweighs the cost of their treatment.

Table 2: Estimated costs associated with Bilharzia in South Africa

Study	Area of Study	No of infections	Treatment costs (once off)	Loss (PA) of productivity	Cost per case
Cox et al. (2003)	Crocodile river catchment	110387	R5 500 000.00	R11 000 000.00	R150.00
Mander et al. (2003)	Lower Thukela river catchment	107512	R15 600 000.00	R12 000 000.00	R257.00
National extrapolation	Republic of South Africa	2 500 000	R363 000 000	R250 000 000-R275 000 000	R245-R257

The costs associated with liver fluke disease in South Africa are thought to be almost entirely made up of costs and losses suffered by livestock farmers. No studies have been carried out concerning the impact of this disease on the country, and extremely little literature was available concerning the parasite in general. This is surprising given that anecdotal evidence from farmers and veterinarians pointed to the fact that the disease carries a significant cost with it, and the fact that in the UK it is estimated that fascioliasis costs the agricultural industry R322 million per year, and in Australia it is estimated to be R520 million per year.

Costs and losses due to fascioliasis are associated with reductions in milk production, reduced calving rates, slower animal growth rates, condemnation of livers at slaughter and the costs of preventative drenching (treatment).

Suggestions for utilizing flow manipulation as part of integrated invertebrate host control

Following a workshop focusing on the habitats of invertebrate hosts, and the impacts of river regulation on these habitats, four possible flow manipulation scenarios are presented below. Each is considered in terms of its possible effect on snails and mosquitoes and its potential efficacy as a control measure.

1. **A sudden increase of flow – 'river flushing'**
    - A sudden increase in the volume and velocity of flow is thought would result in raised water levels and a flushing out of invertebrate hosts from previously protected habitats.
    - Mosquito larvae have no way of combating current and therefore could be swept out of riverside pools and shallow areas, as is demonstrated by Konradsen (1998). Retreating flood waters may however create new pools

and breeding opportunities for mosquitoes, and the short duration of the larval stage means that the flooding will need to be repeated within 10 days.

- Snails are sensitive to increased velocities and several studies have shown natural flooding to significantly reduce snail abundance (Woolhouse and Chandiwana, 1990). Fritsch (1993) demonstrated that flushing of a stream in Tanzania was effective in removing *Bulinus globosus* almost entirely.
- Snails that are dislodged and flushed downstream may provide a source of passive immigration (and infection) to areas downstream of their site of origin.
- A significant volume of water would be required for this type of manipulation, and in South Africa's water scarce environment this could prove to be an insurmountable obstacle.
- A further stumbling block will be the effect of the flushing on the river's ecological health. The damaging effect of flushing on all aspects of aquatic ecosystems was not considered by any of the literature reviewed, and this would need to be carefully assessed.

2. **A sudden reduction in flow**
    - A sudden reduction in the volume and velocity of flow will result in a drying out of habitats located in the marginal areas of streams and rivers, and may result in the desiccation and death of invertebrate hosts living there.
    - It is thought that this will be ineffective as a mosquito control mechanism due to the fact that isolated pools are unlikely to dry out in the limited time that it takes for mosquito larvae to mature.
    - Additionally, the breeding habits of malaria mosquitoes means that limited numbers of them breed in a riverine environment, and most favour rain-filled temporary pools independent of water levels in rivers.
    - Snails generally populate the shallow margins of water bodies and avoid deeper areas where oxygen levels are lower, food is scarce and currents are stronger. A rapid reduction in water level is thus thought may affect snails living in these marginal areas.
    - Snails may aestivate, but it is thought that the majority would die since flow reduction would take place rapidly.
    - Fritsch (1993) recorded a total elimination of snails in a weir's head pond after rapid drawdown.
    - O'Keefe (1985) has documented droughts as interrupting snail population growth.
    - Snails living in residual pools or snails that achieve aestivation will not be killed and will likely provide the basis for a new population once river levels are restored.
    - A successful case study exists where *Simulium chutteri* larvae (Diptera, *Simuliidae*) were controlled in the orange river using flow reduction (Howell et al., 1981)
    - Flow reductions may conflict with the introduction of the Ecological Reserve.

3. **A combination of reduction and increase in flow**
    - The effects of this are largely combining the effects of the two mechanisms outlined above. The major advantage is that the water saved by first reducing flow may then be used to increase the flow at no cost to the users of the impoundment.
    - Snails that survive desiccation through aestivation are likely to be swept away by the following pulse.
    - Using a combination of the two is thought may prove more effective than using either one in isolation.
    - The effectiveness of this approach also means it will probably be the most detrimental to overall river health. The effects are similar to the effects of hydropower dam releases, the damaging effects of which are well documented.
4. **Re-introduction of natural flow variations**
    - The natural variations of flow are not likely to negatively impact mosquito breeding populations due to the flood cycle generally being longer than 10 days, and the extended onset period of droughts.
    - In natural systems, flow variations serve to limit snail population growth (Woolhouse and Chandiwana, 1990; O'Keefe, 1985).
    - Habitat stability is key to the breeding success of freshwater snails (workshop finding) and flow variations serve to de-stabilise snail habitats.
    - The reintroduction of natural flows will serve to improve overall river health.
    - The effect of natural flow variations on malaria mosquito populations is unclear. Anecdotal evidence of early settlers suggest that rivers in a natural condition have supported large populations of malaria mosquitoes in the past.

The impact of river rehabilitation on the transmission of the parasites

River rehabilitation is not generally practiced in South Africa in its true form. It is a discipline which has grown in popularity internationally over the last decade, and is a recent arrival on our shores. Elements of river rehabilitation are practiced here, such as the clearing of alien plants through the Working for Water project, and the establishment of databases recording the health of rivers around the country through the River Health Programme. The introduction of the Ecological Reserve through the National Water Act has served to formalize the idea of flow remediation, and presents an opportunity to manage rivers in a way so as to return them to a more natural state through the reintroduction of more natural flow regimes.

Flow remediation

The consequences of flow remediation for intermediate hosts of disease are varied. Primarily, flow variation will destabilize aquatic habitats which have been un-naturally stabilized through regulation and affect the amount of suitable habitat available in the wetted area.

Remediated flow may also have knock-on effects in terms of the channel shaping function of high flows. Sediment which has settled in the channel in regulated rivers is likely to be scoured out by high flow events, and sediment hungry water released from dams is likely to increase bank erosion and bed armouring. This may affect bankside vegetation and refuge habitats available to invertebrate hosts.

Remediation of water temperatures in the river downstream of dams may also have an effect on invertebrate hosts. It is well documented that dams reduce the seasonal range of temperatures of the rivers downstream of them (Pitchford et al., 1975; Dickens et al., 2007). Winter minimums are increased and Summer maximums are decreased. Modern dams however are able to mitigate against this by releasing water from various levels.

Temperature

Temperature plays a role in determining the fecundity of snails and the development of bilharzia cercariae within the snail. The reintroduction of natural variation in temperature may serve to further destabilise snail habitats and depending on the ambient conditions below the dam may make the river more or less suitable for snail reproduction during various times of the year. *Bulinus globosus*' natural rate of increase peaks at 25°C while *Biomphalaria pfeifferi* peaks at between 20°C and 25°C (Harrison et al., 1966 & Shiff et al., 1966).

Vinson (2001) noted that the introduction of a multi-level release mechanism had made very little difference to the invertebrate assemblage that had become established below the dam after it had been closed. He ascribed this to the dominance of the invertebrates which had established themselves after dam closure. He concluded that temperature remediation on its own may not make a major difference in the composition or abundance of invertebrates.

Review of the ability to predict the occurrence of invertebrate hosts in South Africa

Predicting the presence or absence of invertebrate hosts is not easy. There are no predictive models based on ecological or habitat related variables at a small enough scale for any of them. Prediction therefore relies on whether or not the water body lies in the disease endemic area, and if it is suitable for colonization by the relevant invertebrate. This is problematic since in both bilharzia and malaria, the range of the invertebrate host is wider than that of the disease.

The distributions of the hosts are largely determined by their tolerances of environmental conditions as has been laid out in previous sections. However, under exceptional circumstances (such as dramatic increases in rainfall in the case of malaria) this distribution may spread.

Suitability models have been developed for bilharzia using a variety of masks to predict the occurrence of the host and the disease in several countries. These are however large scale models which do not accurately predict whether a given water body is likely to harbour snails, or if they are susceptible to infection by bilharzia miracidia. These questions are currently only answered by inspection of the water body, comparison with known habitat preferences of the snails and human contact behavior.

Change in infection risk profile in relation to the provision of water services

The provision of water services is unlikely to contribute to the transmission of malaria, or the breeding of vector mosquitoes. This is unless poor water management results in leaks and overflows which may provide *An. arabiensis* with suitable breeding habitats close to human habitation.

Reducing the reliance of people on contact with suitable snail host habitats is expected to reduce the incidence of transmission. This conclusion is based on cases in rural Mpumalanga where piped water, laundry facilities and swimming pools were provided in addition to restricting access to habitats such as streams, which over a long period of time achieved a significant reduction in infection rates (Pitchford, 1966, 1970a&b), and another where the provision of piped water and water-borne sanitation reduced the incidence of bilharzia to almost nil (Pitchford et al., 1967).

The provision of water services can however not be seen in isolation as an anti-schistosomiasis measure, and cannot be divorced from other types of intervention such as chemotherapy and health education. Current thinking suggests that chemotherapy should accompany the provision of water services with the expectation that the immediate reduction in worm burdens would be maintained by the longer term intervention of safe water provision.

Conclusions

It is concluded that, due to the breeding habits and brevity of the larval stage of the *Anopheles* mosquito, they would in fact be poor candidates for control by flow related means. *Anopheles arabiensis* is an opportunistic breeder making use of temporary sunlit rain-filled pools, which are generally not connected to rivers. *Anopheles funestus* distribution has been severely reduced in South Africa and it is concluded that in comparison to indoor residual spraying, flow related measures would have little impact on this species' population and distribution. In addition, due to the brevity of the larval stage in the life cycle of the *Anopheles* mosquito, flow manipulations would need to be repeated impractically often to succeed.

Bilharzia snails prefer stable habitats with still or slow moving water. Their ability to withstand currents is limited and flood events are known to drastically impact populations (Woolhouse et al., 1990). The ability of the snail species to aestivate is also limited making them vulnerable to desiccation in the event of sudden flow reductions. These two factors make freshwater snails good candidates for flow related control measures.

Very little information is available concerning the host snails of *Fasciola gigantica* and *F. hepatica.* Consequently, no meaningful conclusion could be arrived at concerning the flow related control of these species. It is suggested that the measures and results may be the same as those for bilharzia host snails, with the exception of the amphibious *L. truncatula*, which, because it is often found outside of the water on damp mud, and because it is comparably a good aestivator, would be far less susceptible to reductions in flow.

Overall, the merits of flow related control measures must be weighed against the impact such measures would have on the aquatic environment in general, and the limited water resources available. Additionally, it is estimated that only 18% of people living in bilharzia endemic areas in South Africa may benefit from a reduction in risk of infection should manipulation of flow be implemented as a control measure.

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1. Introduction

1.1 Study background

Despite changes in form and appearance along their course, rivers form a single continuous longitudinal ecosystem, possessing gradients of physical and chemical conditions which change continuously from source to mouth. This is the River Continuum Concept (RCC). This concept defines and outlines the role of ‘driving variables’ in rivers. As they change over time and space, these variables elicit responses from variables within the river (‘response variables’). One of these ‘driving variables’ is the flow of a river (Davies and Day, 1998).

A river’s annual flow regime is considered to be made up of a baseflow, floods (large pulses of high flow in the wet season), freshes (smaller pulses of high flow in wet and dry season) and in some rivers, periods of no surface flow at all. Additionally, in dry areas, rivers may vary their discharge by orders of magnitude from year to year (O’Keefe, 2000). According to King (1998), the different magnitudes of flow are responsible for maintaining different aspects of riverine ecosystems. Floods and freshes have important functions in that they trigger and reset a wide range of conditions and events in the river such as fish spawning and migration, flushing out poor quality water, scouring river beds and maintaining habitat diversity.

Interruption of the river’s continuum, such as the construction of a dam or weir, can result in a new set of changes which will have an impact on the habitats that have developed above and below the dam under natural conditions. South Africa’s scarce supply of water has led to nearly every major river in the country being regulated to a certain degree to meet the needs of development (Davies et al., 1993 – as reported in the State of the Environment report 2007). In fact according to Davies and Day (1998), 520 major regulating structures which capture 50% of the countries mean annual runoff have been put in place. In many cases several dams have been constructed on a single river leading to a cascading effect. This means that the riverine habitat downstream of these impoundments has been altered by manipulated flow.

Manipulations of virgin flow regimes represent unnatural disturbances to riverine ecosystems. These may result in hydrological cues, which trigger events such as fish spawning, occurring at the wrong time of year, or not at all, resulting in affected species declining in number. They may also result in other species taking advantage of altered conditions and increasing in abundance. An example of this is recorded by Palmer (1998) where black fly (*Simulium chutteri*) numbers reached plague proportions after natural flows on the Orange river were interrupted by the construction of the Van der Kloof and Gariep Dams. In many cases, regulated rivers downstream of dams support the invertebrate hosts of malaria, bilharzia and liver fluke disease. The relationship between these diseases, their invertebrate hosts and regulated rivers form the focus of this report.

Diseases are typically categorised according to their association with water into 4 groups (Gleick, 2002):

1. water borne diseases,
2. water washed diseases,
3. water based diseases and

4. water related diseases.

The diseases to be focussed on by this report fall into the latter two of these four categories. Bilharzia (Schistosomiasis) and liver fluke disease (fascioliasis) are water based diseases, i.e. they are transmitted through an aquatic invertebrate organism while malaria is a water related disease, i.e. it is transmitted by insects that depend on water for their propagation. Diseases of both of these categories are reliant on an organism other than the terminal host for the completion of their life-cycle. In rivers, these organisms are subject to the changes in habitat brought about by an interruption of the continuum, such as the construction of a dam and the associated regulation of the downstream river.

The WRC has initiated this investigation to bring together current knowledge in an effort to understand the effect flow regulation / manipulation has on the invertebrate hosts of these diseases, and to investigate the possibility of using flow manipulation to negatively impact the populations of their invertebrate hosts, and thus reduce their transmission.

1.2 Project aims and objectives

The principle objective of this project is to draw together available knowledge concerning the impact regulated flows have on the populations of invertebrate hosts of malaria, bilharzia and liver fluke disease, and to investigate the use of flow manipulation as a mechanism to control the abundance of invertebrate hosts and reduce the transmission of their associated diseases.

Little work has been done specifically on the effects of flow regulation on the invertebrate hosts of these diseases, and so, to gain a level of understanding of this relationship, it is important to develop an understanding of the biology of the parasite and the habitat requirements of the invertebrate hosts.

For this reason, the aim of the first section of this report is to describe the biology of the parasites and to understand their invertebrate hosts, their habitat requirements, their relationship to rivers and the effects impoundments have had on these organisms. By developing an understanding of these factors, one can gain insight into possible changes that may result in the distribution and abundance of invertebrate hosts and the changes in distribution and rate of infections due to the regulation of rivers.

From that point, a discussion concerning the use of flow manipulation to control the populations of invertebrate hosts and thus also the transmission of their associated diseases can be initiated. Following sections will thus aim to investigate international experience in control of these organisms, and the finally the possibility of implementing such control in South Africa, and peripheral issues which may affect such control (water services provision for example).

2. Definition and review of the invertebrate hosts and routes of parasitic transmission in the natural environment.

2.1 Malaria – Human plasmodia

2.1.1 Parasite biology

Parasite Species:

Malaria is an acute, febrile illness caused by protozoan parasites of the genus *Plasmodium*. They penetrate, feed on and eventually destroy their hosts' red blood cells. Four species of human plasmodia exist in different parts of the world:

- *Plasmodium falciparum*
- *P. ovale*
- *P. malariae*
- *P. vivax*

In South Africa, *P. falciparum* is not only overwhelmingly dominant in terms of the proportion of diagnosed cases (>85%), but it is also the most pathogenic. *P. vivax* is not thought to occur in South Africa save for isolated cases thought to have been imported from Asia.

Malaria is transmitted to people in salivary secretions injected by female mosquitoes of the genus *Anopheles* as they take a bloodmeal, generally at night.

Life Cycle:

A diagram of the life cycles of the four malaria parasites is provided in figure 1. Infection of the human host occurs following a bite by an infected female mosquito of the genus *Anopheles*. Spindle-shaped sporozoites (10-15 x 0.5-1.0 µm), the parasite's infective stage, are injected with the mosquito's saliva into the host's peripheral blood and within about 30 minutes make their way to the liver where each penetrates a liver parenchyma cell or hepatocyte.

Once inside, the sporozoites multiply asexually by a process called exo-erythrocytic (or pre-erythrocytic) schizogony, a form of multiple budding. These hepatocytes are large cells (up to 200 µm diameter) and allow the production of 30 000 to 40 000 merozoites in each by day 6-8 after inoculation. These merozoites are released into the circulating blood when the infected hepatocytes burst and invade erythrocytes and, now called trophozoites, undergo another bout of asexual reproduction, erythrocytic schizogony.

Probably only the first brood of merozoites is released into the circulation and any left inside the hepatocytes remain in the liver as a residual infection but do not undergo further exo-erythrocytic schizogony. Unlike the other *Plasmodium* species therefore, relapses of *P. falciparum* are rare, occurring only after some of the infected red blood cells become sequestered by the microvasculature of organs like the brain as erythrocytic schizogony reaches completion. When these 'hidden' cells with their mature parasites burst, the progeny (merozoites) join the population in the peripheral circulation and infect new erythrocytes

Division of the trophozoite in the red blood cell (the early stage is the so-called 'signet ring-form' measuring 2-2.5 μm) results in 8-36 merozoites in the mature schizont, but in the South African strain of *P. falciparum*, 10-20 merozoites are usual. Mature schizonts (±5 μm diameter) rupture synchronously to release large numbers of merozoites into the blood, each of which enters an erythrocyte to start a new bout of schizogony. This process repeats itself many times with the numbers of merozoites being released into the blood increasing each time.

When this release of more and more parasites into the blood in addition to increasing amounts of cellular debris and metabolic by-products reaches a critical level, the host becomes sensitized and responds with the well-known malarial fever attack. The periods between malarial attacks, the chills, correspond to the actual process of parasite division.

After repeated bouts of erythrocytic schizogony, gametogony occurs and immature single male or female gametocytes form inside the red blood cells instead of merozoites. These immature gametocytes remain inside their host red cell and are generally found in visceral blood. When they appear in the peripheral circulation, they are mature crescent-shaped cells measuring 9-11 μm (male) and 12-14 μm (female). Gametocytes do not stay in the peripheral blood for long because if they are not taken up by a feeding mosquito, they are likely to be phagocytosed. Once sucked up by a mosquito however, they emerge from the host cell's membrane and continue their development in the insect's midgut.

Inside the mosquito's midgut, the female gametocyte emerges from the red cell's membrane to become a mature macrogamete while the male gametocyte becomes active and as it emerges from its host cell, divides meiotically three times to produce eight flagellum-like microgametes, a process called exflagellation. After fertilization, the zygote becomes a motile ookinete which burrows through the epithelial wall of the mosquito's midgut to encyst as an oocyst on its outer surface, protruding into the haemocoel.

The parasite now divides asexually again, by sporogony, a process similar and perhaps identical to schizogony, to produce about 10 000 sporozoites over about 12 days. During this time most female mosquitoes will revisit houses three or four times to take more bloodmeals. On completion of sporogony the oocysts burst liberating the sporozoites into the mosquito's haemocoel from which they penetrate the pair of salivary glands close to its pharynx. Here they remain until the mosquito takes its next bloodmeal, something it has to do because it needs the proteins from the bloodmeal to produce its eggs.

The 4 species of *PLASMODIUM* infecting MAN : *P. ovale*, *P. vivax*, *P. malariae* & *P. falciparum*

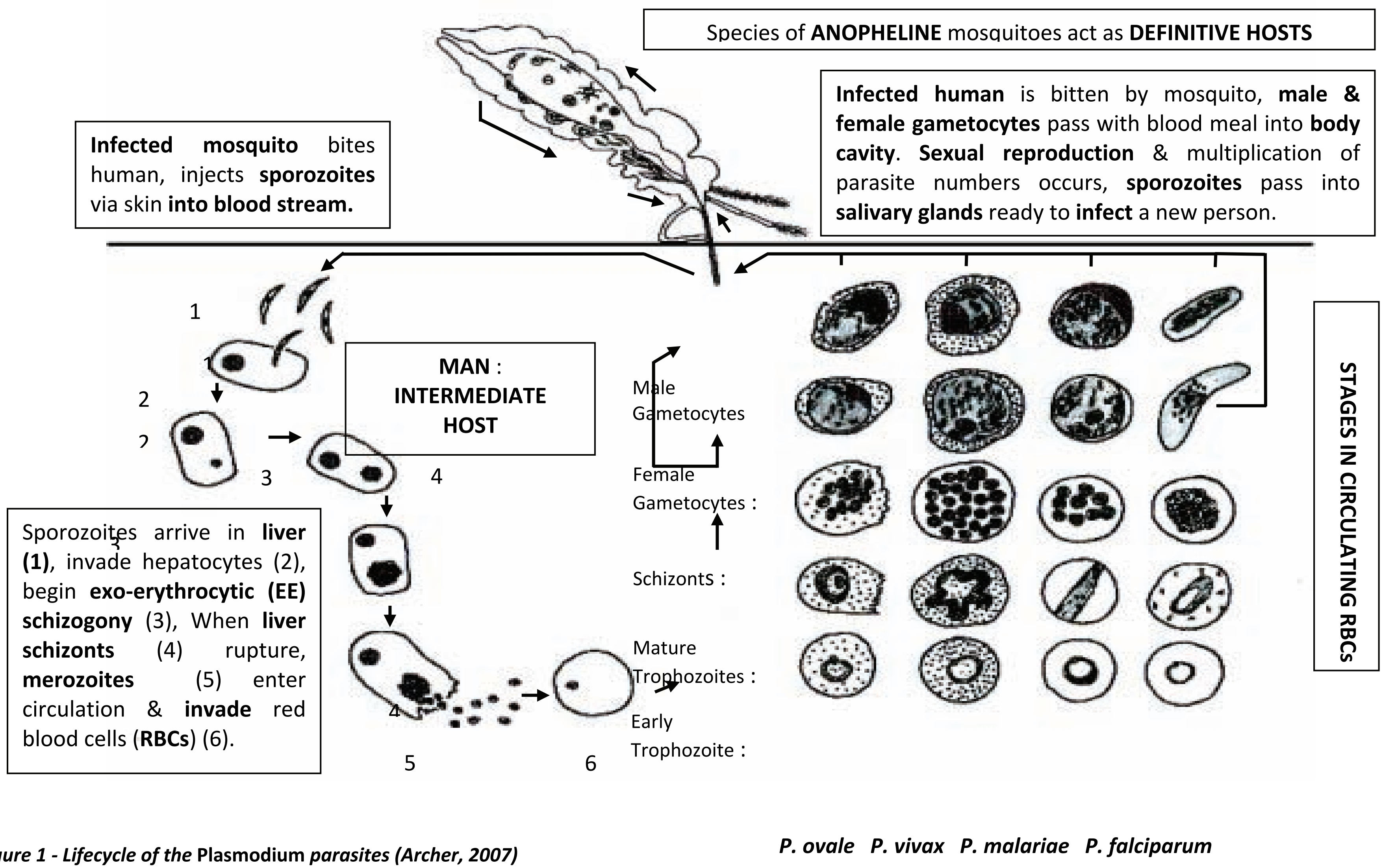

Figure 1 - Lifecycle of the Plasmodium *parasites (Archer, 2007)*

Parasite Distribution:

South Africa represents the southern limit of malaria in Africa. The endemic area covers Limpopo Province, the eastern lowveld of Mpumalanga and the north-eastern corner of KwaZulu-Natal as far south as the Tugela River. Transmission is however not uniform over this area. The distribution of malaria risk areas is depicted in Figure 2 below later in this report.

Using a Geographical Information System (GIS) and the magisterial district as the spatial unit, the highest incidence rates (60-70/cases/1000 population) occur in Ingwavuma district in north-eastern KwaZulu-Natal, slightly lower in Ubombo district to the south (20-30/1000) and lower still (10-20/1000) in several isolated districts in Mpumalanga and Limpopo. Incidences in the rest of the endemic area are between <1 and 10/1000.

In analysis of these data at the 'section' level (average area of 'section' = ±40 km^2) using GIS technology, certain parts of Ingwavuma district have been shown to be 'hotspots', supporting incidence rates in excess of 100/1000 and even above 500 in several 'sections' on the Mozambique border.

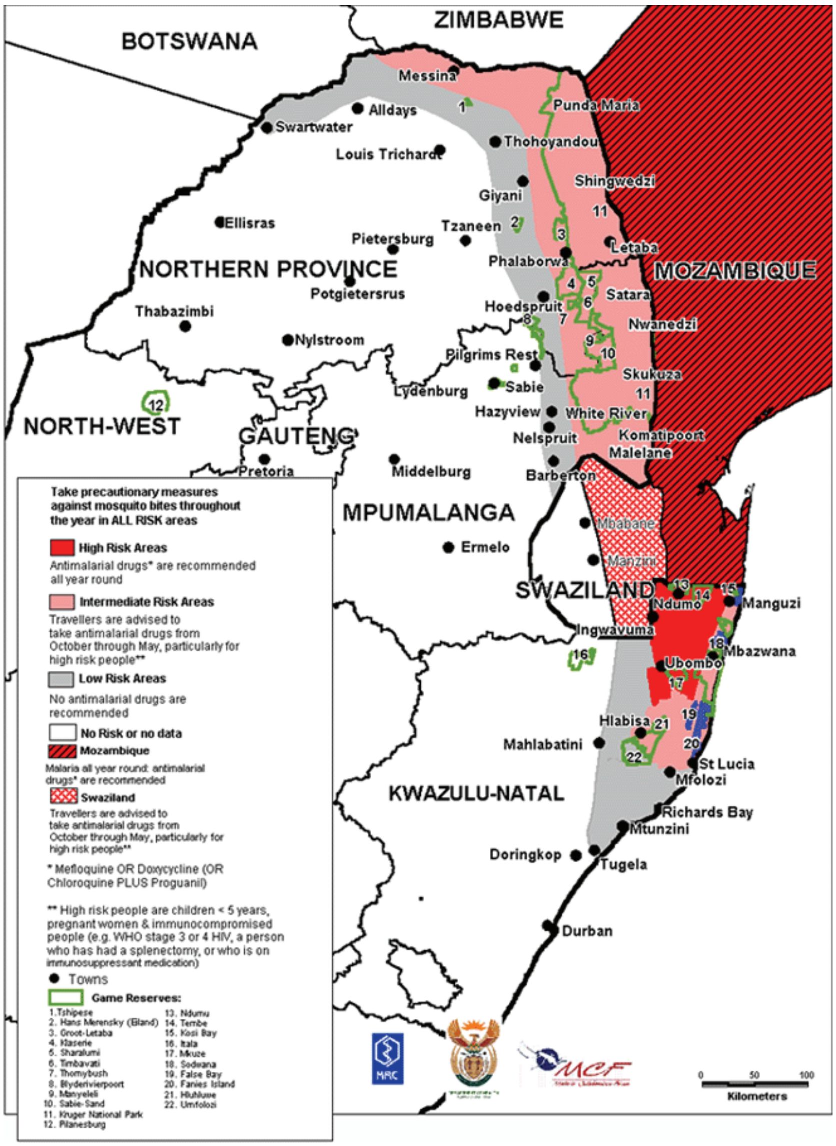

Figure 2: Distribution of malaria risk zones in Southern Africa (Medical Research Council - http://www.malaria.org.za/Malaria_Risk/Risk_Maps/risk_maps.htm)

2.1.2 Bionomics and habitat of invertebrate hosts

Invertebrate host species:

Twenty eight of the approximately 200 species of *Anopheles* worldwide serve as vectors of human plasmodia and three of these do so in South Africa: *Anopheles gambiae* s.str, *An. arabiensis* and *An. funestus*. Two of these, *An. gambiae* s.str. and *An. arabiensis* are members of the *An. gambiae* complex – a group of sibling species closely related to and morphologically indistinguishable from each other. The third, *An. funestus*, belongs to a different complex.

Anopheles gambiae s.str., *An. arabiensis* and *An. funestus*, are efficient vectors of *P. falciparum* while *An. merus*, another member of the *An. gambiae* complex, is rated as a minor vector in East Africa but has not been shown to transmit malaria in South Africa. The most important vector in South Africa is *An. arabiensis* though, where it occurs, *An. funestus* is also important.

Invertebrate host habitat choice:

Anopheles arabiensis are opportunistic breeders and use different types of breeding habitat in summer and winter as shown for the Maputaland coastal plain of KwaZulu-Natal by le Sueur & Sharp (1988) and le Sueur (1991).

During the dry winter the mosquitoes use overflow and seepage irrigation water as well as vegetated margins of larger water-bodies such as the pans of the Pongolo River floodplain. Here the dense foliage of submerged plants such as *Potamogeton crispus* protects the developing larvae from predators.

During the rainy summer the adults radiate out from these refugia to breed in the many small, sunlit pools that remain in previously dry areas for a week or more after rain. These temporary pools are typically man-made, i.e. open, shallow, without vegetation, as small as vehicle tracks and cattle hoof prints (e.g. 20 x 15 x 5cm) and containing as little as 100 mℓ of water. le Sueur (1991) recorded up to 400 larvae developing in hoof prints of less than 500 mℓ.

These small summer habitats are typically well-oxygenated (DO 6 mg.ℓ^{-1} at midnight to 12 mg.ℓ^{-1} at midday), alkaline (pH 7.2-9.3), very low conductivity (0µS cm^{-1} or slightly higher) and often exceed 40°C for 3-4 hours per day. Turbidity was low in most cases.

The physical and chemical characteristics of larger rain pools were investigated in detail by Hamer & Appleton (1991). The pH range was usually narrow, 5.8-7.4, but more alkaline in some cases, reaching 8.9. Conductivity was always low after filling (±76µS cm^{-1}) but increased over the pool's life to ±300µS cm^{-1}. Dissolved oxygen levels were generally low, 5-6 mg ℓ^{-1}) but reached 8.6 mg ℓ^{-1} on occasions. Temperature was generally lower than in hoof print pools but still reached 42°C for short periods. Turbidities were relatively high, ranging from 140-520 NTU (Nephelometric Turbidity Units).

Figure 3 - A female Anopheles mosquito

During a study on the Pongolo floodplain, le Sueur (1991) found *An. arabiensis* breeding in the following habitats:

- Natural pans – main water body – associated with aquatic macrophytes
- Natural pans – Cattle hoof prints at the edge
- Borrow pits – Cattle hoof prints at the edge
- Irrigation overflows – Natural depressions and cattle hoof prints
- Roads – Vehicle tracks
- Rivers – Cattle hoof prints at the edge
- Rain pools – Natural, temporary

An. funestus breeds in larger, more permanent shaded pools with emergent vegetation, e.g. streams, ditches and swamp margins. In their study on the breeding habitat choices in Kenya, Mwangangi et al. (2007) describe *An. funestus* as being found breeding mainly in stable stream pools, and suggested that the lack of *An. funestus* larvae found in some areas during the study was due to a decline in oviposition due to flooding of suitable habitat types at that time.

Research in Kenya suggests that canopy cover is significantly related to the presence of larvae in a habitat, and that the average amount of canopy cover is less in habitats where anopheline larvae are found than where they are not found (Minakawa, Munga et al., 2005). This research paper suggests that land cover type and topography (temporary pools are more likely to form in lower lying areas near the water table than on slopes) play significant roles in the distribution of anopheline breeding habitats.

Figure 4 - Anopheles arabiensis breeding site in Maputaland (Photo – C.C Appleton, 1983)

2.2 Bilharzia – Schistosomes

2.2.1 Parasite biology

Parasite Species:

Worldwide some 23 species of schistosome (blood fluke) parasitize mammals such as rodents, elephants, hippos and antelope, while an additional seven parasitize people. An even larger number parasitizes birds, mostly waterfowl and coastal birds. The life-cycles of schistosomes, whether they be parasites of people or not, are similar. All involve a warm-blooded vertebrate definitive (final) host in which the parasite undergoes sexual reproduction and an intermediate host in which it undergoes asexual reproduction. The latter is an aquatic snail.

Two species of schistosome blood flukes commonly infect people in South Africa, *Schistosoma haematobium* causing urinary bilharzia and *S. mansoni* causing intestinal or rectal bilharzia.

A third species, *S. mattheei*, naturally infects a variety of mammals, especially water-loving antelope such as waterbuck, but has become a common parasite of cattle and sometimes infects people too. Human *S. mattheei* infections, which reach 40% in certain areas, appear to be self-limiting and seldom persist beyond a year (Pitchford & Visser, 1975). In fact, these human *S. mattheei* infections are probably hybrids between *S. mattheei* and *S. haematobium*. Pure *S. mattheei* infections are not thought to occur in people.

The schistosome parasites of birds are also of importance. Their cercariae commonly penetrate human skin but although they do not develop further, they elicit a rash and when they die, a sometimes severe form of dermatitis called ‘schistosome dermatitis’ or ‘swimmer’s itch’ results. Little is known about avian schistosomes that are transmitted in freshwater in South Africa except that at least five species infect waterfowl and other water birds (Appleton, 2006a).

Life Cycle:

A diagram of the lifecycle of the bilharzia parasite is provided below in figure 5. In the human definitive host, adult *S. haematobium* live in the veins of the portal system draining the urinary bladder and those of *S. mansoni* in the veins draining the lower intestine and rectum. Male and female flukes live together, the longer, thinner female curled inside the gynaecophoric groove on the ventral surface of the male worm. About half of the eggs laid by the female pass into the urinary bladder (*S. haematobium*) or the lower intestine/rectum (*S. mansoni*) while the other half is carried by the blood to various organs in the body, notably the liver. Those that enter the bladder or intestine are passed out with either the urine or faeces, depending on the species, while those that are deposited in other organs elicit an inflammatory response and are the cause of disease.

The eggs of *S. haematobium* that pass into the lumen of the bladder are voided in the urine according to a daily rhythm such that approximately 60% are voided during the hottest hours of the day, between 11h00 and 15h00, when children are likely to be swimming. Since it is common for children to urinate while swimming, this synchronous behaviour ensures that miracidia have a good chance of being voided into water and, if the appropriate snail host is present, that it will become infected. The eggs of *S. mansoni* are voided into the intestine to be passed out with the faeces. Although they appear in the faeces according to the same diurnal rhythm as *S. haematobium* (Pitchford & Visser, 1972), *S. mansoni* eggs exhibit delayed hatching so that, provided the faeces remain moist, they can stay viable for up to six days. Since faeces are not normally deposited in water, it is speculated that this delayed hatching increases the chances that eggs in faeces deposited in shady situations near water will be viable if the faeces are washed into water by rain.

When passed into fresh water, the shell of schistosome eggs ruptures due to the rapid change in osmotic pressure and, because they are embryonated when passed out, a motile miracidium is released immediately. These miracidia are non-feeding larvae and so have a free-swimming life of only about 24 hours during which time they must locate and penetrate a snail intermediate host, *B. africanus/globosus* in the case of *S. haematobium* and *Bi. pfeifferi* in the case of *S. mansoni*. If they do not find the appropriate snail species, they will die. In reality if they do not do so within about 12 hours, they will die because they will not have sufficient nutrient reserves left to successfully penetrate the intermediate host and start development.

Once inside the intermediate host, the miracidium metamorphoses into a mother sporocyst which then divides asexually to produce several generations of daughter sporocysts after which cercariae are produced. During this time, the parasite feeds on the snail's tissues, especially the ovotestis. Although this intra-molluscan development (prepatent) period proceeds at a generally slower rate for *S. haematobium* than for *S. mansoni*, both are temperature dependent. For *S. haematobium*, it varies from 35-42 days in summer to 168-175 days in winter and for *S. mansoni* from 28-35 days in summer to 140-147 days in winter (Pitchford & Visser, 1965).

The cercariae, which represent the second non-feeding larval stage, leave the snail at a rate of hundreds per day, to swim freely in the water column in search of a human definitive host, usually children. However, as with the presence of ova in the definitive host's urine, cercariae are shed by the infected snail according to a diurnal rhythm, mostly between 10h30 and 15h00. Underlying this diurnal rhythm is a seasonal one, with transmission taking place largely during spring and summer (Pitchford & Visser, 1962). Greatest numbers of cercariae thus appear in the water not only at the same time of day that children are likely to be swimming but, since swimming is the water contact activity most likely to result in infection (Kvalsvig & Schutte, 1986) and is a summer activity, cercariae need only to be produced at this time. Other water-contact activities such as washing and collecting water are thought to be less important in the South African scenario.

Cercariae making contact with human skin are able to penetrate by using the secretions of their penetration glands to break through the host's epidermis, losing their tails as they do so. Now called schistosomula, these larvae make their way through the dermis to the capillaries of the peripheral circulation and so to the liver where they mature as male or female worms. Once mature, these worms pair up and migrate, apparently against the venous flow, to their target organs, the bladder in the case of *S. haematobium* and the lower intestine/rectum in the case of *S. mansoni*. This maturation phase in the human host lasts between 10 and 12 weeks. Adult worms are estimated to live for 3-5 years.

Parasite Distribution:

Both parasite species occur predominantly in the eastern half of the country (see fig 5 below) with *S. haematobium* reaching prevalence rates >80% in children in the eastern lowlands of Limpopo, Mpumalanga and KwaZulu-Natal provinces but declining to <40% in the former Transkei (Eastern Cape). *Schistosoma mansoni* is less widespread and reaches its highest prevalences (also >80%) in the Mpumalanga lowveld, becomes patchy in KwaZulu-Natal and does not occur south of Port St Johns (Gear et al., 1980).

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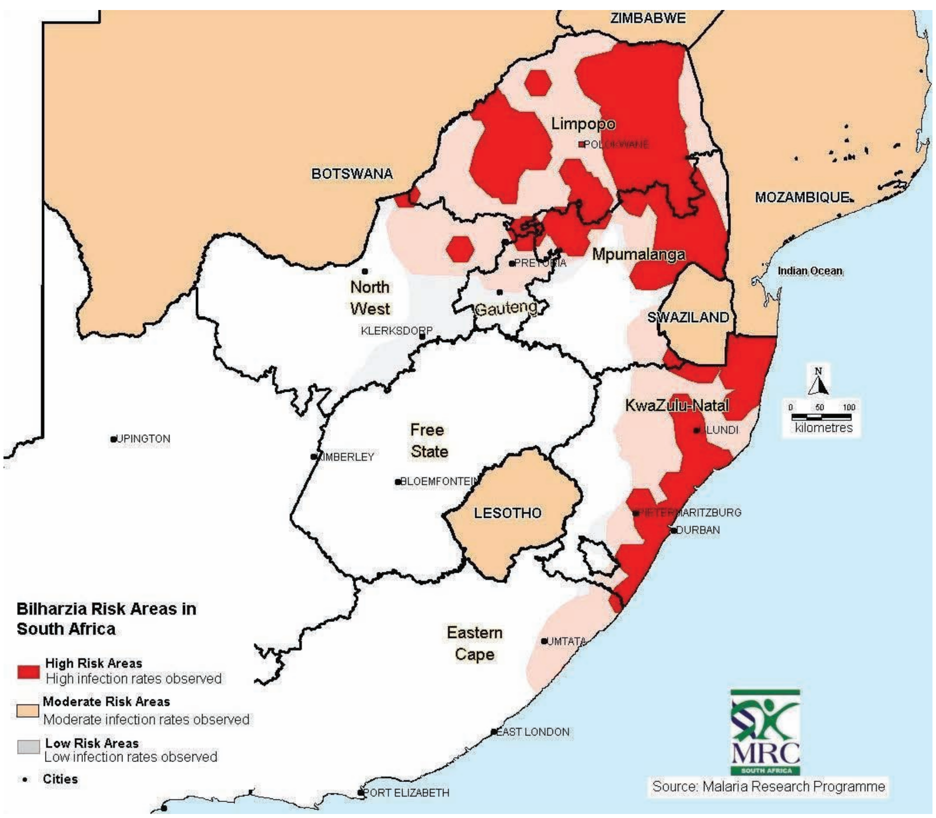


Figure 5: Distribution of Bilharzia risk zones in South Africa (adapted from data from Medical Research Council)

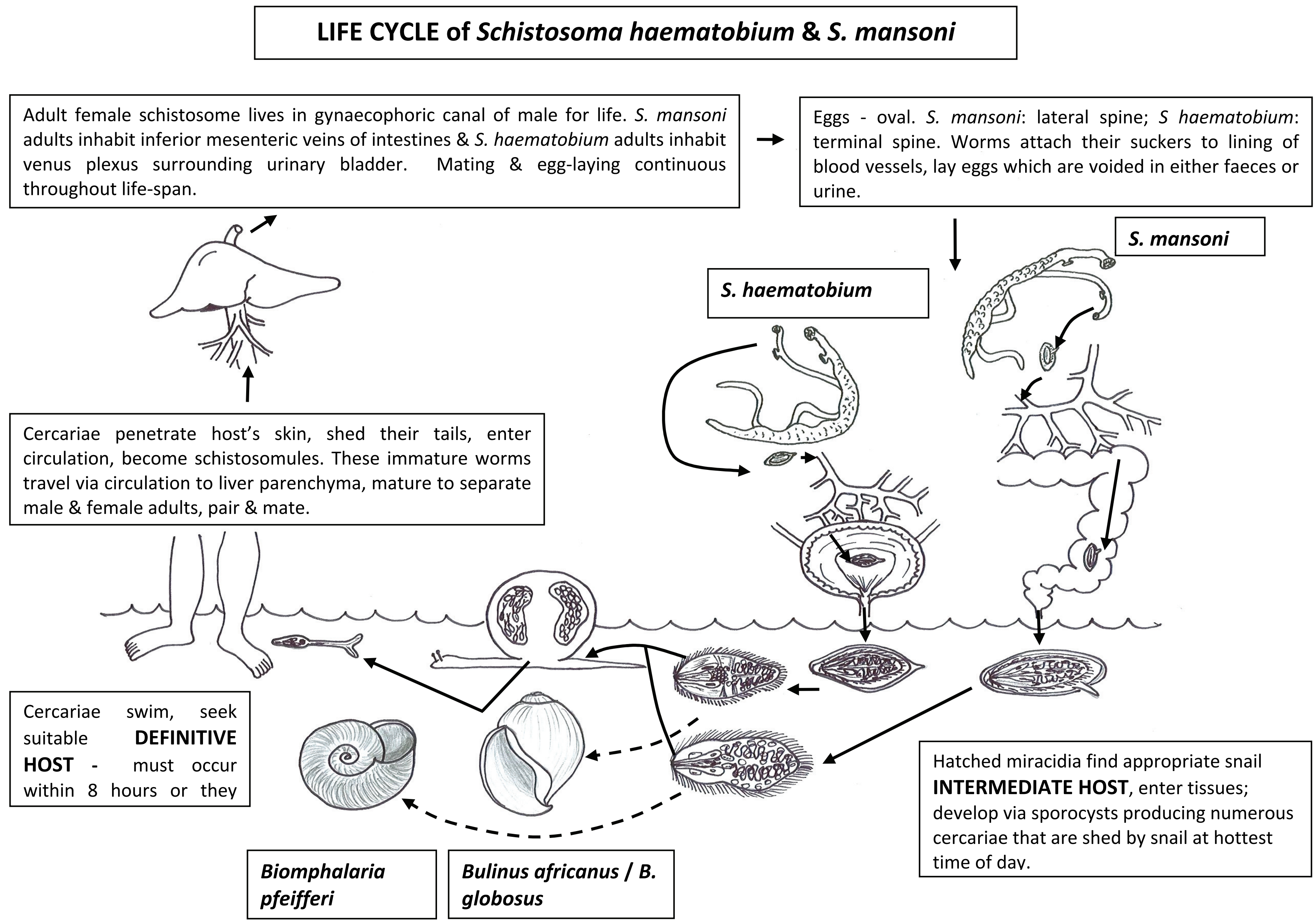


Figure 6 - Life cycle of a **Schistosoma haematobium & S *mansoni (Archer, 2007)***

2.2.2 Bionomics of invertebrate hosts

Invertebrate hosts – Species:

In South Africa, *S. haematobium* has two intermediate snail hosts, *Bulinus africanus* and the closely related *Bulinus globosus*. *S. mansoni* uses *Biomphalaria pfeifferi* as its snail host.

Schistosome infection can take place in any water-body where the snail intermediate hosts occur and with which people have contact. Appleton (1976) found that temperature (in still waters) and current velocity (in running water) were the most important abiotic factors determining the distribution of host snails.

Figure 7 - Bulinus africanus **(left) and** ***Biomphalaria pfeifferi*** **(right) (Photos D. Herbert)**

It is worth noting that in South Africa, temporary water-bodies seldom support transmission. This is because the snail hosts, notably *B. pfeifferi*, do not tolerate desiccation well (Brown, 1994). Also, snail populations in habitats subject to excessive current speeds during floods seldom support transmission of parasites either (Appleton, 1976).

Invertebrate Hosts – Distribution:

Bulinus africanus is the most widespread of the three intermediate host species, occurring over much of the eastern half of South Africa as far south as the Kromme River near Humansdorp in Eastern Cape. *Bulinus globosus* is limited to the extreme eastern parts of Limpopo and Mpumalanga provinces as well as a small area of north-eastern KwaZulu-Natal. *Biomphalaria pfeifferi* has a similar distribution to *B. africanus* but does not extend as far inland or further south than Port St Johns.

Invertebrate Hosts – Habitat Choice:

In a series of papers (2001; 2003; 2004; 2005), Professor K. de Kock and various co-authors have reviewed data that were recorded during the collection of snail specimens for the National Freshwater Snail Collection (NFSC). This entailed collating and reviewing habitat descriptions, geographic locations and any other information captured during collection process. They have attempted to determine the importance of each factor (e.g. water-body type) using a decision tree method based on Cohen's method (1977). Unfortunately, whether or not a river or stream was regulated is not recorded in any of the studies. The data presented in this section are based largely on their work.

Bulinus africanus / globosus (De Kock and Wolmarans, 2005)
Water bodies: *B. africanus* group snails were collected from every type of water body sampled by the NFSC as shown in table 1 below. Specimens were however collected most often from rivers (28.2%) and streams (24.7%), the occurrence of which differed significantly from those of dams (19.6%). Together, these three water body types constitute the habitat of 72.5% of all *B. africanus* group specimens collected.

Table 1 - Water body types where* B. africanus *group snails were found.

Water Bodies	No of specimens	% of total collected
Channel	9	0.3
Concrete Dam	19	0.6
Dams	574	19.6
Ditch	34	1.2
Irrigation furrow	5	0.2
Pan	27	0.9
Pond	76	2.6
Quarry	6	0.2
River	827	28.2
Spring	20	0.7
Stream	723	24.7
Swamp	64	2.2
Vlei	1	0.03
Pool	9	0.31

78% of *B. africanus* group specimens were collected from perennial habitats. This is explained as being due to the fact that *Bulinus* sp snails are vulnerable to desiccation, and also because their intrinsic rate of increase is described as being relatively low. Thus populations are slow to re-colonise water bodies which periodically dry out. When rivers subject to drought conditions are refilled however, *B. globosus* specimens from upstream refugia have been reported to repopulate detached pools that had dried out.

Current velocity: Specimens were most commonly collected from slow flowing or standing bodies of water. A few specimens were however collected from fast flowing water. One explanation for this phenomenon is that within a fast flowing stream over hard bedrock, boulders and pools create suitable microhabitat refugia, sheltered from higher current velocities which would be unfavourable (Brown, 1994).

Temperature: *Bulinus africanus* group specimens were mostly collected in habitats where the mean annual air temperature ranged between 15^{O}C and 25^{O}C. Temperature was described as having a large effect on the snail's distribution.

Substratum: The authors regard substratum as being of minor importance in determining distribution. Results showed that 'muddy' (31.4%) followed by 'stony' (25.2%), followed by 'sandy' (19.5%), followed by 'plant detritus' (2.7%) were the substrata on which *B. africanus* group snails were collected.

Aquatic vegetation was reported as being present in 78.6% of all collection sites.

Bulinus africanus/globosus are tolerant of a range of physical and chemical conditions, with optimal levels as follows: turbidity up to ±190 mg.ℓ^{-1}, conductivity 300-400µS.cm^{-1}, current velocity up to 0.3 m.s^{-1}, calcium and bicarbonate concentrations of 5-40 and 20-200 mg.ℓ^{-1} respectively. Both snail species can survive and lay eggs in salinities up to ±3.0‰ but their hatchlings do not survive in anything but fresh water.

Major factors: these results agree with Appleton's (1976) findings in that temperature and flow velocity appear to be critical in determining this species' distribution.

Biomphalaria pfeifferi (De Kock, Wolmarans et al., 2004)
Water-bodies: *Bi. pfeifferi* was collected from all types of water bodies sampled during the survey, however this species was most frequently collected from dams (27.5% of collected specimens), rivers (27.2%) and streams (12.9%), while ponds, concrete dams and pans were less favoured. This is recorded in table 2 below.

Table 2 - Water body types where Bi. pfeifferi specimens were found

Water Bodies	No of specimens	% of total collected
Channel	6	0.4
Concrete Dam	53	3.2
Dams	451	27.5
Ditch	21	1.3
Irrigation furrow	5	0.3
Pan	20	1.2
Pond	63	3.8
Quarry	2	0.1
River	445	27.2
Spring	8	0.5
Stream	212	12.9
Swamp	32	2.0
Vlei	1	0.1
Pool	3	0.2

Biomphalaria pfeifferi is a fully aquatic species that does not tolerate desiccation well. They are thus found mostly in perennial water bodies, and unlikely to be found in rain-filled or temporary pools (Appleton, 2007). This was confirmed by the findings of this study where 71.5% of snails of this species collected were found in water bodies described as perennial.

The authors established that water-body type plays a significant role in the distribution of this species.

Current velocity: The majority of specimens were collected from standing water (39.5%), while slow moving water constituted 29% of this species' collection sites.

Temperature: The authors suggest that temperature plays a significant role in determining the distribution of this species in South Africa, with both low and high temperatures being limiting. Results show a significant preference for areas with atmospheric average temperatures between 15°C and 25°C. This species were seldom collected in areas falling outside of this band.

Micro-habitat and substrate: In their Tanzanian study, Utzinger and Tanner (2000) found that *Bi. pfeifferi* are most likely to be found in shallow waters (0-7cm) close to the shoreline. As a substrate, they found the greatest densities of snails situated on bedrock and plant detritus with a slight bias towards bedrock.

This is contradicted by De Kock et al.'s substrate findings from the NFSC which show muddy, stony and sandy substrates as roughly equally preferred substrates, with plant detritus being the least common substrate on which the species was collected.

The authors also reported that aquatic plants were present at 72.6% of collection sites.

Like *B. africanus*, *Bi. pfeifferi* are tolerant of a range of physical and chemical conditions, with similar optimal levels as follows: turbidity up to ±190 $mg.\ell^{-1}$, conductivity 300-400$\mu S.cm^{-1}$, current velocity up to 0.3 $m.s^{-1}$, calcium and bicarbonate concentrations of 5-40 and 20-200 $mg.\ell^{-1}$ respectively. Also like *B. africanus*, this species can survive and lay eggs in salinities up to ±3.0‰ but their hatchlings only survive in fresh water (Appleton, 2007).

Major factors: Water-body type and temperature are the two factors which appear to exert the greatest influence over the distribution of this species.

2.3 Liver flukes – *Fasciola*

2.3.1 Parasite biology

Parasite Species:

Fascioliasis is caused by two digenean trematodes, *Fasciola hepatica* (common liver fluke) and *F. gigantica* (giant liver fluke), both of which are present in South Africa.

Although fascioliasis occurs in a variety of domestic and wild animals in South Africa, little is known of its epidemiology. Humans are in fact accidental hosts, but stool analyses show that human infections do occur in the wetter grazing and stock-raising areas of Limpopo, Mpumalanga and KwaZulu-Natal provinces. These are uncommon, <1% in children, and appear from the size of eggs recovered from stools to be mostly due to *F. gigantica*. The possibility exists that eggs found in human stools may have come from eating infected raw liver rather than from patent infections.

Since the 1980s however human *Fasciola* (mostly *F. hepatica*) infections have increased and reached 'emerging disease' status in some countries (Mas-Coma et al., 1990). Human fascioliasis is thus a zoonosis but the numbers of human cases do not necessarily follow increases in the livestock disease. W.H.O (1995) estimates that between 2.4 and 17 million people are infected with *F. hepatica* globally. No age-related risk data are available for South Africa but in other endemic countries people of all ages from 3 to 50 years have been found infected, with most cases and the greatest morbidity occurring amongst children in the 9-11 year age group (Mas Coma (2004).

***Figure 8 - Freshwater snail habitats: Top left (TL) - Floating mat of Ludwigia, TR - Granite, BL - Potholes in Granite, BR - Marginal fringes of* Phragmites. Photos C.C. Appleton**

Parasite Lifecycle:

A diagram of the lifecycle of the liver fluke parasite is provided below in fig 9. Adult *F. hepatica* measure 20-50 x 5-14 mm while *F. gigantica* is larger, 25-75 x 5-15 mm. Unlike the schistosomes, fasciolid flukes are hermaphrodites and produce large numbers of unembryonated, operculate eggs which enter the intestine with the bile and are passed into fresh water with faeces. Development of both species outside the mammalian host is temperature dependent though the evidence suggests that thermal tolerances differ slightly across the species' geographic ranges. Data summarized below apply to *F. hepatica* (Kendall, 1965; Pantelouris, 1965) unless stated to refer to *F. gigantica* (Al-Habbib & Al-Zako, 1981; Altaif et al., 1989).

Maturation of the miracidium inside the *F. hepatica* egg takes from 10-14 days at 26-32°C to 45 days at 11-19°C. Miracidal development times for *F. gigantica* are 12-16 days at 26-28°C but no data are available for low temperatures. On hatching, the miracidia swim into the water column to locate and infect their snail invertebrate hosts, *Lymnaea truncatula* for *F. hepatica* and *L. natalensis* for *F. gigantica*. Miracidial longevity varies from 5½h at 27°C to 20h at 10-13°C. If they do not find the correct species of intermediate host within a few hours, they will die. Those that succeed penetrate the epithelium of the snail's pulmonary cavity, losing their cilia as they do so, and after 3-4 days (at 25°C) become mother sporocysts, usually in the pre-oesophageal region. Germinal cells within these mother sporocysts then differentiate to form rediae, another type of germinal sac.

Unlike sporocysts, rediae are mobile and after breaking out of the mother sporocyst migrate to the snail's digestive gland or liver by day 14 post-infection. Rediae are equipped with a mouth, pharynx and gut enabling them to feed actively on gonad and liver tissue. They divide asexually to produce 3 or 4 generations of daughter rediae until, after about 20-26 days post-infection, cercariae are produced instead. By day 30-42 these cercariae leave the rediae via a birth pore. On day 36-40 they leave the snail by way of its pulmonary cavity to enter the water where they encyst on vegetation such as *Commelina* spp. just above or below the waterline. Intra-molluscan development of *F. hepatica* thus takes between 32 and 42 days and between 30 and 51 days for *F. gigantica*. The whole life-cycle of *F. hepatica*, from egg to egg takes between 98 and 160 days (14-23 weeks) (Chen & Mott, 1990).

The upper and lower developmental null points for complete intra-molluscan development lie around 32°C and 9-10°C respectively for *F. hepatica* and for *F. gigantica* at 30°C and 15°C respectively. At temperatures below the lower null points, development does not run to completion for either species, stopping at the redial stage in both cases. Thus development at 15°C and 30°C reaches the sporocyst stage by days 21 and 4, the redial stage by days 37 and 11 and the cercarial stage by days 73 and 25 respectively. Clearly *F. hepatica* is able to develop at temperatures several degrees lower than *F. gigantica* which accords with the predominance of the former in high altitude areas and of the latter in lowland areas.

Inside the cyst the cercaria metamorphoses into a metacercaria which is infective within 24 hours of encystment and remains so for up to several weeks, depending on temperature and, if exposed to the air, to relative humidity as well. Relative humidity is critical here and Ollerenshaw & Rowlands (1959) found that 70% RH was necessary for prolonged survival of *F. hepatica* cysts, i.e. the minimum needed during spring and summer when infections can be expected to occur. If they are not eaten by a grazing mammal during this period of encystment, the cysts die. If eaten, metacercariae excyst in the host's stomach, penetrate the stomach wall, migrate to the liver and after about two months attach to the wall of the bile duct as reproductively mature flukes. These adults are longer-lived than schistosomes and are estimated to produce eggs for eight years or more.

Parasite Distribution:

In accordance with the ecological requirements of their respective snail invertebrate hosts (see below), the two fluke species appear to have different altitudinal distributions in South Africa and seem to be largely allopatric. *Fasciola gigantica* is generally associated with lower lying land while *F. hepatica* is usually found above an altitude of approximately 800 m. A similar situation extends over sub-Saharan Africa but the disease is nowhere common in people.

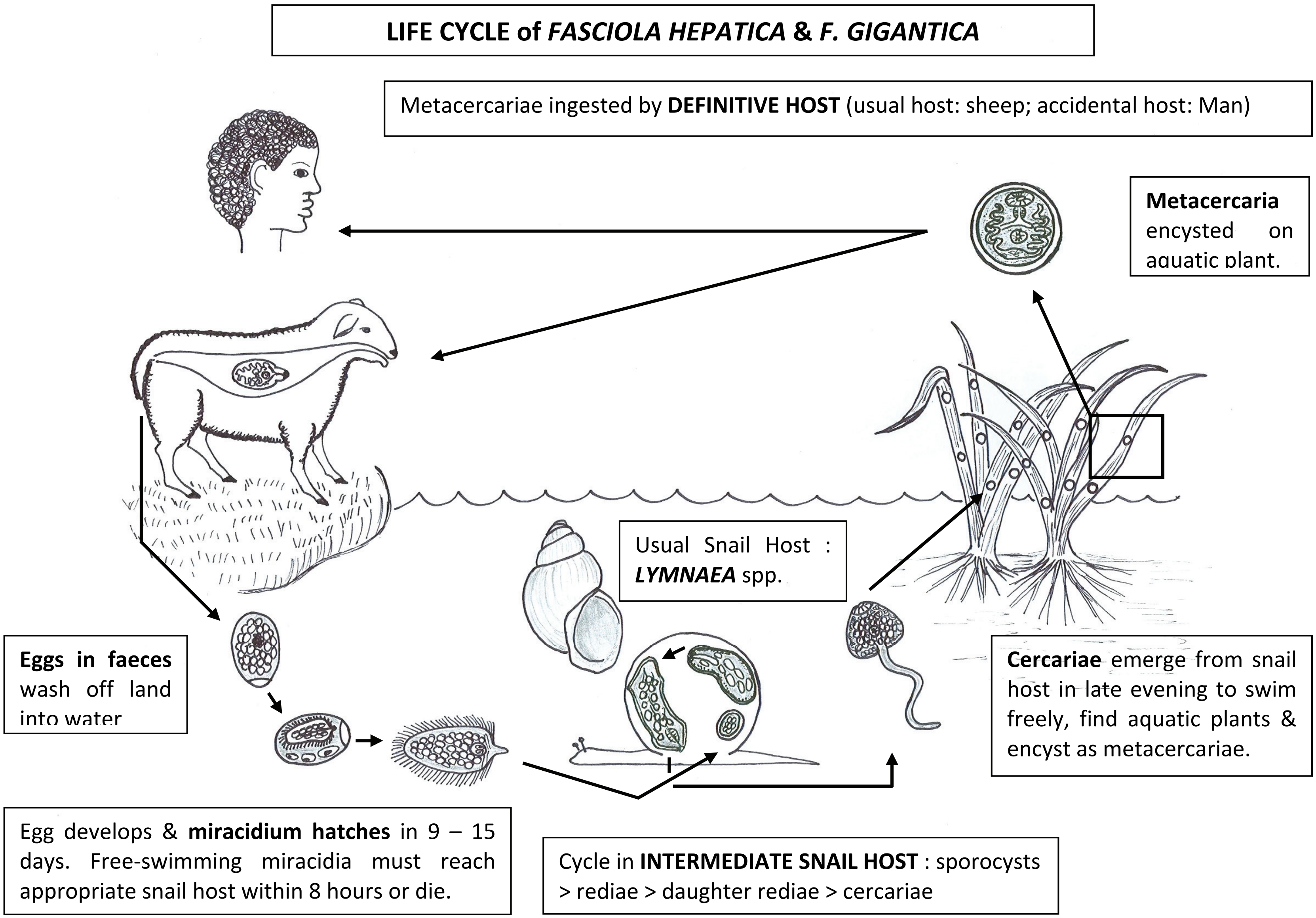


Figure 9 - Life cycle of Fasciola hepatica and F. gigantica (Archer, 2007)

Information on the distribution of veterinary fascioliasis in South Africa consists mainly of case reports or outbreaks in isolated places and mostly in artificial habitats such as drinking troughs. Neitz (1965) recorded *F. hepatica* infection in horses from Eastern Cape and Alves et al. (1988) cited records from Kokstad, KwaZulu-Natal, condemnations of equine meat at Johannesburg Municipal Abattoir and reported on another case from Gauteng. *Fasciola gigantica* was reported being transmitted to goats in low-lying marshy ground in Limpopo and KwaZulu-Natal provinces (Varta & Krecek, undated). Evidence from Limpopo province suggests that in certain situations antelope such as impala and kudu using natural waterbodies (not specified) can serve as reservoir hosts for *F. gigantica* infection in domestic animals.

From a distributional point of view however, the metacercarial cyst is the 'weak link' in the *F. hepatica* life-cycle. This is because the cyst is susceptible to desiccation and high temperatures, i.e. RH<70% and temperatures above 25°C, particularly the former although they survive longer at lower than at higher temperatures (Ollerenshaw & Rowlands, 1959; Kendall, 1965; Chen & Mott, 1990). Whether this applies to *F. gigantica* is not known. The only area in South Africa satisfying these cut-offs for *F. hepatica* is the central Drakensberg mountain range in Lesotho and the northern part of Eastern Cape (Schulze, 1997). This includes the area where Prinsloo & Van Eeden (1973) reported high incidences of fascioliasis in sheep.

The only other areas where the mean daily spring/summer relative humidity exceeds 70% are the coastal strip of Eastern Cape and KwaZulu-Natal and lowveld of Mpumalanga and Limpopo, but mean daily temperatures are above 25°C here. Probably therefore the paucity of data on these parasites in South Africa reflects the fact that they are not common and their distributions are more restricted than those of their invertebrate hosts.

2.3.2 Bionomics of invertebrate hosts

Invertebrate hosts – Species:

Certain members of the pulmonate family Lymnaeidae serve as invertebrate hosts for *Fasciola* spp. In South Africa *Lymnaea truncatula* is the intermediate host for *F. hepatica* and *L. natalensis* for *F. gigantica*. An unknown factor is the role played by *Lymnaea columella* in the transmission of fascioliasis in South Africa (Appleton, 2007). This North American invader species is well documented as being naturally infected in Australia and other parts of the world, where it is also an invader species (Boray et al. (1985) as reported in Brown (1994)).

Invertebrate hosts – Distribution:

Lymnaea truncatula prefers the cooler areas and is most abundant in the high lying areas such as Lesotho and the northern parts of the Eastern Cape, while *L. natalensis* is widely distributed, but is excluded from the cooler drier areas of South Africa, mainly the Western and Northern Cape (Brown, 1994).

Invertebrate hosts – Habitat Choice:

Lymnaea truncatula

Water bodies: *Lymnaea truncatula*, the snail primarily responsible for transmitting *Fasciola hepatica*, is an amphibious species and although they may occur in permanent streams, they characteristically occur on damp mud just above the water level in small, temporary habitats such as swamps, bogs, canals, drains, irrigation ditches in pastures and even hoof prints.

Table 3 - Water body types where* L. truncatula *specimens were found

Water Bodies	No of specimens	% of total collected
Channel	2	0.3
Concrete Dam	1	0.1
Dams	69	9.5
Ditch	19	2.6
Irrigation furrow	4	0.6
Pan/Waterhole	2	0.3
Pond	12	1.7
River	88	12.2
Spring	18	2.5
Stream	139	19.2
Swamp	304	42.0
Not indicated	65	

De Kock et al. (2003) found the greatest number of samples collected for the NFSC were collected from swamps (42%). This differed significantly from any other habitat type. Snails were also collected relatively frequently from streams (19.2%), rivers (12.2%) and dams (9.5%). These results are shown in table 3 above.

81.3% of samples were collected from water bodies described as perennial. This is in contradiction with Appleton's assertion above, though his description of the habitats (i.e. swamps, bogs and springs) fits well with the findings of De Kock et al. (2003).

Current velocity: Most samples were collected from slow flowing water. There appeared to be no significant difference between the numbers collected in fast flowing water and those collected in standing water.

Temperature: It is documented that this species shows a distinct preference for cooler areas (Brown, 1994). This is supported by De Kock et al.'s findings where 99.4% of specimens were collected in the temperature range of 5-20°C. These authors suggest that temperature is an important factor in determining this species' distribution

Micro-habitat and substrate: In a study in Lesotho, Prinsloo and Van Eeden, (1973, 1974, 1976) found that *L. truncatula* was the most widespread freshwater snail present. It was found overwhelmingly in two habitat types, spring-swamps and swamps, where population densities exceeded 3600 m^{-2}.

These habitats were characterised by being well oxygenated, pH between 6.5-8.0, absence of organic nitrogen enrichment, 'slight' flow, shallow (only a few centimetres deep), high O_2 concentration, soil moisture level exceeding evaporation and a clay substratum.

De Kock et al. (2003) report that aquatic plants were recorded as being present at 91.6% of collection points for the NFSC.

Major factors: According to their decision tree analysis, temperature and then water body type were the most important factors affecting the snails' distribution.

Notes: Importantly, the authors in the Lesotho study did not find it in rivers and only rarely in dams rendering them unable to invoke the two-habitat colonization strategy of Taylor (1964) to describe the situation in Lesotho, viz. low-density populations maintained in permanent habitats such as rivers and lakes serving as reservoirs for spread to 'extension' habitats. These 'extension' habitats are usually temporary, drying out during the non-rainy season but which allow the snail to reproduce rapidly as the rains begin, often resulting in extremely dense populations (see also under Malaria).

It has been reported that *L. truncatula* is able to aestivate for up to 12 months and that infections can survive in the snail over this period of stress (Kendall, 1965).

Although this is an amphibious species, they still need to lay their eggs below the surface (Appleton, 2007).

A further feature of *L. truncatula* is its ability to migrate upstream. Rondelaud et al. (2005) reported migration in small watercourses in France during the non-rainy season at up to 160 m per month.

Lymnaea natalensis

Water bodies: De Kock et al. (2001) found *Lymnaea natalensis*, which transmits *F. gigantica*, to be the most widespread *Lymnaea* species in South Africa. It is completely aquatic and occurs predominantly in larger, permanent water bodies. Data recorded for the NFSC on the nature of the water body from which the snails were collected (see table 4 below) show that 46.1% of the samples were collected in rivers (24.4%) and streams (21.7%). 23.1% of snails collected came from dams.

Table 4 - Water body types where L. natalensis specimens were found

Water Bodies	No of specimens	% of total collected
Concrete Dam	75	1.6
Dams	1050	23.1
Ditch	59	1.3
Irrigation furrow	26	1.0
Pan	29	1.0
Pond	123	2.7
River	1110	24.4
Spring	42	1.0
Stream	987	21.7
Swamp/Vlei	204	4.5
Not indicated	793	17.4

70.6% of samples were collected from perennial water bodies, and it appeared to be absent from the more arid areas of the country. This is explained by the fact that due to the shape of its shell, *L. natalensis* cannot withdraw deeply into its shell to survive adverse conditions. It also cannot effectively seal off the aperture of its shell against moisture loss.

Reports on aestivation by *L. natalensis* by Shiff (1960) and Cridland (1967) showed that the species cannot aestivate for more than about three weeks. It may however lay its eggs on damp mud and these remain viable for several weeks. These eggs have the unusual ability of being able to hatch in the absence of water and the hatchlings then seek out humid microclimates to await refilling of the habitat.

Current velocity: Of the samples that were collected, 71.8% came from either slow moving or standing water. This is consistent with the other snail species reviewed earlier, and with Appleton's findings that snails are rarely found in water moving faster than 0.3 m/s.

Temperature: Temperature appeared to have little effect on the distribution and habitat choices of this species, as snails have been collected in both the warmest and coldest areas of the country.

Micro-habitat and substrate: Micro-habitat preferences of *L. natalensis* are almost identical to *Bi. pfeifferi*, being found in shallow margins of perennial water bodies, only *L. natalensis* was found in slightly shallower water (0-2cm predominantly). Substrate preference also reflected plant detritus and bedrock, only a stronger bias towards detritus (Utzinger and Tanner, 2000).

De Kock et al.'s (2001) findings on substrate contradict this and plant detritus is reflected as being the least favoured substrate type (2.3%), while 'muddy' (32.1%), 'stony' (23.7%) and 'sandy' (20.4%) were far more frequently encountered.

They also established that aquatic plants were present in 80% of habitats from which snails were collected.

Major factors: De Kock et al.'s decision tree findings suggest the most important factor determining the distribution of this species to be the presence of permanent water bodies.

2.4 Summary of invertebrate hosts' habitat choices

2.4.1 Water body type:

Water body type undoubtedly plays a role in determining the suitability of a habitat for snails and mosquito breeding. This includes the rate of flow in a water body.

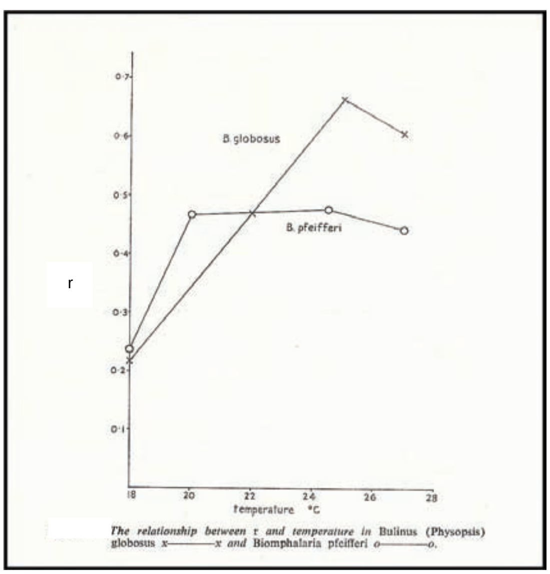
In the case of *An. arabiensis*, the most important vector of malaria in South Africa, small temporary sunlit pools of standing water appear to be optimal, where the absence of predators, the presence of food (fine suspended detrital matter) and the warm conditions ensure rapid development of larvae. Although small water bodies such as hoof-prints appear to carry many larvae, it has been shown that larger, more stable pools, such as borrow pits may be more productive in terms of producing pupae and adults (Mutuku et al., 2006). The majority of their breeding habitat however, is not related to rivers. *Anopheles funestus* is also an important malaria vector, but only in certain areas. This species is more likely to use larger, more permanent habitats for breeding including, but not limited to, rivers and streams. In general, flowing water is avoided by mosquitoes for breeding purposes.

The majority of the snail species prefer standing or slow moving water in permanent water bodies. Certainly none of the snail species reviewed in section 2.2 is adapted for life in fast moving water. Brown (1994) suggests this is because the shapes of their shells are not well adapted to resisting dislodgement. Appleton (2007) writes that rivers and streams provide particularly suitable habitats for host snails where they flow over hard bedrock such as granite or basalt that erode unevenly to form detached or semi-detached pools and backwaters. This would allow snails to find areas of shelter from fast moving water in a riverine environment. Loreau and Baluku (1987) suggest that high flow rates inhibit breeding success through forcing snails to use more energy in trying to resist the current, whilst high currents are also responsible for sweeping young snails away. Water body type and particularly flow rate is thus an important habitat determining factor.

<u>Note:</u> For the purposes of this report, it is worth noting the emphasis placed by several authors on the limiting influence of current velocity on the suitability of habitats for the host snails considered in this report. In his review of existing literature, Appleton (1978) found that the abiotic factor most influential in determining the distribution of host snails in flowing waters was current velocity. De Kock et al. (2004) remark that "Intermediate host snails have been found to have a remarkably narrow tolerance range to current velocity". Brown (1994) writes that "A strong current for only a brief period may prevent a non-specialised species from establishing itself in a river." O'Keefe (1985) writes that "The other major potential catastrophe for a bulinid snail population is a sudden flood, which may sweep away a large proportion, since they are unable to withstand fast currents"

2.4.2 Temperature:

Temperature plays a large part in determining the suitability of habitats for snail hosts. With the exception of *L. natalensis* which was found in the warmest and coldest parts of the country, all species reviewed showed a level of sensitivity to temperature, and a distribution corresponding to certain temperature bands. Temperature also plays a role in determining fecundity of snails, with temperatures outside certain bands inhibiting breeding success, as is illustrated in Figure 10.



The relationship between r and temperature in Bulinus (Physopsis) globosus x———x *and* Biomphalaria pfeifferi o———o.

Figure 10 - The intrinsic rate (r)of natural increase of bilharzia host snails over a range of temperatures - from Shiff & Husting (1966)

Temperature also has a definite influence on the development of parasites within the snail. Developmental null points, threshold temperatures below which theoretically no cercarial development is possible (14.2°C in the case of *S. mansoni* and 15.3°C in the case of *S. haematobium* (Pfluger,1980 & 1983)), are the extremes of a temperature range which limit the transmission of the disease in colder parts of the country and during colder periods (Moodley, Kleinschmidt et al., 2003).

It should be noted, that many studies (such as those conducted by De Kock et al) use air temperature recorded in Stevenson screens rather than actual water temperature. Appleton's 1974 and 1977 studies used water temperatures recorded via thermographs.

Temperature, along with rainfall, are the most important factors influencing *Anopheles* mosquito distribution (Coetzee, Craig et al., 2000). Temperature also plays a role in mosquito larvae development, though this is the temperature of the water-body rather than air temperature.

2.4.3 Aquatic vegetation:

Aquatic or emergent vegetation appeared consistently in the habitats from which snails were collected. Although the authors suggested it had little influence in determining the distribution of the snails, locally it seems significant and should be considered a factor in their microhabitat selection. This is illustrated by several case studies where the growth in a snail population was attributed to an increase in the amount of aquatic vegetation in a particular area. Particularly, vegetation offers refuge from predators, from excessive current speeds and it forms shaded areas moderating temperatures. Dense aquatic vegetative growth however is known to reduce water oxygen levels.

Vegetation also appears prominent in the breeding cycles of *Anopheles* mosquitoes. On the Pongolo floodplain, le Sueur (1991) described how *Potamogeton crispus* plays an important role in protecting larvae from predation in larger water-bodies during the dry season, when small temporary water-bodies are not available. *Anopheles funestus* is described as breeding in water bodies with emergent vegetation such as swamp edges.

Table 5: Summary of parasites and invertebrate hosts - their habitats and distributions.

Disease	Parasite	Parasite Distribution	Vector	Int. host / vector breeding habitat	Int. host/vector distribution
Malaria	*Plasmodium* sp *viz.*: *P. falciparum*, *P. ovale*, *P. malariae* and *P. vivax*	South Africa is the southern limit of Malaria in Africa. It is endemic to Limpopo province, the eastern lowveld of Mpumalanga and the north eastern corner of KwaZulu-Natal stopping at the Tugela river. This distribution has been reduced through effective vector control programmes.	*Anopheles arabiensis*	Opportunistic breeders. During dry winter, vegetated margins of larger water bodies, e.g. pans. During Wet summer months, small, temporary sunlit pools, e.g. rainfilled cattle and vehicle tracks	In South Africa *An. arabiensis* distribution is much the same as that of Malaria *Plasmodium* spp.
			Anopheles gambiae s.str.	As for *An.arabiensis*	As for *An. arabiensis*
			Anopheles funestus	Larger, more permanent shaded pools with emergent vegetation, e.g. streams and swamp margins	As for *An. arabiensis*
			Anopheles merus	Saline pools and ponds, formed by depressions in exposed Cretaceous marine deposits, filled by rain. Also tidal rock pools diluted by rain	*An. merus* is restricted to coastal areas north of the Tugela.
Schistosomiasis (Bilharzia)	*Schistosoma haematobium* (Urinary bilharzia)	Predominantly in the eastern half of the country, from Limpopo lowlands, Mpumalanga and KwaZulu-Natal, to the Transkei.	*Bulinus africanus*	A variety of permanent water body types, both natural and artificial. Rivers and streams provide particularly suitable habitat, especially where detached and semi-detached pools exist. Flow rate <0.3 m/s. Adults can survive brack water , but hatchlings require fresh water.	Most of Eastern half of S.A. Occurring as far south as the Kromme river in the Eastern Cape
			Bulinus globosus	As for *B.africanus*	Extreme eastern parts of Limpopo and Mpumalanga, and small areas of North eastern KwaZulu-Natal
	Schistosoma mansoni (Intestinal bilharzia)	As for *S.haematobium*, but nowhere South of Port St Johns	*Biomphalaria pfeifferi*	Found in a variety of permanent water body types, both natural and artificial. A fully aquatic species thus predominantly in permanent water bodies such as rivers and dams as they do not tolerate desiccation well.	Similar to *B. africanus*, but not as far inland, and not further south than Port St Johns. Temperature influences dist – absent from both high and low ranges.

Disease	Parasite	Parasite Distribution	Vector	Int. host / vector breeding habitat	Int. host/vector distribution
Fascioliasis (Liver fluke)	*Fasciola hepatica*	Usually found above an altitude of 800 m, with relative humidity >70% and temps <25°C as the metacercaria are vulnerable to desiccation.	*Lymnaea truncatula*	Amphibious species found at the water/soil interface in shallow marshy habitats such as bogs, canals, drains, irrigation ditches and hoof prints. Not generally found in rivers or dams. Areas with mean annual air temperature of 10-20 degrees C	Extensive but discontinuous distribution, except in Lesotho and in parts of the Mpumalanga, Gauteng and North West province. Temperature appears limiting, thus found in cooler regions above 800 m.
			Lymnaea columella (prob.)	Very successful invader species. *L. columella* cluster mainly in rivers or streams with perennial, slow flowing, or stagnant freshwater with aquatic vegetation and a mud substrate	The eastern half of the country, extending westwards along the Orange River, and along the southern coastal strip to the W. Cape
	Fasciola gigantica	Usually associated with lower lying land and more widely spread than *F. hepatica*, otherwise not much is known.	*Lymnaea natalensis*	A variety of permanent water bodies, both natural and artificial, with aquatic vegetation. Requires standing or slow flowing water which is clear and fresh. Does not tolerate desiccation – hence only permanent water habitats	The eastern half of the country, extending westwards along the Orange River, and along the southern coastal strip to the W. Cape

3. Present interventions affecting invertebrate host life cycles in regulated rivers.

3.1 Dam development and invertebrate hosts of disease

There is little doubt that worldwide, the changes brought about by the damming of rivers has caused an increase in the incidence of water related diseases (Singh, Merah et al., 1999; Sow, De Vlas et al., 2002; Lautze, McCartney et al., 2007). This is largely attributed to the increase in habitat suited to the invertebrate hosts of diseases that is associated with the impoundment of water. A large portion of this habitat creation takes place within the impoundment itself, but because of various changes in water quantity and quality, it can also occur in the river below the impoundment.

Specifically because infection rate increases are associated with large water infrastructure development, the World Health Organization, in its bid to combat water related diseases, recommends an integrated approach to the control of these diseases (W.H.O 2000). This includes careful development planning, innovative engineering solutions and species-appropriate environmental management aimed at limiting vector habitat creation. This may be implemented in conjunction with the use of appropriate chemical pesticides. It also includes immunization of 'at-risk' populations where possible, and the administering of curative treatments to infected individuals.

Globally, attempts to control water related and water based disease outbreaks have been varied in their methods. The majority of projects have attempted to control disease through chemical means, centred on using pesticides to control vector populations together with curative treatments targeting the pathogen in the human body (Sturrock, 2001). Residual spraying for mosquitoes with chemicals like DDT, and using molluscicides such as Bayluscide™ (niclosamide) against snails in rivers has proved effective to varying degrees.

A more environmentally sustainable approach attempts to prevent or reduce infection rates at the source, through limiting vector habitat availability. Since both pathogens and vectors can develop resistance to chemical control agents, environmental management solutions have received increasing consideration (Thomas and Tait, 1984). Several studies have reviewed the effect of habitat manipulation on vector species abundance. One such study showed a significant decline in malaria vector mosquito numbers in an area following the removal of filamentous algae from breeding pools along a river (Bond, Rojas et al., 2004). A similar methodology was followed by residents in Akka oasis in Morrocco, where the clearing of aquatic vegetation from canals and streams resulted in a significant decrease in snail densities (Boelee and Laamrani, 2004).

In rivers where impoundments have interrupted natural changes in flow, artificially controlled flow regimes are established in their place. The case studies which follow illustrate the consequences for water based and water related diseases which result from the imposition of artificial flow regimes. It is the goal of this report to understand these changes and to evaluate the possibility of using manipulation of river flow to control the populations of invertebrate hosts in rivers below these impoundments. Flow manipulation is a little considered aspect of environmental management based control for diseases, yet it was proposed by the W.H.O expert committee on vector biology and control (1980) as one part of a recommended integrated control Programme.

3.2 Case studies

There are a number of studies done on the effect of impoundments on incidents of water related diseases, some of which are reviewed below. The majority of work has focused on comparing disease prevalence before and after development (see case studies below). Although these studies do not deal specifically with flow related causes and effects, they nevertheless form a valuable background against which the issue of diseases in regulated rivers can be considered.

The case studies reviewed below can be grouped into 2 categories namely, those that illustrate the impact water infrastructural developments have on the disease burden of local people (Case studies 1, 2 &-3) and those that describe the intentional manipulation of flow brought about specifically to control vector species (Case studies 4 & 5). The latter group is perhaps presented prematurely as flow related control is dealt with in more detail in later chapters, however all case studies are presented together for the sake of comparison and report conciseness.

Figure 11 - Regulation of rivers by dams such as the Pongolapoort dam has major implications for riverine ecosystems. (Photo K. Pringle, 2009)

3.2.1 Case study 1

Malaria and the Narmada-river development in India : a case study of the Bargi dam (Singh, Merah et al. 1999)

Invertebrate hosts:
Anopheles culicifacies and *An. fluviatilis*

Study description:
The Bargi dam was built between 1974 and 1988. Water has been stored at full capacity since 1990. Increases in the number of malaria cases have been noted in the area including a major outbreak of falciparum malaria in 1996. This study investigated prevalent infection rates in 'partially submerged' villages, i.e. villages with areas partially inundated by the dam, and 'dry' villages, i.e. villages away from the dam not inundated at all.

Results:
A study of health records for the area shows an increase in malaria cases from 184 per year in 1979 to 4279 per year in 1997. Despite vector control measures implemented after the outbreak of malaria in 1996, infection rates for partially submerged villages were found to be significantly higher than those of the dry villages. Anopheline densities were also found to be much higher in the partially submerged villages than in the dry villages. Although the abundance of *An. culicifacies*, the dominant malaria vector in the area, has decreased somewhat since 1987, the abundance of *An. fluviatilis* has increased.

Discussion:
The results of this study indicate that the villagers living close to the lake are far more vulnerable to infection than those living away from the lake. The study has also demonstrated that overall infection rates have increased greater than 100 fold since the dam was completed. This leaves little doubt that the primary contributing factor to the increase in incidents of malaria is the construction of the dam.

This study, although it demonstrates the possible impacts of large scale hydrological engineering projects, is largely not relevant to this report for two main reasons:

1. The study done by the World Commission on Dams showed that the construction of Kariba Dam in Southern Africa had no effect on the malaria incidence rate in this area. This was attributed to the fact that the predominant vector species, *An. arabiensis*, does not breed in large bodies of still water. Since *An. arabiensis* is also the predominant species in South Africa, this case study should be viewed purely as a source of background information.
2. The impact of downstream flow regulation on populations of malaria vector mosquitoes is not considered.
3. The impoundment in this case was also kept at 100% (non-fluctuating), a situation that does occur in South Africa, but only occasionally. Deliberate fluctuation in water level may be a possible solution that needs to be considered but this has other negative impacts.

3.2.2 Case study 2

Epidemiology of human Schistosomiasis in the Senegal River basin. (Picquet, Ernould et al., 1996)

Invertebrate hosts:
Bulinus globosus, *B. senegalensis* and *Biomphalaria pfeifferi.*

Study description:
Studies that were conducted on infection rates and snail species present before and after the construction of two large dams in the Senegal River basin (SRB) were compared and analysed. Reasons for the differences that were found have been suggested.

Results:
Before – Prior to construction of the two dams, villages in the middle and lower reaches of the Senegal river were free of intestinal schistosomiasis (*Schistosoma mansoni*), and levels of urinary schistosomiasis (*Schistosoma haematobium*) were considered low. The most abundant bulinid snail present was *B. truncatus*, which in this area, is known to be an inefficient vector of human schistosomiasis. *Bulinus globosus*, a proven intermediate host of *S. haematobium*, was found only in niche habitats. *Biomphalaria pfeifferi* (an intermediate host snail of *S. mansoni*) was found in only two isolated points in the delta. River levels would fluctuate naturally up to 13 m, and annual flood events occurred during the rainy season. River water pH was slightly acidic (approx 6). During dry conditions, sea water would push up into the delta resulting in saline conditions as far as 170 km from the coast.

After – The construction of the Manantali dam in Mali regulated the flow of water, resulting in stable flow conditions. The Diama dam 30 km from the coast in Senegal restricted the flow of salt water into the delta, ensuring fresh water throughout the delta. The pH increased to more alkaline levels which are more favourable for snails and their reproduction (though no explanation is given for the pH change). Together, the dams created new habitat areas for the snails *B. globosus* and *Bi. pfeifferi*. This resulted in a spread of their range and an increase in their population sizes. There was a clear increase in the levels of *S. haematobium* and *S. mansoni* infection rate. There are also reports of increases in malaria cases.

Discussion:
Bulinus globosus is a proven intermediate host of *S. haematobium* here as *Bi. pfeifferi* is of *S. mansoni*. Authors state quite clearly that the change in flow rate brought about by the Manantali dam favoured the expansion of freshwater host snails, particularly *B. globosus* (Picquet, Ernould et al., 1996) and *Bi. Pfeifferi* (Ernould and Sellin, 1999). The change in tidal influence brought about by the Diama dam was also partly responsible for the spread in distribution of *Bi. Pfeifferi* and thus also *S. mansoni*. This delta situation will not be replicated in many places in South Africa though, and this somewhat limits the applicability of the study.

Additional references: (Ernould and Sellin, 1999; Sow, De Vlas et al., 2002)

3.2.3 Case study 3

Schistosomiasis in Ghana: a case study from the Volta River (Phillips et al., 1993)

Invertebrate hosts:
Bulinus truncatus and *Biomphalaria pfeifferi.*

Study description:
This study does not really constitute a single experiment, but more recorded observations concerning the changes that have occurred in the Volta river valley since the regulation of river flow through the construction of the Akosombo hydro electric dam, and the Akuse Dam including the Kpong headpond. This was part of a cost benefit analysis study for the WHO.

Results:
Before – Prior to construction of the two dams, there was no record of intermediate host snails in the Volta River itself, though some freshwater lagoons associated with the river were infested. There was no record of intestinal schistosomiasis (*Schistosoma mansoni*) occurring in the region, though urinary schistosomiasis (*Schistosoma* haematobium) was present (infection rates between 25-35%). The river level fluctuated seasonally such that during the wet season, high flow levels existed, and fresh water was discharged at the river mouth. During the dry season, the level dropped significantly, and salt water was able to push upstream. This cycle of events kept the lower river relatively free of aquatic plants and the silt buildup in the estuary was flushed clear during periods of high flow.

After – The construction of the dams has meant that the river flow has been regulated to a continuous low volume discharge of freshwater. This has resulted in a build-up of sediment in the estuary creating sand bars which restrict the inflow of salt water. The resultant conditions have proved favourable for the growth of various freshwater vegetation species, and the proliferation of schistosomiasis intermediate host snails. Schistosomiasis infection rates in the Volta lake have soared, and this has been transferred downstream by human movement. *Schistosoma haematobium* infection rates reached 88% in some villages. *Schistosoma mansoni* infection rates, from not being recorded at all, reached 20% in some villages.

Discussion:
The regulation of the flow of the Volta River has without doubt been responsible for the large increase in human schistosomiasis infection rates in the lower Volta region. The establishment of a continuous low flow regime has encouraged the growth of aquatic vegetation, providing new areas of suitable habitat for the intermediate host snails in the river itself. This has provided new and far more widespread areas of potential risk of infection. It has also resulted in the introduction of *S. mansoni* into an area in which it was previously not recorded. This study can be considered representative of potential situations in South Africa, with the possible exception of the delta area.

(Phillips et al., 1993)

3.2.4 Case study 4

Anopheles culicifacies breeding in Sri Lanka and options for control through water management (Konradsen et al., 1998)

Vector:
Anopheles culicifacies is the primary malaria vector species in Sri Lanka. It is known to use natural streams and rivers for breeding purposes, especially pools isolated from the stream as its level drops. This knowledge has led to past efforts to reduce the abundance of this species through periodic flushing of streams and rivers. These have fallen away since the introduction of chemical spraying programs. This study attempts to gauge effectiveness of this disused approach.

Study description:
Anopheles larvae were sampled in the stream and streamside pools of a stream impounded for irrigation purposes, fortnightly for a period of 27 months. Stream depth and velocities were also measured. The goal of the experiment was to gauge the effect of changing flow rates/depths on the numbers of mosquito larvae in the stream bed. Volumes of water released were also recorded.

Results:
The numbers of mosquito larvae present were greatest when the 14 day average water level was below 20 cm (85% of larvae collected). Only 4% of larvae were collected when the 14 day average was greater than 50 cm. When the stream level reached 20 cm or greater, the number of isolated pools, and the number of larvae present, dropped significantly.

Discussion:
This case study does suggest that vector numbers increase during periods of low flow. The presence of pools alongside rivers is shown to provide habitat suitable for Anopheleline breeding. These pools are also shown to be cleared by periods of high flow, and that breeding success is reduced. Thus this study does indicate that that control of vectors which utilize streamside pools as breeding habitats is possible through flow manipulation.

This study's model may not be transferable to a South African scenario due mainly to the following factors.

- *An. culicifacies* is known to breed in streamside pools, *A. arabiensis* and *A. funestus* (the major South African malaria vectors) only partially breed in streams but mostly in temporary water bodies (some of which may be on river banks) (le Sueur, 1991).
- This study was conducted on a small stream – it may not apply to the bigger rivers which may be used in manipulated flow scenarios in South Africa.
- Water volume required for raising stream flow levels may not be available due to the high demand for water resources, and the limited supply in South Africa.

3.2.5 Case study 5

Environmental management for Schistosomiasis control: River flushing (Fritsch, 1993).

Invertebrate hosts:
Biomphalaria pfeifferi and *Bulinus globosus*

Study description:
Schistosomiasis (*S. haematobium* and *S. mansoni*) is endemic in the Kilombero district of Tanzania. A river flushing weir was constructed to impound a river in Namwawala village in an effort to flush the river clear of host snails. Flushing commenced in 1989. Water was impounded and released as a flood, repeated several times at intervals of up to 12 days over 2 seasons. Populations of *Bi. pfeifferi* and *B. globosus* were monitored below the weir.

Results:
The flushing of the river proved successful in reducing the occurrence of *Bi. pfeifferi* and *B. globosus* below the weir. Following sustained flushing at short intervals (up to 12 days), survey teams found no snails of either species below the weir or in the impounding room.

Discussion:
Fritsch suggests several reasons for the drop in the numbers of snails present. The first is most obviously the flushing effect of the water on the snails themselves, dislodging individuals and washing them away downstream. The success of the operation in dislodging snails appeared to depend mainly on the generation of turbulent flow and brief periods of high stress.The other reason is the effect flushing has on food supply, as vegetation (both alive and dead/rotting) is cleared from the river bed. Finally he also suggests that the stresses placed on the remaining snails by the flushing reduces their breeding potential. He attributes the reduction in snail populations in the impounding room to the high rate of drawdown during flushings, which results in the stranding and drying out of snails living there.

This study demonstrates the effectiveness of variable flow rates in limiting freshwater snail distribution. The findings of this study are augmented by the findings of Woolhouse and Chandiwana (1990) who noticed drastic reductions in abundance of snails in a river following high volume flow events due to heavy rain.

Fritsch also alludes to the possibility that malaria incidents may be reduced simultaneously by flushing larvae from streamside pools (See case study 4 above).

It should be considered though that snails dislodged by high flows are not necessarily killed, but swept away. Their fate may be important in as much as they may augment existing populations (or create new populations) downstream of their original position. However, of the case studies reviewed in this report, this study perhaps is the one which best suggests that control of freshwater snail distribution is possible through the manipulation of regulated flows.

3.3 Conclusions from literature

The literature reviewed for this report largely did not deal specifically with the impact river regulation has on disease invertebrate hosts. Some of the most relevant examples were included in the case studies reviewed above. It is thus difficult to draw direct conclusions concerning the relationship between the regulation of rivers and the invertebrate hosts of diseases. There is however sufficient peripheral information to inform the discussion and to develop a broader view of the relationship between invertebrate habitat and the consequences of regulated flow.

3.3.1 Anopheline mosquitoes

Links to regulated rivers:

Volume and rate of flow:
It is difficult to assess the effects of river regulation on mosquito breeding success. According to le Sueur (1991), *Anopheles* mosquitoes are able to breed in a wide variety of temporary and permanent water bodies. They are not exclusively bound to rivers. In his study, the majority of their breeding habitat was found away from rivers. Some *Anopheles* species larvae were found in streams and along river edges. *Anopheles arabiensis* larvae however, were found mainly in small temporary water-bodies. Alongside rivers, they were only found in the hoof-prints of animals such as cattle (The proportion of the total sample reflected by this group is not recorded). *An. funestus* is however described as breeding almost entirely in rivers in Kenya (Mwangangi, Mbogo et al., 2007). This species is a proven vector of malaria in South Africa, but its distribution in South Africa has been significantly reduced through chemical spraying.

For those mosquitoes that do breed in or alongside rivers, flow rate is important. Mosquito breeding habitats associated with rivers are generally confined to isolated pools outside of the main current or water body. Case study 4 illustrates the fact that under a variable flow regime, these pools may be flushed during periods of high flow, clearing them of the majority of larvae present. Results showed that fewer larvae existed in the stream system during and after periods of higher flows than during low flow periods. Larvae in these isolated pools are also vulnerable to desiccation during periods of drought/low flow. Both of these flow extremes would disrupt the mosquito breeding cycle. The regulation of flow may thus allow pools to remain undisturbed, contributing to anopheline breeding success.

The opposite may also however be true, as with a natural high/low flow cycle, residual pools are created as the water level drops. Several studies have shown that anophline species, especially *An. funestus,* breed in riverside pools. Consequently, should the level not rise again sufficiently quickly to interrupt the development of larvae into adult mosquitoes, these pools will provide mosquitoes with ideal breeding opportunities. Experimental conditions have showed that pre-imaginal development (i.e. larval and pupal stages) of *Anopheles arabiensis* lasts approx 11.8 days (Mwangangi et al., 2006). This is the only period during a mosquito's life cycle when it may be subject to the physical / chemical conditions brought about by the regulation of a water body. Should fluctuations occur in a cycle that is greater than this period of time, breeding success of mosquitoes may be amplified. The regulation of a river's flow may thus result in fewer residual pools being formed, thus providing fewer breeding sites for mosquitoes.

Vegetation:
The proliferation of vegetation that may result from the regulation of rivers (see case study 3) may be significant. Le Sueur (1991) has shown that *Anopheles* mosquitoes will breed through the dry winter period in permanent water bodies such as lakes when temporary rain-filled pools are unavailable. Here aquatic vegetation, particularly *Potamogeton crispus*, provides refugia for larvae.

In Mexico, Bond et al. (2004) showed that the removal of filamentous algae from riverside pools markedly decreased the abundance of *An. pseudopunctipennis*. By losing the ability to flush out aquatic vegetation and algae, regulated rivers may potentially provide additional over-wintering habitats for A*nopheles* mosquitoes.

Conclusions:

Overall, *Anopheles* mosquitoes, and thus malaria, appear to have a tenuous association with rivers in Southern Africa. A literature review shows that little of this relationship has been studied here, and this is largely because it is generally understood that the majority of mosquitoes will breed opportunistically in a wide range of water-bodies. Furthermore, transmission of the malaria parasite is conducted entirely independently of water, and rivers (regulated or unregulated) play no part in this aspect of the parasite's life cycle. Owing to this tenuous link and the paucity of existing information, few conclusions can be drawn from this literature review about a relationship between flow regulation and anopheline breeding habitat in South Africa. Nevertheless, situations that need to be examined include:

- Increase in marginal vegetation (*Phragmites,* etc.) due to regulation and the potential for mosquito habitat increase
- The role of river flow and the regulation thereof, on floodplain wetlands and mosquito breeding.

3.3.2 Freshwater snails

Links to regulated rivers

<u>Volume and rate of flow</u>:
The relationship between freshwater snails and rivers is far stronger than that of malaria mosquitoes and rivers. Varying the conditions in a river is thus likely to have a more pronounced effect on snail populations.

Flow rate is a key factor in the habitat selection of snails in rivers (Appleton, 1978). Studies have shown that flow velocities of greater than 0.3 m/s will most likely dislodge snails (Appleton, 1976). Case study 5 is a very good illustration of the use of current velocity to dislodge snails and eliminate them from an area. This is an application of a natural flood event which naturally reduces snail abundance. Woolhouse and Chandiwana (1990) have shown how populations of *Bulinus globosus* were greatly reduced in number by periods of high flow after heavy rain events.

Not only will the volume and velocity of flow have direct impacts on the snail itself, but it will have an effect on the habitat types to be found in a regulated river. In the case of a low and slow release regime, slower flow rates mean vegetation volumes will increase along river channels. Case studies 2 and 3 illustrate how the regulation of a river's flow can lead to an increase in snail habitat (largely through aquatic vegetation growth, which provides refuge for snails from predators and from unfavourable current speeds) which in turn leads to an increase in the abundance of snails and an increase in disease burden. In some of the cases reviewed, this factor encouraged the spread of intermediate host snails into areas where they were not previously present (see case study 2 & 3).

A further influence that should be considered is the effect that the volume and velocity of flow has on the deposition of sediment and detritus. Greater flow velocities mean that snail food sources are more likely swept away downstream, and less likely to be deposited in higher velocity flow areas (Marti, 1986 – as reported in Brown, 1994 and Woolhouse and Chandiwana, 1990). Added to the stress of a scarce food supply, snails attempting to live in areas with a strong current will expend a great deal more energy simply trying to resist the current. These factors together mean that the energy available to the snail for reproductive purposes, and thus fecundity, is greatly reduced (Loreau and Baluku, 1987).

Temperature:

It has been shown that temperature is an important factor in determining habitat suitability for freshwater snails. Several authors have also shown that temperature is important in determining the fecundity of snail species and plays an important role in the ability of snails to colonise previously unpopulated habitats (Shiff, 1964; De Kock et al. (2001; 2003; 2004; 2005)).

Water temperature in a river is usually affected by the construction of a dam. Pitchford and Visser (1975) measured river temperatures below the Verwoerd (now Gariep) dam before and after construction. Their findings showed a narrowing of the range of mean monthly maximum and minimum temperatures, i.e. a lowering of summer average temperatures, and a rising of winter average temperatures. Their assertion was that changes in river temperature may contribute to the establishment of previously non-existent intermediate host snail populations. Fortunately, it was reported in Davies and Day (1998) that this was not the case.

Work by Dickens et al. (2007) on the Umgeni river below Albert Falls Dam supports this trend of temperature range reduction, and suggests that the recovery point, i.e. that point at which the river regains the natural thermal characteristics it displayed when entering the dam, would lie some distance downstream of where Nagle dam is situated. This distance is not recorded but is greater than 24 km.

Since temperature is an important factor influencing the distribution and biology of freshwater snail species, this is an issue which should be closely considered for the purposes of this report. Assumptions could be made based on the work that has been carried out on the relationship between temperature and snail breeding success, however, the impact of reservoirs on downstream river temperature and their effect on freshwater snails has not been specifically studied in any of the work reviewed for this section.

Chemistry:

Water released from dams is chemically different from the water entering the dam. pH, salinity, water hardness, etc. are all likely to change under the influence of a number of features of a reservoir such as its age, its morphometry and the retention time imposed on the water (Davies and Day, 1998). This has an effect on the habitat to be found downstream of the dam. The effect of these changes on snail population dynamics is not adequately reported on in the works reviewed for this report, and this issue should be further considered.

Conclusions:

In conclusion, based on the literature and case studies reviewed for this report, the regulation of rivers may well have some influence over the distribution of freshwater snails (which include the invertebrate hosts of both schistosomiasis and fascioliasis). Snails appear to have a reasonably strong relationship with rivers and a reasonably strong link with flow rate and other factors influenced by river flow regulation. This link suggests that control of snail populations through the manipulation of flow is a plausible theory, and one which should be investigated further.

4. Flow related control in South African rivers

4.1 Introduction

The concept of manipulating river flows in order to control the invertebrate hosts of diseases has been thought possible by various sources. Indeed, Fritsch (1993) has proved it to be possible on a small scale with respect to bilharzia in Tanzania (see case study 5 above), and cases have documented successful control with regards to malaria in other countries (Konradsen, 1998). This chapter sets out to investigate the extent of such a proposal, to suggest those candidate rivers in South Africa which may potentially be manipulated (based on dam size thresholds used as a proxy for the ability to significantly manipulate a river's flow), and additionally, to estimate the number of people who might potentially benefit from this form of disease control.

Flow control requires the use of mechanisms which allow more or less water to be released into a river at will. Many rivers in South Africa are regulated by large dams, and it is suggested that these dams might be utilised to manipulate the flow of rivers, which may be used to achieve a measure of control of the populations of invertebrate hosts of the three diseases. It is proposed that only rivers which flow through disease endemic areas (see figs 12 and 13 below), and that are regulated by these large dams are feasible candidates for this form of control.

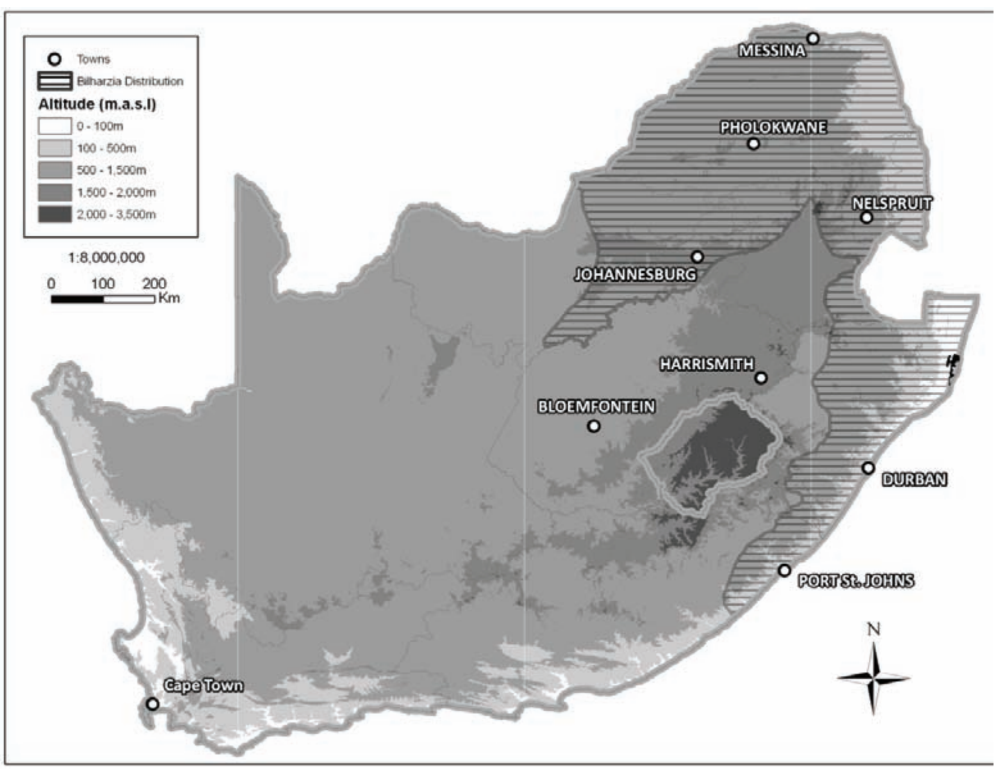


Figure 12 - Distribution of bilharzia endemic areas in South Africa (Intestinal bilharzia - S. mansoni - distribution is completely included within this distribution) Adapted from the Bilharzia Atlas (Gear et al., 1980).

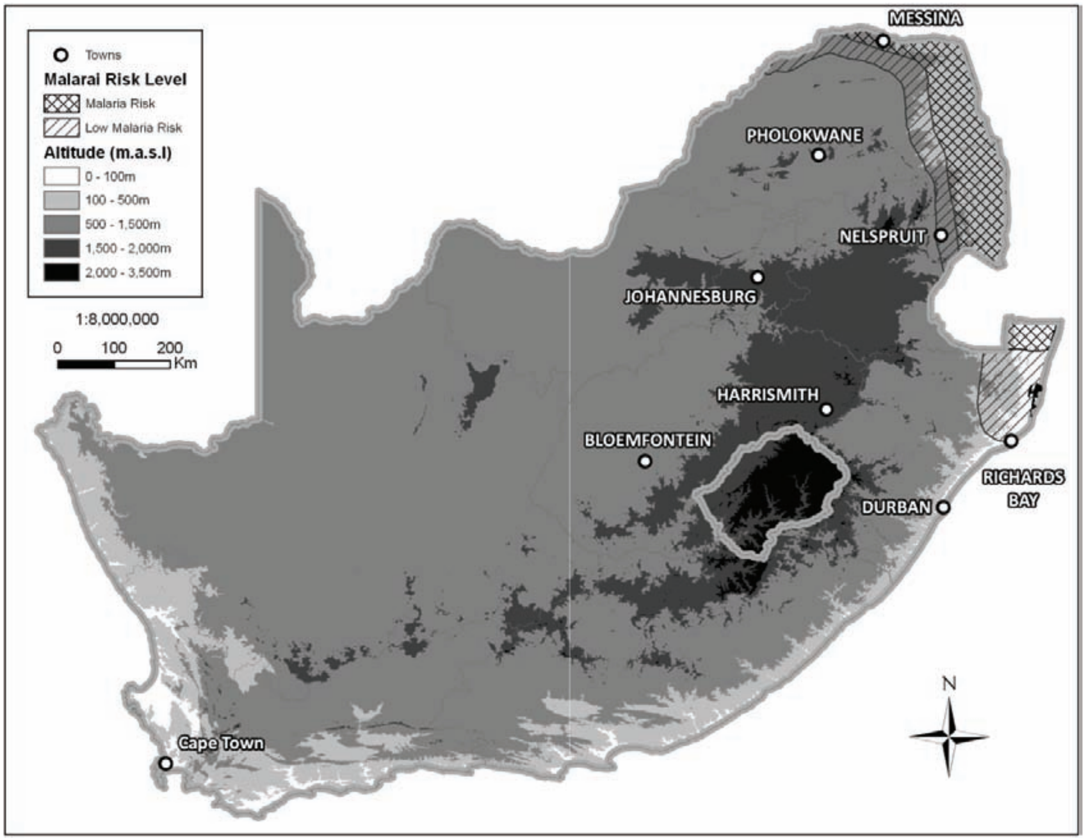


Figure 13 - Malaria risk areas in South Africa (adapted from MRC's Malaria South Africa program website)

4.2 Candidate dams and rivers

Large dams are defined as impoundments with a capacity greater than 10 million m^3. Large dams are preferred as candidates for flow manipulation since it is assumed that they will have the infrastructure to release or retain calculated volumes of water at will, and will have the capacity to store these volumes. It is also assumed that larger dams will be managed more effectively, and that the implementation of flow manipulation will be a more realistic proposition at these dams (this thus excludes typical farm dams with no release manipulation capability, and dams which do not have sufficient capacity to influence a significant length of river).

All dams of capacity greater than 10 million m^3 were drawn from the DWAF dam safety database. From this list, 128 candidate dams were selected as possible flow manipulation dams, based on the fact that water released from them flows through disease endemic areas. This list is included as appendix 3.

Though dams themselves often represent significant transmission points, only river reaches below the selected dams are considered as candidate rivers. Candidate rivers are selected based only on the endemic areas of malaria and bilharzia. The distributions of the two species of liver fluke parasite are largely unknown and thus cannot be included in this mapping exercise.

In summary, rivers that are possible candidates for flow manipulation control have been selected based on the following requirements. They must be:

1. rivers that flow through disease endemic areas,
2. rivers that are regulated by dams with a storage capacity larger than 10 mill m^3.

4.2.1 Affected population

Once candidate rivers have been selected, an area buffer was applied on either side of the river. This constitutes an area representing 'people at risk' due to diseases related to the river. This can be seen as the area representing people who would potentially benefit from control of the invertebrate hosts along this stretch of river.

In the case of bilharzia, transmission takes place within waterbodies which requires that people immerse themselves in water, either through swimming, collecting water or washing. According to Kvalsvig and Schutte (1986), swimming in rivers is recognised to be the activity most likely to result in transmission. Spatially speaking this limits the 'at risk' population to those people living near to, and utilising the water body. It is estimated that children will walk up to five kilometres when going for a swim, and they thus form the basis for selecting this distance as a buffer distance representing the 'at risk' population.

Malaria in contrast does not require immersion at all. Female *Anopheles* mosquitoes, having emerged as adults, will fly great distances from the water body in search of a bloodmeal, and will be able to transmit malaria within the radius of their flying ability. This distance can be made complicated by wind-assisted travel, but it is estimated that three to five kilometres represents the most feasible distance (Menach et al., 2005; Ghebreyesus et al., 1999). Spatially speaking then, the potential transmission population for mosquitoes emerging from a particular water body are those people living inside a 5 km radius from the water body. A buffer distance of 5 km was thus used to estimate the population 'at risk' from malaria mosquitoes originating from candidate rivers.

The number of people resident in each of these areas is estimated from 2001 census data using proportional areas and assuming that households are evenly distributed across sub-place areas. This figure is then compared to the number of residents living in the entire endemic area, and is converted to a percentage. This represents the proportion of people living within the endemic areas, who will benefit from reduced risk if control of invertebrate hosts in these rivers is effected.

A map representing the results of this study is included below (fig 14)

4.2.2 Limitations

This study has a number of limitations. The majority are related to the limited amount of documented research available concerning this subject. Issues such as the distance along a river below a regulating dam that a manipulated flow will be effective in changing invertebrate habitat have not been taken into account. This efficacy is likely to be reduced due to the mitigating effect of tributaries joining the river and reintroducing natural flow variation. Also the 5 km distance selected as the buffer with which to define the 'at risk' population for bilharzia is based on an assumption that children will walk this distance in order to find a place to swim.

The biggest limitation is however the dam selection threshold of ten million m^3. In the absence of data reflecting the mechanisms by which dams release water, this value was used as a proxy for dams which would have the ability to release more or less water on demand and have the capacity to store or release more water when required. This value does exclude several potential regulating dams such as Henley, Nungwane and Shongweni dams in KwaZulu-Natal, but it is felt that the inclusion of dams which are not suitable on the basis of their not being able to significantly manipulate the flow of rivers would be a more significant flaw.

4.3 Results

Table 6 below reflects the outcome of this ‘population at risk’ study. It is estimated that approximately 18% of people living in bilharzia-endemic areas and 40% of people living in malaria-endemic areas, live within 5 km of a candidate river. This does not mean that 18% of bilharzia infections or 40% of malaria infections originate from these rivers, however it does give an idea of the population that is ‘at risk’ from parasites who’s lifecycle is linked to rivers where flow related control is thought to be possible.

Table 6 - Proportion of the population of disease endemic areas that are living within 5 km of flow related control candidate rivers.

Disease	Total population living in endemic areas	Population within 5 km of candidate rivers	Percentage
Malaria	3,684,737	1,472,271	40%
Bilharzia	28,751,537	5,143,366	18%

It is important to remember that a water body occurring within a disease’s endemic area does not necessarily hold the invertebrates required to facilitate transmission. In chapter 1, the habitat choices of the invertebrate hosts associated with these diseases were outlined in detail, and this subject is further expanded on in chapter 6. Nor do people living within the ‘at risk’ zone necessarily come into contact with the water, as many are likely to have water provided to their homes, or to a community standpipe.

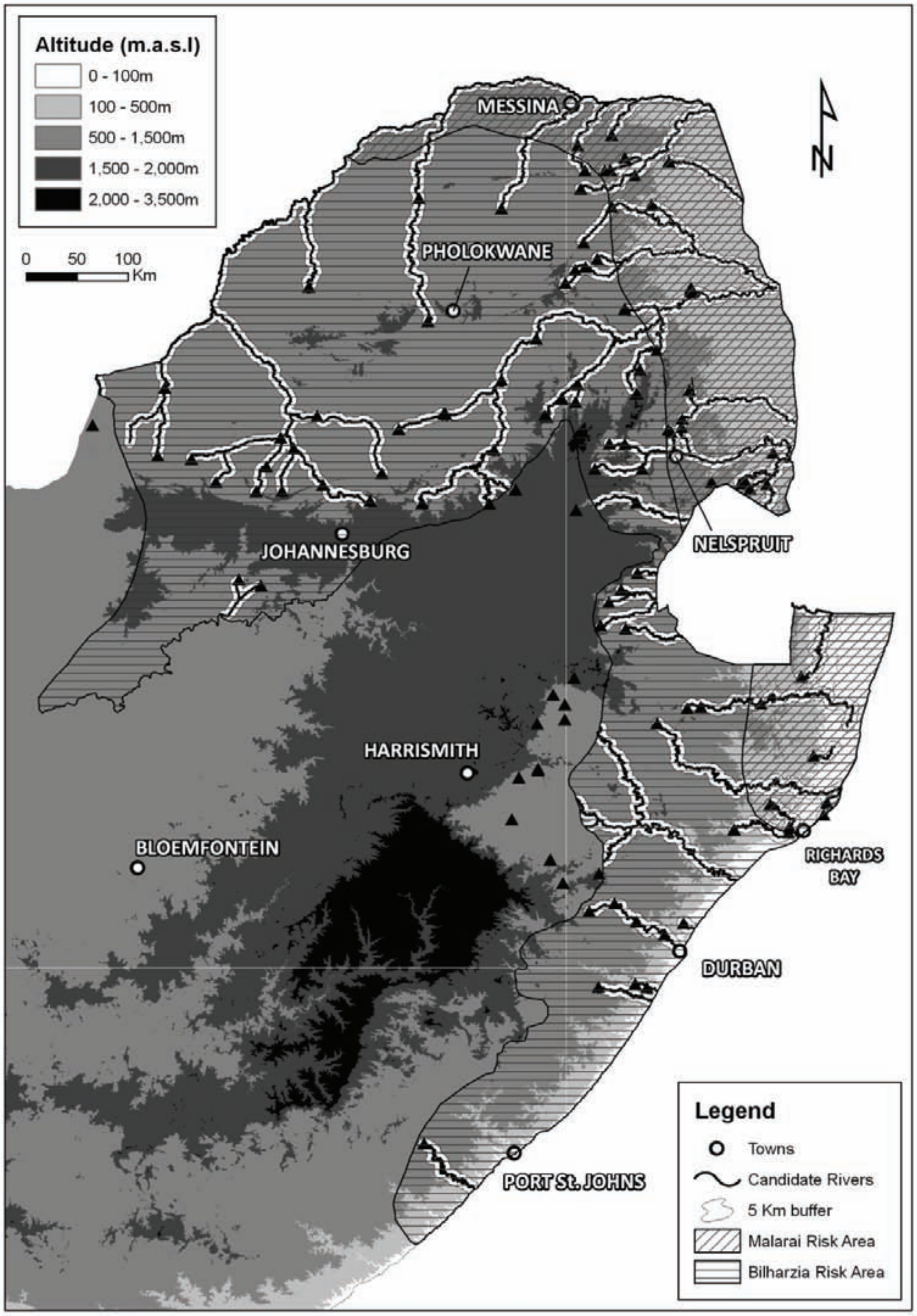


Figure 14 - Candidate dams and rivers for flow related invertebrate host control in the bilharzia and malaria endemic areas of South Africa

5. Estimation of the costs associated with the diseases in South Africa

5.1 Introduction

It is unquestionable that all around the world, parasitic diseases carry with them significant costs which must be borne by the infected individual, their community, and by the nation's economy as a whole. Gallup and Sachs (2001) have estimated that between 1960 and 1990, taking into account initial poverty, economic policy, tropical location, and life expectancy, among other factors, countries with intensive malaria grew 1.3% less per person per year than those without it, and a 10% reduction in malaria was associated with 0.3% higher growth.

The costs associated with a disease are used in many cases to assess the benefits of particular interventions, however, they are often difficult to estimate since records of infection are often poorly kept (especially in developing countries which are often the worst affected countries). Studies thus often rely on estimates, and proxies are often used to represent factors such as the presence of the disease and the income earned by an individual, with varying degrees of success (Goodman et al., 2000). Successful studies are thus scarce and vary in their methodology, making comparisons, and extrapolations difficult (Ettling et al., 1991, Shepard et al., 1991).

In addition to this, the economic costs associated with parasitic disease infection are not limited to the obvious direct costs of treating the patient, but they also involve a wide range of somewhat hidden indirect costs. These indirect costs vary significantly according to the nature and severity of the infection, and the socio-economic situation of the infected individual.

Parasitic diseases are in many cases considered diseases of the poor. Barlow (1967) writes that malaria is associated with lower income groups primarily because it is avoidable, and thus those people with higher incomes and better education will generally be better equipped to avoid the disease or treat it if infection occurs. The same can surely be said of many parasitic diseases including bilharzia. The consequences of this situation make studies of this nature difficult.

The majority of studies attempting to estimate the costs of parasitic diseases utilise a wage rate method, where economic impacts are based on estimates of time lost due to the disease multiplied by the value of a day of work. This method, although popular, has several problems linked to it when used in poorer areas:

1. Per capita income is difficult to assess in areas where subsistence agriculture and informal employment/unemployment predominates.
2. In areas where unemployment is high, loss of time does not necessarily equate to loss in productive output since substitute labour is often available. Nur and Mahran (1988) showed how 62% of work hours lost due to malaria and bilharzia were compensated for by family members in Sudan (reported in Goodman et al., 2000)
3. Adult ill-health may have a pervasive effect on the incentives, behaviour and strategies of households which are not accounted for (Goodman et al., 2000).

Significantly, despite these problems, the majority of studies undertaken in Sub-Saharan Africa have utilised this method. Finding studies that estimate these costs, and that are specific to South Africa, has however proved difficult.

5.2 The costs of disease burden and treatment in South Africa

As is noted above, the literature available on this particular subject is particularly thin. Some studies have been carried out, but they predominantly focus on particular areas of South Africa , and thus conclusions for the whole country have to be extrapolated.

One study which estimated the national costs of malaria in South Africa, was an undated study by Richard Tren[1] (http://www.malaria.org/tren.html). Two studies were found which attempted to estimate costs associated with bilharzia. Both of these were spatially limited, and extrapolation was used to obtain national estimates for the purposes of this report. No literature was found concerning the costs attributed to liver fluke disease in South Africa.

5.2.1 Malaria

As with most areas around the world, assessing the economic cost of malaria in South Africa is complex and difficult. The 'total cost' of the disease is made up of direct and indirect costs and it varies from year to year based on the number of infections, as is illustrated below (see table 1 and figs 1 and 2).

1. Direct costs are usually borne by both public and individual parties.
   → Public expenditure includes the direct costs of:
      - establishment and maintenance of health care facilities which includes the cost of medical staff and the cost of equipment for administering the treatment,
      - mosquito control programmes such as spraying homes and buildings with persistent insecticides and providing insecticide treated bed nets (this is a significant cost borne by state anti-malaria programmes and NGO campaigns such as the Roll Back Malaria Campaign and the Lebombo Spatial Development Initiative),
      - education and
      - research.

   → Individual expenditure includes the direct costs of
      - anti-malarial drugs and other preventative measures such as bed nets and insect repellents,
      - medical treatment including drugs and doctors fees,
      - Transport to and from health care facilities

2. Indirect costs are almost entirely borne by the infected individual and their immediate family or care givers. These include costs created by:
   - the loss of productivity of those infected
   - the reduction in productivity of those caring for infected individual
   - the loss in future earnings due to mortality
   - the direct costs associated with a death such as the cost of funerals and
   - the loss of productivity of people attending funerals.

The indirect costs are difficult to estimate and vary from case to case according to the infected person's life situation, income and the length of time before treatment is sought. They are not only borne by the patient and their household/family/caregivers, but also by society as a whole where there is a loss of productivity (for an estimated breakdown of costs associated with malaria, see tables 2 & 3).

[1] The credentials of this study could not be verified as it is unknown if the work was ever published or peer-reviewed.

Table 7: The number of cases of malaria recorded annually between 1990 and 2006 (Dept of Health website - http://www.doh.gov.za/facts/index.html)

Year	Number of Cases	Fatalities	Case Fatality percentage
1990	6822	35	0.5%
1991	4693	19	0.4%
1992	2872	14	0.5%
1993	13285	45	0.3%
1994	10289	12	0.1%
1995	8750	44	0.5%
1996	27035	163	0.6%
1997	23120	104	0.4%
1998	26382	197	0.7%
1999	51444	406	0.8%
2000	64622	458	0.7%
2001	26506	119	0.4%
2002	15649	96	0.6%
2003	13459	142	1.1%
2004	13399	89	0.7%
2005	7755	63	0.8%
2006	12098	87	0.7%
Average	19304.7	123.1	0.6%

The number of cases of malaria recorded each year also varies. Table 7 (above) and figures 13 and 14 below show the numbers of cases and the numbers of fatalities reported annually since 1990 (data sourced from the National Department of Health). What is noticeable is the dramatic rise in the numbers of cases and fatalities reported between 1996 and 2001, with 1999 and 2000 showing particularly high numbers of both infections and fatalities.

This rise is ascribed by authors to several contributory factors, amongst which is the particularly heavy rainfall over that period, increasing drug resistance in some *Plasmodium* spp, the possible increase in imported cases from Mozambique and the replacement of DDT with synthetic pyrethroids in the residual spraying programme (Tren undated, Kleinschmidt et al., 2002).

This variation in numbers of infections however, means that the national cost of the disease also varies significantly from year to year. The values presented in table 2 are illustrated graphically in figures 14 and 15 below.

On average over this period, **0.6%** of cases of malaria have proved to be fatal. The average number of cases reported per year since 1990 is **19305** and the average number of fatalities is **123 per year**. These average numbers are pushed significantly higher by the numbers of cases and fatalities recorded during the epidemic between 1998/99 and 2000/01.

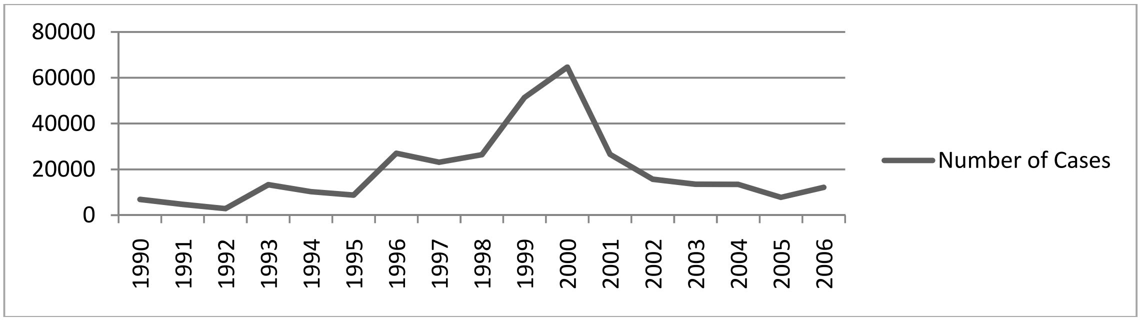


Figure 15: Number of reported malaria cases between 1990 and 2006 (Dept of Health)

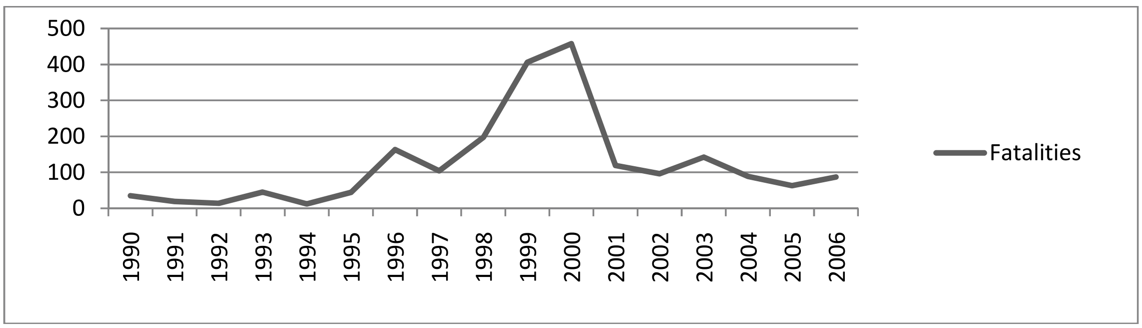


Figure 16: Number of reported malaria deaths between 1990 and 2006 (Dept of Health)

Full economic assessments of malaria in South Africa are rare. However, according to Tren (undated – www.malaria.org/tren.html), the cost per case associated with 22 690[2] malaria cases in 1998 worked out to be approximately R5492.00 (which adds up to a total national cost of R124.5 million attributed to malaria for that year). This value includes a significant value attributed to malaria control programme costs, which is a questionable inclusion in a cost per case (CPC) value. Ideally, the CPC value should include only those costs associated with the infection and the consequences of the infection such as required treatment, morbidity, mortality and associated costs. The costs of prevention should be assessed separately as a 'cost per case averted' (if this comparative data is available) or simply as part of the total cost of the disease to the country.

Tren's assessment also includes significant costs attributed to treating and hospitalising patients and costs attributed to fatality due to loss in future earnings. Less significant values are ascribed to the loss in productivity of the patient and their family/home care givers, and to the less systematically reported cases of malaria that present outside of the malaria endemic areas. These figures are presented in table 8 below.

The indirect costs presented below reflect an economic assessment based on 1994 estimates of income in the employment sectors most represented in the malaria endemic areas of South Africa (Data reported was sourced from DBSA). Should these costs be inflated by an average of 5.3% per annum (inflation figures supplied by KPMG), and preventative programme costs separated, the cost per case estimate for 2006 (latest malaria infection figures available) will be roughly **R3 527.00 per case (See table 9)**. Based on this figure and the number of recorded cases, the total national cost of malaria in 2006 is estimated to have been approximately **R140 million**.

[2] This figure is significantly different to the figure supplied by the DoH for reported cases in 1998 and to the figure quoted in the body of Tren's report (both show 26382 cases). Details of this were not available.

Table 8: The costs in Rand of malaria to South Africa (Tren, undated)

Type of Cost	1996 (Rand)	1997 (Rand)	1998 (Rand)
Number of malaria cases	23 907	20 513	22 690
Direct Costs			
Malaria Control Programme	55 000 000	60 000 000	68 424 164
Cost of treating and hospitalising patients	7 171 599	5 653 828	5 902 062
Indirect Costs			
Malaria patient lost productivity	6 640 120	6 166 245	6 016 356
Care giver – lost productivity	138 803	157 737	190 689
Mortality costs	31 993 131	20 845 528	42 438 360
Cases outside malarial areas	2 006 771	2 321 515	1 663 230
TOTALS	**102 950 427**	**95 144 855**	**124 634 863**
Cost per case	**4 304**	**4 638**	**5 492**

In the extrapolated costs table presented below (table 9), the costs associated with the malaria prevention programme have been separated out from those direct and indirect costs associated with a malaria infection. This is to better reflect the actual cost per case value.

Table 9: Extrapolated figures showing estimated costs in Rand associated with malaria for 2006 (based on 5.3% inflation)

Type of Cost	1998 costs (Rand)	2006 costs (Rand)
Number of malaria cases	22,690	12,098
Direct Costs		
Cost of treating and hospitalising patients	260.12	370.41
Indirect Costs		
Malaria patient lost productivity	265.15	377.58
Carer – lost productivity	8.40	11.97
Mortality costs	1,870.36	2,663.39
Cases outside malarial areas	73.30	104.38
Infection related costs (cost per case)	**2,477.33**	**3,527.72**
National infection related costs (cost per case * no of cases)	56,210,697.00	42,678,391.61
National preventative costs (malaria control programme)	68,424,164.00	97,436,009.54
TOTAL Cost to Country	**124,634,861.00**	**140,114,401.14**

5.2.2 Bilharzia

Unlike malaria, bilharzia is not a notifiable disease. This means that people are diagnosed and treated without any record being kept as to the number of cases of the disease, and the geography of the infections encountered. This fact makes data gathering and current total cost of treatment estimations extremely difficult. It has however been estimated that approximately 2.5 million people are infected with bilharzia in South Africa at any one time (Moodley et al. (2003), reported by Appleton et al. (2006)).

Estimating the costs associated with the burden and treatment of this disease is a difficult task. This is not only due to the paucity in infection and treatment data, but also because, as with malaria, the cost of treatment is only part of the cost associated with the disease. Kieser (1938) postulated that the disease carried with it a severe debilitating effect which resulted in a marked loss of productivity in the patient, stunted the growth of children and inhibited their cognitive development. Further evidence of this was provided by Kvalsvig et al. (1991). The costs associated with the deleterious effect bilharzia can have on an individual's life earning potential (if left untreated) are enormous, and realistically unquantifiable.

A small proportion of infected individuals are, however, effectively treated, but the costs associated with the individual's reduced productivity from the time of infection until the time of treatment, and the extent of reduced cognitive development in child sufferers even if eventually treated, is extremely difficult to estimate.

Cox et al. (2003) examined the economic considerations of the Ecological Reserve and the estimated value of goods and services provided by the Crocodile River. In doing so, they estimated the costs associated with bilharzia in this catchment as R5.5 million for the treatment of the disease, and a further R11 million for the loss of productivity associated with the disease for an estimated 110 387 infected individuals. The treatment cost figure is not an estimate of current treatment costs, but rather an estimate of what it would cost to treat all infected individuals in the catchment. The loss in productivity figure is based on an average of 4 life days lost per year, and an average income of R25 per day (see Table 4).

Mander et al. (2003) carried out a study on the Lower Thukela river catchment as part of the Reserve determination study, and calculated a treatment cost of R15.6 million, and a further R12 million associated with loss in productivity for an estimated 107 512 infected individuals.
Between the two studies, they estimate a once off treatment cost (assuming no re-infection) of between R50 and R145 per person. The difference in these two values is accounted for by a difference in the cost of praziquantel estimated by the two studies. The Crocodile River study estimated treatment at R20.00 per infection, while the Thukela study estimated this as R105.00 per infection. According to Mander, the costs used in the Thukela study were taken from the Crocodile river study and updated. R105.00 per infection is thus considered a more current estimate. An additional cost of between R100 and R110 per year for loss of productivity of infected individuals is included in the total estimate.

Applied to the estimated number of infected individuals on a national scale (2.5 million), this results in a once off, national treatment cost of approximately R363 million. A further value of between R250 million and R275 million has been estimated to reflect lost productivity every year. It should be noted though that this figure is entirely hypothetical, since many infected individuals do not seek treatment, and the long term productivity loss costs carried by these individuals far outweighs the cost of their treatment.

Re-infection, although slower than some of the soil-transmitted parasites, is also problematic since the drugs used to treat infected individuals have no long lasting effect and individuals do not develop immunity to the parasite. The WHO estimates that treatment intervals of between one to two years are sufficient to prevent severe morbidity. If appropriate measures are not taken to prevent infection at bathing/washing/water collection sites, treatment of individuals will be necessary on an on-going basis. There are also currently no state control programmes targeting the invertebrate host snail on more than a local scale, which means that a single infected person, in association with a healthy population of snails can infect a disease free local population. This has been shown to occur when the migration of infected people has brought the disease into an area previously free of it, or to an area that has been treated (Ampofo et al., 1995; Joubert et al., 2001).

Mander (2003) goes on to make the point that these figures are in all likelihood underestimates since, if left untreated, the effects of bilharzia on cognition and school performance will probably condemn the infected individuals to a life of poverty. This disease thus carries a high social cost, one which is very difficult to estimate.

Table 10: Estimated costs associated with Bilharzia in South Africa

Study	Area of Study	No of infections	Treatment costs (once off)	Loss (PA) of productivity	Cost per case
Cox et al. (2003)	Crocodile river catchment	110387	R5 500 000.00	R11 000 000.00	R150.00
Mander et al. (2003)	Lower Thukela river catchment	107512	R15 600 000.00	R12 000 000.00	R257.00
National extrapolation	Republic of South Africa	2 500 000	R363 000 000	R250 000 000-R275 000 000	R245-R257

5.2.3 Liver fluke disease

The costs associated with liver fluke disease in South Africa are almost entirely made up of costs and losses suffered by livestock farmers. Human cases of fascioliasis are rare, and the costs associated with the human form of this disease should be seen as negligible.

Internationally, it is estimated that liver fluke costs the cattle industry of the United Kingdom GBP23 million a year (R322 million) (White, 2005), and the Australian industry Aus$80 million (R520 million) (Boray, 1999 – reported in Molloy and Anderson, 2006). According to Pimentel (2003), no economic assessment has been carried out on the economic impact of liver fluke disease on the livestock industry of South Africa. Literature concerning the costs of this disease in South Africa is thus essentially non-existent, and so for this literature-based report, costs have been speculated on, but not researched beyond that.

In total, it has been estimated that infection with liver fluke costs the UK farmer between 10% and 15% per animal (http://uk.merial.com/producers/dairy/fluke_facts.asp). In trying to assess the total costs of the liver fluke parasite to the agricultural industry in South Africa, economic costs can be associated with the following issues:

1. animal fatalities,
2. lost productivity in milking cows,
3. reduced wool production,
4. delayed conception,
5. reduced calving/lambing rates,
6. reduced weight gain and loss of condition in slaughter animals,
7. loss of revenue from condemned livers at slaughter.

According to a veterinarian, as a rough estimation for South Africa, costs associated with preventative drenching in a commercial livestock setting located in *Fasciola* endemic areas are estimated to be R15.00 per animal per annum for cattle in areas where dosing is carried out once a year (using triclabendazole which is effective against all mammalian stages of the fluke's development), while in some warmer areas, farmers are required to dose up to three times a year (using adulticides – drugs effective only against the adult stages of the fluke), pushing costs up to approximately R30.00 per animal (D. Clowes – pers comm.).

Milk production is estimated to be reduced by 0.5 ℓ/day, conception and calving rates reduced by 30% and in beef cattle, rates of growth are reportedly reduced by approximately 14% (Chick et al., 1980). The condemnation of livers at slaughter is estimated to cost the farmer approximately R300.00 per infected animal, assuming a liver weight of 20 kg and a liver price of R15/kg.

Table 11: Some estimated costs of liver fluke to the South African cattle industry

Cost	Per annum cost	Once off cost
Preventative drenching	R15-30 per animal	
Reduced Milk productivity	R500 per infected animal	
Liver Condemnation		R300 per infected animal

It is more difficult to estimate the costs associated with liver fluke in sheep since they are dosed regularly with combination drugs which target a range of parasites. The cost portion attributable to liver fluke is thus difficult to separate from that associated with other parasites.

Aside from the basic estimates of some of the more obvious costs that are presented above, no meaningful assessment of the economic impact of liver fluke disease is possible without national, provincial or regional infection statistics. None of these data are available.

The paucity of information concerning this subject continues the trend established earlier in this report, which suggests that extremely little is known about this parasite or about its invertebrate host. No meaningful conclusions can thus be reached concerning its cost to the country and the potential economic benefit of controlling its snail hosts.

5.3 The cost of manipulating the flow of rivers

A simple assessment of the costs of implementing flow manipulation as a control mechanism for the invertebrate hosts of diseases is presented below. A detailed costing would require detailed site specific research and this does not fall within the scope of this desktop study. For this reason the costing is limited to a basic assessment based on the value of bulk potable water. *It is important to appreciate that this cost analysis did not consider other costs such as those due to the negative impacts on aquatic ecosystems and biodiversity and the impacts on downstream users.*
The cost of flow manipulation implementation will vary in nature according to the different type of manipulation conducted. Two basic manipulation options have been considered here:

1. An increase in flow – a flushing / flooding mechanism, and
2. A reduction in flow – a desiccating mechanism

5.3.1 Increase in flow

Assuming that insufficient excess water is available in a catchment to conduct flushing type control mechanisms, the cost of the water that will be needed to undertake flow manipulation can be calculated by using the value of the saleable water stored in an impoundment[3]. According to Umgeni Water, bulk potable water is supplied to customers (primarily municipalities) at an average cost of R3.48 per kilolitre.

If a test case site is chosen such as the uMgeni river below Albert Falls dam, where the summer daily flow equates to approximately 5 kℓ/second (**January** reading from DWAF website) or 432 Mℓ/day, a

[3] Should sufficient excess water be available, the cost to the water provider will be negligible.

minor flood of an extra 108 Mℓ/day (25% more flow), will cost R15 660.00 per hour (or R281 880.00 per day) in lost saleable water, and a significant flood of 100% additional flow will cost R46 980.00 per hour or (R1.127 million per day). Bigger rivers, such as the Vaal, will cost significantly more to flood.

It is noted however that only selected dams are used to supply treated potable water. Dams which primarily supply irrigation water will be cheaper to use given that the cost of raw water is less than that of treated water.

Table 12: Estimated costs in Rand of flooding the uMgeni river below Albert Falls dam based on the cost of lost sales of treated water.

% Flow increase	R per hr	R per day
25	15,660.00	375,840.00
100	62,640.00	1,503,360.00
200	125,280.00	3,006,720.00

The Tanzanian flushing example of Fritsch (1993) used flooding times of just under an hour for the release of a fixed volume of water. This flood provided a hydrograph of high volumes and velocities at the beginning of the flood, tapering off to natural flow levels after approximately 50 minutes. This time period proved sufficient to effectively reduce snail densities below the impoundment. In the case of regulated rivers in South Africa, the rivers would most likely be significantly larger than the stream in the Tanzanian example. Larger rivers will require larger volumes of water and possibly also longer periods of time in order to be effective.

Because annual wet season flooding has largely been eliminated in regulated rivers, people living downstream of regulating dams may have encroached on the river's natural floodplain, and may also bear some of the costs of a flooded river. The costs estimated for the release of water would need thus to be supplemented by the cost of replacement of any agricultural produce which might be damaged by an induced flood, and costs associated with downstream community safety considerations.

Although costs have not been defined for it, the Lesotho Highlands Development Authority has a procedure in place for warning people who live downstream of their major dams about imminent floods (Unpublished report, LHDA). Flooding may result from water being released from time to time in order to imitate natural flooding conditions as part of Instream Flow Requirements or due to emergency events (in the case of a natural flood during which the dam spills, or in the case of a dam breach). The costs associated with this involve training various bodies such as the police, army and health department staff as to how to co-ordinate a flood warning, supplying VHF radios to communities downstream, posting warning notices at crossing and bathing points and other methods of making people aware of the risk of flooding. Additionally, the costs of managing the flooding process, such as administration costs in deciding when to flood and engineer manpower time, would also need to be taken into consideration.

5.3.2 Reduction in flow

The alternative manipulation mechanism, i.e. reducing the flow will involve a different costing process. A reduction in flows will provide an additional quantity of water to bulk water suppliers that were not previously available, and will thus provide a gain in saleable water. Again, the value gained will depend on the volume of water available in the catchment, since in a catchment with excess water, the gain in real value will be nil. Furthermore, it is assumed that dam capacity will allow for the retention of additional water.

The volume of water gained will depend on how much the flow is restricted by, and the length of time deemed to be necessary in order to effectively reduce the population of invertebrate hosts. Because it may take a significant length of time to dry out backwater habitats and pools, the lengths of time needed for desiccation to be effective may be significantly longer than those required by flooding. Assuming the catchment has less water than is required, the value of the additional water may be expressed as in table 6 below.

Table 13: Estimated value of the gain in saleable treated water through reduction in flow of the uMgeni river below Albert Falls dam

% Flow reduction	R per hr	R per day
5%	3,132.00	75,168.00
25%	15,660.00	375,840.00
50%	31,320.00	751,680.00
75%	46,980.00	1,127,520.00

The extent to which flows may be restricted will be influenced to a large extent by environmental considerations, which will dictate the minimum volume of flow which must be released.

The costs of this flow reduction process may be felt by people downstream of the dam, who utilise the river's waters as a resource. A reduction in irrigation/abstraction potential and mortality of bioresources such as fish may be some of the costs incurred by the residents downstream of the dam. These costs will depend entirely on the site situation, and attempting to estimate them does not fall within the scope of this study.

6. Suggestions for utilizing flow manipulation as part of integrated invertebrate host control

6.1 Introduction

It has been shown many times that the construction of dams influences the distribution and incidence of invertebrate hosted diseases. What is not well documented is the effect the regulation of rivers has on the habitats and lifecycles of these invertebrate hosts. The objective of this report is to investigate these effects where they have been documented, and to assess the possibility of using flow manipulation as part of an integrated invertebrate host control strategy.

This chapter aims to suggest possible flow manipulation control measures that may be implementable for the control of the invertebrate hosts of malaria (mosquitoes), bilharzia and *Fasciola* (both freshwater snails) based on literature examples and the outcomes of a workshop held in Pretoria on the 27th of August 2008. The paucity of information surrounding this particular subject has required that the majority of the ideas and information for this section have come from the workshop where experts discussed the effects river regulation might have on invertebrates and their habitats and then attempted to develop a set of possible flow manipulation situations which may inhibit the invertebrate hosts based on these discussions.

6.2 Possible 'flow manipulation' control options

The discussion regarding manipulating the flow in an attempt to control the invertebrate hosts of disease has been distilled down to the most basic and easily implementable options. These have been discussed under four categories:

→ Implementing a sudden increase in flow
→ Implementing a sudden reduction in flow (even if not to a point of desiccation)
→ A combination of the above
→ A return to a natural flow regime.

6.2.1 A sudden increase of flow – 'river flushing'

A sudden increase in flow volume could be brought about by the release of a larger than normal quantity of water from a dam over a short period of time. This would result in raised river levels and increased flow velocities that would potentially result in a flushing out of invertebrate hosts from previously protected habitats. The increased flow would potentially wash the organisms downstream and disrupt the lifecycles of both invertebrate hosts and disease parasites. It is also thought that increased flow may reduce detritus accumulation and algal growth in the river bed which would reduce the food supply available to snails.

Effect on Mosquitoes

- Mosquito larvae have no way of combating current and therefore could be swept out of shallower pools and vegetated areas that are affected by the flow increase. However, increasing the water level and then reducing it back to its normal flow risks creating more isolated streamside pools and thus increasing mosquito breeding potential after the flood event has passed.

- Case studies of flushing streams clear of malaria mosquito larvae do exist in Sri Lanka (Konradsen et al., 1998), though the species of malaria mosquito which occurs in Sri Lanka (*An. culicifacies*) is known to breed in river channels. This is unlike the primary vector in South

Africa (*An. arabiensis)* which prefers temporary sunlit pools such as rain-filled animal hoof prints (le Sueur, 1990) and would thus not be affected by altered flows.

- *An. funestus* is also an important malaria vector in Southern Africa which does breed in the shaded margins of streams, however its geographical range in South Africa is limited and indeed pesticide spraying has possibly already removed this vector species from South Africa (workshop finding). The immigration of individuals from Mozambique has however occurred (1999) and may do so again.

Effect on Snails

- Snails are sensitive to increased flow velocities and are generally unable to resist flows greater than approximately 0.3 ms^{-1} (Appleton, 1976). It is thought that increased flows may be effective in reducing snail densities in certain areas. O'Keefe (1985) and Woolhouse and Chandiwana (1990) have shown that flood events have catastrophic effects on freshwater snail populations, dramatically reducing their number at any particular locality.

- Woolhouse and Chandiwana (1990) showed that populations of *Bulinus globosus* in a stream in the highveld of Zimbabwe were reduced to almost zero after significant natural flood events. They also recorded that no population in their study recorded growth in abundance during the rainy season.

- A successful case study does exist of using flushing as a control mechanism, where *Bulinus globosus* snails were purposefully flushed from a stream in Tanzania. Fritsch (1993) constructed a flushing weir on a stream in order to be able to flood the stream during the dry season, when snail population numbers were at their highest. This method proved successful, and after successive flushings, no snails were found downstream of the weir in the study area. The project was successful, though impacts on other aquatic biota were not considered.

- It is thought that a periodic increase in flow may also reduce the accumulation of food (algae and detritus) in the quieter areas of rivers. This may reduce the growth and breeding potential of snails.

Discussion

The use of flow manipulation to control mosquitoes is considered problematic due to the short duration of the larval stage of the life cycle. This stage lasts little more than a week and so any flushing control mechanism would need to be repeatedly implemented in a cycle spanning no longer than 10 days, or else the flushing of streams, and the associated creation of stream side pools, risks increasing mosquito breeding potential.

In a naturally functioning environment, snail populations are subjected to increased water levels and accompanying velocities during the rainy season. As is described above, snails are vulnerable to increased flow velocities and prefer habitats where they are protected from greater current speeds. The implementation of a flood/flush mechanism may result in snails being flushed from their sheltered positions. The fate of snails that are flushed downstream (through natural flooding or human intervention) is not well documented. It has been shown that areas are washed clear of snails during periods of high flow, but it is not known if these snails then die, augment existing populations downstream or indeed if they start new populations downstream and thus develop new potential areas for bilharzia transmission. Woolhouse and Chandiwana (1990) indicated that locally, populations may be augmented by passive immigration, but that overall, no populations in their study sites showed an increase during the months of the rainy season.

Although Fritsch's Tanzanian case study (1993) demonstrates that the flushing of a stream is possible and although it is thought that this might prove effective against snails in South Africa, two major stumbling blocks to the implementation of this potentially effective control measure are immediately conceivable.

- The first is the shortage of water available for release from dams. For flushing to be effective, a significant volume of water will be required to alter flow conditions in backwater habitats and in pools that are normally protected from high current velocities. The constant state of water scarcity in South Africa means that the volume of water required to effectively alter habitat and to flush out snail populations would probably not be available.
- The second stumbling block is the effect the manipulation would have on the river's health in general. Any destructive impacts the measures may have on the targeted invertebrate hosts will also be felt by other riverine flora and fauna. This would need to be carefully studied before implementation could be considered.

6.2.2 A sudden reduction in flow

A sudden reduction in the volume of water released from a dam will result in the drying out of habitats located in the marginal areas of streams and rivers, and may result in the desiccation and death of invertebrate hosts living in these habitats.

Effect on Mosquitoes

- It is thought that a reduction in stream flow level and the desiccation of backwater habitats might impact portions of the malaria transmitting mosquito population breeding in stream bodies. In South Africa, this appears to be true only for *Anopheles funestus*, as other species of malaria vectors are not known to breed in streams. However, since it is thought that it would not be possible to dry out isolated pools where the mosquitoes are most likely to breed; this method will most likely be ineffective as a control mechanism.

- The brevity of the larval stage of the mosquito life cycle means that habitats will need to be dried out very quickly. This will not always be achievable as it is thought that pools that form along the margins of rivers will retain enough water long enough for the larvae to reach adulthood.

- Additionally, due to the extremely limited distribution of *An. funestus* in South Africa, a control mechanism specifically targeting these mosquitoes in rivers is unlikely to significantly reduce the incidence of malaria in South Africa.

Effect on Snails

- Snails generally populate the margins of water bodies and avoid the deeper areas where food is scarce and currents are stronger. A rapid reduction in water level will thus affect snails living in the marginal areas of the main water body

- If habitats dry out, the majority of snails living in them will die, though some may survive in damp refuges and through aestivation. Snails are not known to seek out the best habitat for aestivation and desiccation may take place too rapidly for the snails to aestivate in any case.

- O'Keefe (1985) records how drought interrupts snail breeding which, in the tropics, normally occurs all year round under normal conditions. In more temperate regions, there are several identifiable generations in a year (Appleton, 1974), and so the effect of drought on snail breeding may differ.

- Fritsch (1993) describes how rapid drawdown of the water levels in a weir head-pond on a stream in Tanzania resulted in snails being stranded and the population in the head-pond being reduced to nil.

Discussion

Although it is thought that it might be possible to reduce the level of a river sufficiently to kill the snails living along the margins of rivers, it is likely that some individuals will survive through aestivation or in pools that are formed by the receding water. These individuals may well form the basis of a new population once normal flow is restored. This process, however, should result in a significant reduction in the breeding population and if implemented periodically, it may prove effective in maintaining a smaller snail population overall.

A successful case study is documented using this method to control blackfly larvae (*Simulium chutteri*) populations on the Orange river (Howell et al., 1981). It is noted however that the larvae of the blackfly are unlikely to survive in pools since they occupy a niche habitat on rocks, close to the surface, in rapidly flowing water. They are thus considered easier to target using relatively minor water level fluctuations.

A significant issue regarding the implementation of desiccation mechanisms that should be considered is that the reduction in flow is likely to conflict with the volume of water required to be released in terms of the Ecological Reserve. Ecological Reserve allocations are designed to provide the minimum level of flow required to maintain ecosystem integrity. Assuming that the volume of water that will normally be released is based on the minimum requirement determined by the Reserve, a prolonged reduction in this flow is likely to jeopardize the river system's health.

This measure on its own is unlikely to succeed in removing snails and mosquitoes entirely due to the limited time period over which this measure could be implemented. In order for it to be successful, sufficient time for the residual pools to dry out would have to be allowed. The continuation of these pools would act as reservoirs from which, once river levels are restored, surviving individuals could radiate out and repopulate the reach (see "pothole" in Fig. 8 BL). It is thought however that this measure may cull individuals which may help to control the expansion of the invertebrate hosts' populations.

6.2.3 A combination of reduction and increase in flow

This measure combines the effects of both the drying out and flushing methods (discussed previously) on both mosquitoes and snails. It would involve lowering the river level for a period of time, then raising it rapidly so as to flood the channel with the water that was stored during the low flow period. A reduction in the flow of a river over a period of time, followed by a sudden increase in flow may prove effective in first desiccating invertebrate hosts, and then flushing out those that have survived in residual pools.

Effect on Mosquitoes

- The effects of flushing and drying out of rivers on mosquitoes are largely as discussed above.

- Mosquito breeding cycles are likely to be impacted in the short term by this action, however, due to the brevity of their larval stage, the lowering and raising of the water level would need to be conducted at least every 10 days, which is unlikely to be practically possible, in order for it to have an effect in the longer term.

Effect on Snails

- The effects of flushing and drying out of rivers on snails are largely as discussed above.

- It is thought that an initial reduction in stream flow level will either kill the snails living in the marginal areas of the river, or force them to aestivate (though the reduction in level is likely to occur too rapidly for this to happen). The follow-on effect of raising the level will likely flush out those individuals that have managed to survive through aestivation or in the residual pools that have formed.

- It is thought that the combined effect of drying out and flushing might be more effective than using either one in isolation.

Discussion

This combination method attempts to combine the effects of desiccation and flushing and in this way destabilize river margin habitats which are favoured by both snails and some species of malaria transmitting mosquito.

This measure may also be practicable since, while introducing the controlling effects of both desiccation and flooding, it may also circumvent the prohibitive issue of water availability and the issue of the ecological reserve. This is possible since the water that is required for the flood event is initially stored up during the period designed to dry out habitats.

Unfortunately the potential effectiveness of this approach also means that this would be the most detrimental to other biota in the river and thus to the overall ecosystem health. Similar water release scenarios occur during hydropower generation and the damaging effects of these are well documented (Fisher and LaVoy, 1972 and Ward, 1976).

6.2.4 Re-introduction of natural flow variations

It is thought that the re-introduction of natural flow variations will re-introduce natural habitat instability and will reverse invertebrate host population increases that may have come about due to the regulation of flow. This could be achieved by managing the release of water from a dam to mimic incoming fluctuations. Accepting that the dam needs to store a percentage of the water coming into it, the water that is released could be released in synchrony with the varying levels of the incoming river.

Effect on Mosquitoes

- Naturally rising and falling river levels are not likely to negatively impact mosquito breeding since the changes occur infrequently and often over an extended period of time.

- The exception to the above is flooding, the onset of which may occur rapidly. However, the infrequent nature of flooding events means that it is unlikely to reduce mosquito breeding and may in fact provide additional breeding opportunities by creating off-channel pools as flood waters recede.

Effect on Snails

- The natural impacts of floods and droughts are to regulate snail populations and their breeding potential. The reintroduction of natural variability into highly regulated systems may thus reintroduce natural control mechanisms that have been lost through the removal of flood and drought events.

- Habitat stability is considered to be key to the breeding success of freshwater snails (workshop finding). Introducing any form of flow variation will decrease the level of habitat stability.

Discussion

The greatest advantage this measure has over any of the others mentioned above, is the negation of the impacts that unnatural regulated flow may have on the health of the river. By simply re-introducing natural flow variation, any habitat stability that has been unnaturally introduced due to the regulation of flow is removed. Snail populations which have benefited from increased habitat stability are thus once again faced with the natural population controlling events of floods and droughts.

The same cannot be presumed for malaria mosquito populations, both larval and adult. The anecdotal and written evidence of European explorers in Africa who were confronted by malaria suggest that rivers in a natural condition have supported large populations of malaria carrying mosquitoes in this region. The incidence of malaria in South Africa has been significantly reduced over the past 20 years largely through residual chemical spraying, and the extent to which changes in river flow (brought about through regulation) have contributed to this reduction is unclear.

6.3 Integrated control of invertebrate hosts

It is necessary to consider any suggested control mechanisms in the context of any broader efforts to control invertebrate hosts, and the diseases they carry, that are currently in operation in South Africa.

According to the WHO (1980), *Integrated invertebrate host control* is the carrying out of various programmes and control measures (often simultaneously) targeting different stages in the lifecycle of the invertebrate hosts of parasitic diseases.

Integrated vector management (IVM) is a process for managing vector populations in such a way as to reduce or interrupt transmission of disease. Characteristic features of IVM include:

- methods based on knowledge of factors influencing local vector biology, disease transmission and morbidity;
- use of a range of interventions, often in combination and synergistically;
- collaboration within the health sector and with other public and private sectors that impact on vectors;
- engagement with local communities and other stakeholders;
- a public health regulatory and legislative framework.

An IVM approach takes into account the available health infrastructure and resources and integrates all available and effective measures, whether chemical, biological, or environmental.
World Health Organisation - http://www.who.int/malaria/integratedvectormanagement.html

Integrated disease control is a broader concept and includes measures and programmes targeting the various stages of the parasite's life cycle in addition to targeting the invertebrate hosts. This includes chemotherapy of infected individuals and providing prophylactic treatment for individuals who may be exposed to infection.

Integrated Malaria Control

Malaria control programmes in South Africa are currently made up of several components, the majority of which utilise chemical means to kill either the vector mosquito in houses or the parasite in the human body. The overwhelmingly dominant method used outside of the human body involves targeting the vector mosquitoes by spraying the inside walls of houses with persistent insecticides such as DDT and Deltamethrin, which kill mosquitoes on contact. This form of spraying – termed 'Indoor Residual Spraying' – has been particularly effective against *An. funestus*, since this particular mosquito rests indoors during the day (endophilic). The partially exophilic *An. arabiensis* is less so inclined and may move outdoors during the day to find a place to rest (usually on the underside of leaves) and residual spraying is thus less effective against this species.

Residual spraying has been the most effective malaria control measure implemented in South Africa and has been primarily responsible for the decrease in incidence and the spatial distribution of malaria cases. This is largely through the devastating effect it has had on *An. funestus* and *An. gambiae s.str*. According to the MRC, between 2000 and 2004, malaria incidence reduced by 90% in KwaZulu-Natal, 65% in Mpumalanga, 90% in Swaziland and parasite prevalence by 88% in children in Southern Mozambique (Malaria Research Programme website – http://www.Malaria.org.za/MRP/Research/Lubombo SDI/ lubombo_sdi.html). The majority of this work forms part of the Lebombo Spatial Development Initiative (LSDI). This programme is attempting to eradicate malaria from the trans-frontier area around Northern KZN, Southern Mozambique and Swaziland. Residual spraying, such as those implemented under the LSDI, in conjunction with chemotherapy measures are proving successful in reducing the number of malaria cases in South Africa and across our borders.

There has also been extensive research into the use of insecticide treated bed nets (ITBNs), not only as an additional malaria control measure, but also as a possible alternative to residual spraying. A collaborative study between the MRC and the Department of Health produced encouraging results (Mnzava et al., 2000) with significantly larger reductions in incidence experienced in studied areas equipped with nets when compared to similar areas treated only by spraying. The re-treatment of nets with insecticide has proved to be a problem in some areas, but the advent of long lasting insecticide treated nets means that nets only have to be re-treated every 3 years, significantly improving the overall efficacy of the method.

The treatment of individuals infected with malaria obviously also plays an important part in the integrated control of this disease. Infected individuals are a source of further infection for the area concerned, and quick successful treatment limits the time period in which the person remains infectious. Infected individuals are treated with a variety of antimalarial drugs, usually in a combination of two independently effective components. The majority of treatments recommended by the WHO are Artemesinin based Combination Therapy (ACT) treatments. The combination of two independent components is designed to avoid, or significantly delay the development of resistance in the parasites to either of the drugs (http://www.who.int/malaria/docs/TreatmentGuidelines2006.pdf).

Chemoprophylaxis is also part of the integrated control of malaria. Preventing the onset of malaria reduces the pool of infectious individuals, and helps to break the cycle of infection. According to the guidelines for malaria prevention published by the Department of Health, various drugs are available in South Africa, with the most commonly used being Mefloquin, Doxycycline and a cocktail of Chloroquine and Proguanil. Some of these drugs attack the erythrocytic stages of the parasite (once it has invaded the blood stream) and are known as suppressive prophylaxis, whilst others attack the pre-erythrocytic form within the liver, and are known as causal prophylactics.

Environmental management is a control measure that is not given a great deal of coverage in the malaria literature in South Africa. This could be due to the overwhelming success and controversy surrounding the residual spraying of persistent insecticides such as DDT and Deltamethrin. It may also be a result of the fact that in South Africa, malaria mosquito breeding habitat is particularly difficult to target on a large scale using environmental management methods. *An. arabiensis* in particular does not utilise larger open bodies of water such as borrow pits or trenches which could be filled in, but is extremely opportunistic and will breed in any small temporary water body.

6.3.1 Integrated Schistosomiasis (Bilharzia) Control

Based on the results of the literature review and the outcomes of the workshop, it is apparent that bilharzia control in South Africa is limited to applications which target the human related phase of the parasite's lifecycle. According to the Department of Health's website, this is limited to chemotherapy treatment of infected individuals and educational campaigns to alter individual's behaviour and personal hygiene regimes. There are no co-ordinated control programmes in existence which target the snail hosts of either *S. haematobium* or *S. mansoni*.

Current chemotherapy programmes are limited to 'ad hoc' treatments at clinics and utilise the drug praziquantel to target bilharzia parasites predominantly in school children. Schools are selected for mass treatment according to infection rates, and children are dosed from once every 2 years to twice a year in isolated cases, depending on the intensity of their infection.

A great deal of research has gone into the development of effective synthetic molluscicides which could be used to control freshwater snails in bilharzia areas. Although effective molluscicides such as Bayluscicide have been in existence for a long period of time, the costs of application appear to limit its application in mass control programmes, as does the potential for wider negative impacts on the environment. A significant body of research has also developed around the search for local plant molluscicides. It can be said however, that molluscicides play no part in co-ordinated integrated bilharzia control programmes in this country, largely since programmes such as these do not exist.

6.3.2 Integrated Fascioliasis (Liver Fluke Disease) Control

As with the control of schistosomiasis, the control of fascioliasis in South Africa appears to be limited to ad hoc chemotherapy of the terminal hosts (mostly livestock in South Africa), targeting the adult fluke. In livestock, flukicides such as Oxyclozanide and Fenbendazole are generally used, with farmers drenching once or twice a year depending on the intensity of infection (D Clowes – pers com).

Very few cases of human infection have been recorded in South Africa, and no creditable literature recording methods of control targeting the snail hosts of this disease (*Lymnaea natalensis* or *L. truncatula)* could be found. Control of these snail species, as part of a co-ordinated, integrated control programme for liver fluke disease, is not operational in South Africa.

6.4 Discussion

6.4.1 Timing of flow events

An important factor to consider in the implementation of flow manipulation control measures is the timing of the implementation. It is thought that selecting a strategic time of the year when snails are particularly vulnerable may influence the efficacy of the measure.

Unfortunately, very little is known about the effect flood and drought events have on the life cycles of invertebrate hosts in rivers. In the Fritsch case study (1993), it is shown that snail densities are greatest during the low flowing drier months of the year, and flushing proved to be most effective in reducing this density to zero, although at this time a high flow would also be the most ecologically damaging. According to O'Keefe (1985), snails breed all year round in the tropics, the exceptions to this being during periods of drought and flood. Temperature is known to play a role in the rate of increase with relatively warmer conditions favouring rapid increases in abundance. However, habitat stability is important, and as is seen in the Tanzanian example (Fritsch, 1993), and as is demonstrated by Woolhouse and Chandiwana (1990) and O'Keefe (1985), it is when riverine habitats stabilise in warm drier months that densities are able to increase significantly.

Little can be recommended regarding the timing of flow manipulations other than to recommend that focused research be carried out on the triggers which drive the life cycle of the invertebrate hosts in rivers. If this is understood, a clearer strategy may emerge as to using flood events or low flow periods to manipulate the population densities of invertebrate hosts. It will be important though, to consider any conclusion together with the impacts that are experienced by the rest of the biota in the river and thus the overall river health.

6.4.2 Frequency of flow events

Also of importance would be to establish the frequency of implementation required to make flow manipulation most effective. In Fritsch's Tanzanian example (1993), in the first year of implementation, the river was flushed three times, at intervals of seven and forty five days. The snail population was reduced by 77% for *Bulinus* spp and 66% for *Biomphalaria* spp after the first flushing, and the subsequent flushings maintained the populations at low levels. A little over two months after the last flushing however, the population had recovered to its original levels. In the second year of implementation, the flushing was implemented repeatedly (46 events in total) at between one to eleven day intervals. This frequency of events resulted in the population being reduced to nil.
In the *Anopheles* mosquito breeding cycle, the larval stages last approximately 10-12 days, so flushing events will be required to be repeated at least every 10 days to ensure that breeding success is reduced. Should this not be done, flushing events may in-fact favour the breeding of mosquitoes, as the receding flood water will leave residual pools behind providing additional breeding habitat.

It is clear that the frequency of the implementation of flow manipulation events has a major role to play in the efficacy of the flow manipulation event being used as a control measure. It is however acknowledged that the relationship between event frequency and invertebrate abundance is poorly understood and that the effects of frequently raising or lowering the water level on the river ecosystem are not well studied in the context of South African rivers. The most significant literature on this subject is in relation to hydropower generation and suggests that this practise is highly detrimental to river health (Fisher and LaVoy, 1972 and Ward, 1972).

6.4.3 Effectiveness of flow manipulation control mechanisms

It is clear from literature that single control measures, on their own, are unlikely to be effective in controlling diseases and their invertebrate hosts in the long term. Even currently successful measures such as residual spraying for mosquitoes will, due to resistance built up in mosquitoes, ultimately be unsuccessful if not implemented in co-ordination with other measures such as education, personal behaviour alteration (such as the use of mosquito nets and not urinating in rivers in the case of bilharzia), effective chemotherapy for infected individuals and environmental management.

In this chapter, it has been considered whether flow manipulation in regulated rivers might be effective as one part of an integrated control strategy. In the light of the findings of the workshop, and the literature review concerning current control programmes in operation in South Africa, it is suggested that flow manipulation will, in comparison to existing chemical based methods (spraying and insecticide treated nets), have little impact on the incidence of malaria in South Africa, and thus is unlikely to play a role in the integrated control of the disease. Due to the fact that *Anopheles arabiensis* is an opportunistic breeder and prefers small temporary rain-filled water bodies such as animal hoof prints in which to breed (le Sueur, 1991), it is unlikely that their breeding success will in any way be compromised by the manipulation of regulated river flows. *Anopheles funestus* may possibly be impacted by the manipulation of river flows, but this species' range is extremely limited in South Africa and it is thought that it may have been driven out of South Africa altogether by residual spraying, although immigration from Mozambique is known to occur (workshop finding). It is thus proposed that the manipulation of regulated river flow would prove ineffective in significantly reducing the breeding success of malaria carrying mosquitoes in South Africa.

Freshwater snails which are responsible for the transmission of bilharzia and liver fluke disease are vulnerable to desiccation as well as increased water velocities. This fact has been highlighted by several authors (Appleton, 1975; Fritsch, 1993; Woolhouse and Chandiwana, 1990) and this serves to indicate that manipulation of flow may be effective in limiting the abundance of snails in regulated rivers. Flooding especially presents a problem which snails in naturally functioning habitats are generally not able to overcome due to the suddenness of the onset of flood events. Floods thus appear to play a major role in the natural regulation of snail abundance in rivers. The lowering of water levels in a dry period would be equally effective in reducing snail population numbers if it were to occur with equal suddenness, as is shown by Fritsch (1990) who demonstrated this using rapid draw-down of a weir headpond (during a natural dry period, river levels would take weeks to lower, allowing snails the time to follow the receding water level). It is proposed thus that the rapid manipulation of water levels could possibly be effective in reducing the numbers of snails present in river systems.

In the case of bilharzia, it thus appears as if manipulating flow levels in regulated rivers may well have a limiting effect on the populations of intermediate host snails, and this, implemented in conjunction with chemotherapy and education programmes, may be effective in reducing the disease burden attributable to bilharzia along regulated rivers.

The assessment of the applicability and efficacy of flow manipulation as part of an integrated control strategy for the liver fluke parasites which occur in South Africa, *Fasciola hepatica* and *F. gigantica,* is made difficult by the lack of published research concerning the distribution and epidemiology of this disease. More importantly from this report's point of view, very little information is available concerning current control efforts, almost all of which centres on chemotherapy for livestock. This is perhaps a reflection of the very low numbers of cases of human fascioliasis recorded in South Africa. 'Integrated' control of fascioliasis and its intermediate hosts is assumed to be limited to individual farmers manipulating the access livestock has to marshy environments, draining and canalisation of wetlands on their properties and drenching of their livestock with flukicides.

Flow manipulation control measures, especially flushing mechanisms, may, as in the case of bilharzia snails, have a limiting effect on the populations of *Fasciola* intermediate host snails. Desiccation may be less effective than for bilharzia snails due to the amphibious nature and greater aestivation ability of some Lymnaeid snail species. Flow manipulation measures however may introduce an element of regional control in the absence of anything else. If effective, however, its benefits will be restricted to livestock farmers located along regulated rivers.

6.5 Recommendations

The objective of this report is not to recommend that any particular control measure be implemented, but to identify flow related control measures that may disadvantage the invertebrate host populations of the three diseases concerned and which may contribute to the integrated control of these organisms. The four options outlined earlier in this chapter represent the outcomes of this objective. All four of these options will inevitably impact the populations of disease invertebrate hosts in some way, but they will vary in their potential efficacy as a control measure, their potential negative impact on the broader river health, and in their practicality of implementation.

The measures suggested above have been considered through a detailed literature review and an expert workshop and arrived at after debate and discussion. No field research has been undertaken in arriving at these suggested measures. The efficacy of these proposed mechanisms in controlling the density and distribution of the invertebrate hosts of diseases, and the incidence of the diseases themselves is unknown. It should also be noted again that the effects of any form of stream flow manipulation will not be limited to invertebrate hosts of disease, but will be experienced by the entire cross section of fauna and flora in the river system. It is therefore the recommendation of this report that these potential options, and their broader impacts, become the subject of focused research projects, and that this be undertaken as the next step in assessing the theory that flow manipulation can be used to control the intermediate hosts of disease in regulated rivers in South Africa.

7. The impact of river rehabilitation on the transmission of the parasites

7.1 Introduction

7.1.1 The definition of river rehabilitation

River rehabilitation (sometimes called restoration) is the process by which projects return the structure and function of a degraded river ecosystem to the closest achievable approximation of its natural (pre-impact) state, mostly through physical alteration of the form and nature of a river's channel and adjacent environment. Rehabilitation projects generally focus their efforts on specific reaches of a river, but may also involve efforts to restore water quality and quantity arriving from upstream of the project reach.

This is in contrast with river remediation, where the goal is not an endpoint which resembles its original condition, but improvement of the ecological condition of the river (Breen and Walsh, 1999 – as reported in Uys, 2003). This is usually based on an improvement of one or two parameters of the riverine environment.

7.1.2 River rehabilitation in South Africa

Globally the discipline of river rehabilitation has been developing over the last few decades, but in South Africa, river rehabilitation is an emerging science, with very few true rehabilitation projects having been undertaken and documented. Those that have been undertaken tend to have been carried out on an *ad hoc* basis which has done little for the development of a formal discipline in South African catchment management (Uys, 2003).

Some of the projects which have been documented as rehabilitation projects cannot strictly be classified as such, since their goal was not the re-establishment of the river's natural ecosystem, but rather, simply cleaning up the river banks and 'greening' the urban environment. Other 'rehabilitation projects' can be better described as river remediation projects, with the restoration of individual aspects of the river's health being the focus.

Case Study: Davies and Day (1998) have documented an attempt at a true rehabilitation project on the Liesbeek River in Cape Town which involved trying to deconstruct the structures and effects of canalisation and return the river to a more natural state. Their efforts were met with resistance from municipal engineers, and the final result was a compromise more akin to remediation that rehabilitation. This consisted of a series of 20 holes that were drilled through the concrete (1 m in diameter) to allow the river to connect with the hyporheos, and a series of six small weirs, which allow the river to pool in certain places, offering a wider range of habitats. Despite the simplicity of the final resulting changes, invertebrate species diversity increased from 7 species to 35 in a matter of months.

There is also currently no process in South Africa to incorporate the discipline of river rehabilitation into any aspect of formal integrated catchment management or water resource management. According to Uys (2003) the major challenges facing the formal introduction of a river rehabilitation programme into South Africa include:

- a poor understanding of what rehabilitation actually means,
- the paucity of research attention and funding directed towards it,
- the lack of a scientific basis for rehabilitation and

- the dominance of traditional engineering approaches over innovative bio-engineering techniques.

Nevertheless there exists a great opportunity to implement river rehabilitation in the process of satisfying the requirements of the Water Act (1998) and the principles of the Ecological Reserve where it becomes necessary to improve the Ecological Category of a river in order to achieve a particular Management Class.

The Ecological Reserve, as introduced in the National Water Act, requires that water resources are maintained in a condition to be decided upon via the process of the Water Resources Classification System. In many cases, as so many rivers are already stressed in terms of having excessively reduced water quantity and also quality, this may mean that a river needs to be remediated or rehabilitated to return it to its Management Class. The actual targets of this rehabilitation will be as defined in the Management Class and in the Resource Quality Objectives.

Currently however, the majority of work involving aspects of river rehabilitation is conducted under the auspices of other initiatives and consequently it does not attract attention as a field in its own right (Uys, 2003). Some of the best known initiatives which are linked to or could be linked to river rehabilitation type work are the River Health Programme, the Working for Water Programme and the Working for Wetlands Programme.

a. **The River Health Programme** aims to serve as the source of information regarding the ecological state of rivers in South Africa, and thus is well placed to inform the understanding of the need for rehabilitation activities. The basis of the programme's river health evaluations are biological indicators which provide a direct and integrated measure of the health of a river.

b. **The Working for Water Programme** is a combined catchment management and social upliftment programme which was launched with the dual goals of reducing alien plant pressure on South African river catchments whilst additionally providing employment for marginalised sectors of society. The removal of alien species is an important element of river rehabilitation, and the most common element practiced in South Africa.

   A great deal of work has been done on the impact of alien species on the watercourses of South Africa, and on methods of their removal. The benefits of their removal are – Increased water volume, restoration of riparian ecosystem functioning and buffering of aquatic ecosystems through erosion control.

c. **The Working for Wetlands Programme** is a programme which champions the protection, rehabilitation and sustainable use of South Africa's wetlands. Wetlands are important sources of water for many rivers, and improving their condition indirectly improves the condition of these rivers through improved flow levels.

Because river rehabilitation is a relatively unknown concept in South Africa, documented research is difficult to find. For the purposes of this project, the definition of river rehabilitation has thus been limited to simply improving the overall condition of a river, which as has already been discussed, is termed river remediation.

7.2 River remediation with reference to regulated flow

An 'improvement in river condition' can encompass a wide range of improved conditions in a river which may come about as a result of an equally wide range of improved management practices.

Since the focus of this project is the effect that regulated flows have on the invertebrate hosts of diseases, it is appropriate to focus the discussion on the improvement (remediation) of river flows. ***For the purposes of this report it is assumed that the improvement in river condition envisaged is based on a remediation of flow regimes in regulated rivers***.

An improved flow regime is defined here as one which provides flow levels which better approximate natural flow conditions. This includes floods (large pulses of high flow during wet season), freshes (smaller pulses of high flow in wet and dry seasons), and periods of low flow during droughts (King, in Tharme and King, 1998).

In most cases in South Africa, river flow remediation is achieved by changing river and catchment management strategies such as removing alien plants from river banks, managing abstraction volumes and changing the timing and magnitude of flows released from dams. The programmes outlined above, such as the Working for Water Programme, implemented together with the National Water Act, are by and large the vehicles currently used for mobilising this type of work. In the future, as the Ecological Reserve begins to be implemented, the release of water from dams will become a major driver of rehabilitation efforts.

Before the effects of this type of improvement on the invertebrate hosts of diseases and their habitats can be discussed, it is useful to outline the effects that flow regulation has on river health and habitats.

7.3 The effect of regulated flows on river health and habitats

Dams have a great effect on the ecology of rivers, and the regulation of flow is widely documented as disrupting natural processes which determine the form and function of a river (Ward et al*.,* 1983, King, in King et al*.,* 2000). The nature and extent of this disruption varies greatly according to the release regime implemented by the dam management authority, which in turn depends on the intended function of the dam. A good example is a hydro electric dam, which releases water in response to varying daily electricity demands. As the volume of water released changes, the flow below the dam fluctuates accordingly, changing the forces at work in the river and the habitats available to biota.

Another good example is Albert Falls dam in the uMgeni catchment in KwaZulu-Natal. This dam is used to provide water to supplement downstream Nagle Dam particularly during the drier winter months, and flow levels in the uMgeni river between these two dams are thus elevated in the dry season (winter) rather than in the wet season (summer). This situation alters the downstream ecosystem in numerous ways as was documented by Dickens et al. (2007).

The effects of regulating dams are dissipated over distance from the dam, and diluted by the tributaries joining the main river (Stanford and Ward,2001; Dickens et al., 2007). In a situation where many streams join the main channel shortly after the dam wall, the recovery of the river to a situation resembling natural conditions may be relatively quick.

The potential effects on disease vectors of the following regulated flow scenarios are briefly considered in this report as part of background information. Due to the paucity of hard information describing these effects, the results below are mainly the result of an “expert workshop” held at the WRC headquarters in Pretoria on the 26th of August 2008. Situations that were considered include:

- → Consistent reduced flow during the rainy season
- → Consistent reduced flow during the dry season
- → Consistent increased flow during the rainy season

→ Consistent increased flow during the dry season
→ Variable hydro-power dam releases (daily variations)

i. **Reduced flow during the rainy season** will generally result in a more stable habitat, with reduced flow variability and flooding frequency. This will have the effect of allowing more bankside vegetation to become established, providing shaded areas in the water course, and providing refuge habitats for biota. The decreased flow will also lessen the physical removal of many species of biota that may normally be washed away by strong currents. This may allow species not normally present in a system to become established. In this way diversity of species may actually increase in a reduced flow situation provided that the original naturally occurring species are not excluded. This has been documented by Tharme in Tharme and King (1998), and by Armitage (2006). Because however, the new community that develops after flow is regulated most likely develops in the absence of major flow perturbations, it is thought that it will be dynamically fragile and sensitive to any further changes in flow regime (such as those which may be brought about through flow remediation) (Armitage, 2006).

A decrease in flow and a limitation of scouring floods may lead to a build-up in fine sediments and detritus contributed by tributaries downstream of the dam. This may alter the geomorphology of the river bed by filling in the spaces between coarser gravel, pebbles and rocks and thus may alter the in-stream habitat profile. Less flooding also leads to the accumulation of in-stream vegetation, which will significantly alter the in-stream habitat especially in the case of snails.

Flood events often act as triggers that initiate spawning in fish. A reduction in the frequency of floods will in many cases reduce the opportunities for fish to breed.

Slower steadier flow is expected to also allow greater in-stream heating but this will be countered by generally cold water releases from dams. The water released from dams is generally less variable in temperature than water in unregulated rivers, which increases the stability of the river habitats downstream of the dam.

Lack of seasonal flooding and the reduced deposition of nutrients will most likely reduce effective seed dispersal of plants and increase seedling desiccation in floodplain areas (LeRoy Poff et al.*,* 1997).

The fact that regulated rivers flood less frequently also encourages people to live closer to the river banks. This may result in more bankside vegetation being removed and less shaded area occurring along the water course in inhabited areas. This may affect the temperature of the water as well as the availability of refuge habitats for biota.

ii. **Reduced flow during the dry season** will mean a reduction in a river's wetted width, reducing in-stream habitat availability. Tharme (Tharme and King, 1998) suggests that in many cases, the reduction in wetted area is roughly proportional to the reduction in volume/flow. It may also result in the loss of important back water / isolated pool habitats. Depending on the nature of the dam's operation, water flow may cease entirely during this period, resulting in an almost total loss of habitat.

As with reduced flow in the rainy season, instream habitat changes may result in new habitats being made available (often at the expense of others) and a possible increase in biotic diversity.

Also similar to reductions in flow during the rainy season, reduced flow during the dry season will also mean a build up of finer sediment particles filling the spaces between pebbles and rocks, covering hard substrates and thus further altering the in-stream habitat profile.

Reductions in flow may also result in elevated water temperatures due to greater in-stream heating (Pitchford and Visser, 1975).

iii. **Increased flow during the rainy season** will result in increased current velocities, which will change the nature of in-stream habitats in the watercourse. For example, prolonged increased flows will result in a loss of riffle habitat. It will also result in a lateral expansion of the river's wetted area, possibly providing additional habitat. Reductions may also occur in the amount of bankside vegetation present due to inundation and flooding.

According to Pitchford and Visser (1975) and Dickens *et al.* (2007), dams narrow the range of temperatures found in the river downstream of the dam over the course of a year, increasing the minimum temperature and decreasing the maximum temperature. Assuming the rainy season is also the hotter season, increasing the flow during this period may result in a reduction in the water temperature.

iv. **Increased flow during the dry season** will potentially result in many of the same impacts as those associated with increased flow during the wet season such as more habitat area being made available, since the river will occupy a greater area, and habitats such as riffles being reduced. Current velocities will increase in the main channel, and dry season low flows will be prevented, thus increasing habitat stability. This may result in new species becoming established which would previously have been eliminated by lower flows.

Increased current velocities will mean a decrease in the deposition of detritus and sediment, over a period when, in a naturally functioning system, deposition could normally occur. This may alter the geomorphology of the river and consequently the range of in-stream habitats.

In systems where high flows act as trigger mechanisms for the breeding of fish, increased flows during the dry season could result in an alteration of the timing of fish spawning.

Temperature levels may be adjusted by isothermal dam releases. In most cases the dry season will occur during winter, which, according to Pitchford and Visser (1975), will mean that temperatures will be shifted upwards.

v. **Variable hydro power dam releases** result in greatly unstable river habitats. This effect is well documented (LeRoy Poff et al., 1997; Otto, 1993) and is shown to be highly detrimental to natural ecosystems.

The deleterious effects of varying hydropower releases are noticed over much greater distances downstream in the river than the effects caused by other types of impoundments (Otto, 1993). The most notable effects are a high mortality rates amongst aquatic species due to physiological stress brought about through repeated stranding and washouts (LeRoy Poff et al., 1997). This is most noticeable in shallow edge habitats, where water level fluctuations result in drastic changes from aquatic to terrestrial habitat.

Ecologically, the rivers affected by variable releases are likely to become dominated by generalist species, with specialist species being suppressed or eliminated (LeRoy Poff et al., 1997).

7.4 Consequences of river flow remediation for invertebrate hosts

The transmission of diseases like malaria, bilharzia and liver fluke disease is directly linked to the biology of their respective invertebrate hosts. The objective of this chapter is to examine how the remediation of rivers may affect the transmission of these diseases. This is directly linked to the success or lack thereof of the populations of the respective invertebrate hosts in the remediated river.

The recipe for success for these invertebrates has been looked at in some detail in terms of their habitat requirements (see chapters 2 and 5). The remediation of flow in regulated rivers will have a marked effect on aquatic habitats, and it is thought that these effects may have knock-on consequences for the degree of success or failure of invertebrate host populations downstream of dams. This will influence the potential for the transmission of the three diseases which are the subject of this report.

7.4.1 Remediation of water quantity

Improvement in the supply of water to a river can be achieved through initiating more natural release patterns from regulating dams, and through the removal of alien vegetation from riparian areas in the river's catchment. The remediation of flow levels in a river will mean a pattern of release mimicking natural floods and droughts.

The majority of impacts which may result from improved flow management, and which may affect invertebrate host populations, are likely to be related to stability of riverine habitats and the associated increase or decrease in suitable habitat. This may come about as a result of the expansion or reduction in wetted area or through the change in nature of instream habitats brought about by changes in current velocity. Tharme (in Tharme and King, 1998) recorded increased levels of invertebrate diversity during the period of lowest baseflow during a natural dry period. This is reversed during the wetter months when flow is increased. She also reported that during extreme unnatural reductions in flow (84% reduction), diversity decreased markedly.

With respect to invertebrate hosts, perhaps the most important change brought about by the re-introduction of natural flows is the associated habitat instability which will result. According to the findings of the project workshop, habitat stability is a key factor in a freshwater snails' suite of habitat requirements. Remediation of flows will destabilise the unnaturally stable regulated flow, flow volumes and velocities will become variable and incidents of high flow will prove limiting to the growth of freshwater snail populations (Appleton, 1976; De Kock et al*.,* 2004; Fritsch, 1993; Woolhouse and Chandiwana, 1990)).

Mosquito populations may in fact benefit from the reintroduction of naturally variable flows. Receding flood waters will leave behind residual pools and isolated water bodies which may provide additional breeding sites. The degree to which this will be true of malaria mosquitoes in South Africa is questionable, firstly due to the propensity of *An. arabiensis* to utilise temporary habitats away from rivers, and secondly due to the very small current geographic distribution of *An. funestus* in South Africa.

7.4.2 Remediation of temperature

It is well documented that dams have an effect on water temperatures in the river below the dam. This is known to comprise a narrowing of the seasonal ranges, with increased minimum temperatures and decreased maximum temperatures (Pitchford, 1975; Dickens et al*.,* 2007). In more modern dams, this change in temperature can be mitigated against through the release of water from varying depths in the dam. Re-introducing the natural range of temperatures will re-introduce seasonal variation and instability into the river habitat downstream of the dam. Depending on the climate / ambient conditions below a particular dam, increases or decreases in temperature due to changes in the dam's water release temperature may favour or disfavour invertebrate populations.

Temperature changes may have an effect on snail population dynamics. It is well documented that temperature plays a role in determining the natural rate of increase of freshwater snails (O'Keefe, 1985; Shiff, 1964; Harrison and Shiff, 1966; Hairston, 1973), with the optimal temperature for growth and breeding in *Bulinus globosus* being determined as 25°C. Therefore, the closer the temperature of a dam's released water is to 25°C, the more suitable the downstream habitat will be for *Bulinid* snails. The same is true of *Biomphalaria pfeifferi* at between 22-27°C (Appleton, 1977; De Kock et al., 1986). If the narrowing of seasonal temperatures is mitigated against, and the natural seasonal temperature variation reintroduced, this will destabilise the regulated river habitat slightly which may disadvantage snail populations living in areas where the temperature range is marginal for their success.

It is also documented that warmer water increases the rate at which mosquito larvae mature (Mwangangi et al., 2007). Largely though, *An. arabiensis* use rain filled pools in which to breed (le Sueur, 1991), and since these pools are largely independent of rivers, and are warmed by the sun, changes in river water temperature brought about by dam releases will in most cases be inconsequential.

However, in a study conducted in the USA, Vinson (2001) looked at the effect the introduction of a multilevel intake mechanism (and thus the partial remediation of downstream temperatures) had on macro-invertebrate composition in a river below a major dam. The construction of the dam had resulted in a decrease in invertebrate taxa from >70 to <30, whilst invertebrate density remained the same. Twenty years after partial remediation of the river's instream temperature, contrary to expectation, species richness remained unchanged despite the mean summer temperature increasing from 6°C to 12°C, and the number of annual degree days increasing from 2340 to 3200. This was ascribed to the dominance of other invertebrates which had established themselves after the closure of the dam, and also possibly to differences that remained in the thermal cycles despite remediation.

Power et al. (1995) describe how biological factors such as food web interactions need to be given consideration when trying to understand the effects of the regulation of rivers, and not just physical factors such as flow, geomorphology and temperature. Temperature remediation on its own is thus shown to not necessarily make a major difference in the composition or abundance of invertebrates in regulated rivers.

7.4.3 Geomorphology

In a river which becomes regulated, the geomorphology of the channel may be altered in a number of ways. According to Merz et al. (2006), in regulated rivers, sediment load is rarely transported past large dams. In these cases, sediment-starved flow can erode the channel bed and banks, producing channel incision, bed material coarsening, and gravel loss. Upon reintroduction of periodic high flow events (remediation of flows), the additional sediment-starved water may exacerbate this erosive effect since the river's sediment load remains trapped behind the dam.

The opposite effect has also been described but primarily further downstream from a dam, whereby the absence of scouring floods means that deposition and build-up of fine sediment and detritus causes a narrowing of the river channel, and the altering of the nature of the channel bed from a harder substrate to a softer one (Grams and Schmidt, 2002). Which of these two scenarios actually plays out will depend largely on the nature of each individual reach of a river, its channel morphology and flow regime.

In either scenario, remediation of flow might not necessarily result in a remediation of the channel's geomorphic processes and form. Sediment hungry water released from a dam may, if released in naturally fluctuating volumes, result in excessive erosion and channel incision. This may reduce bank-side vegetation and reduce invertebrate habitat area.

In the latter scenario (absence of scouring floods leading to deposition and narrowing of the river channel), the build-up of detritus might benefit snails though providing a greater supply of food. However the build-up of soft fine sediment would most likely disadvantage Bulinid snails as this may cover their preferred substrate (firm surfaces such as rock and vegetation stems) and their food. It is thought that soft muddy substrates will also reduce the opportunities for egg laying. This is thought to be less important for the Lymnaeid snails which are often found on softer substrates (Workshop finding). Additionally, the build up of sediment may result in the filling in of refuge habitats such as gaps and cracks between rocks (workshop findings) thus exposing snails to conditions of the main river channel.

In this case, an improvement in the geomorphology of the river channel brought about by an improved flow regime may benefit snails in that it would make more suitable substrate and refuge habitats available for snail subsistence and breeding. It may at the same time disadvantage them, since the accumulation of food brought about through regulated low flow deposition may then be limited.

It is unknown how changes in channel geomorphology will affect mosquito populations below a dam. It is thought that it is possible that changes in bankside vegetation and backwater habitat may occur, especially if the erosive nature of the river is accentuated by the introduction of a 'natural' flood pattern, but the extent of this effect will depend to a large degree on the nature of the water course below the dam.

7.5 Discussion

The impacts of the remediation of rivers on the invertebrate hosts of these three diseases are not well researched. The existing literature concerning the rehabilitation of rivers does not to any significant degree examine the effects that rehabilitation will have on specific groups of invertebrates. Added to this, the body of literature surrounding the rehabilitation of South African rivers is extremely small owing to the very recent arrival of this concept on our shores. Together, these facts make the desk-top research of this topic extremely difficult, and in many cases, highly subjective, being limited to expert opinion.

In general, the remediation of river flows may well change the conditions that snail populations utilise below dams. These changes (positive or negative) will only however affect the portion of the river below the dam before its natural conditions are re-set by the contribution of tributary inflows. This distance may differ for each situation and is dependent on the nature of tributary contributions downstream.

8. Review of the predictability of the occurrence of invertebrate hosts in South Africa

8.1 Introduction

Predicting the presence/absence of the invertebrate hosts of malaria, schistosomiasis and fascioliasis in a given waterbody is not easy. There are no predictive models based on ecological or habitat-related variables at a small enough scale for any of them. Prediction therefore has to rely on whether or not the waterbody in question lies within the relevant disease's endemic area (or risk zone if available) and is suitable for colonization by the relevant invertebrate host.

If these constraints are satisfied, and if the habitat is situated close to human habitation, it should be considered a potential transmission site but of course for malaria, the biting and resting behaviour of the adult mosquitoes and various parasite-related factors come into play here as well. Not only is transmission of these diseases patchy but certainly for schistosomiasis the range of the snails is wider than that of the disease – a fact recognized by Porter in 1938 when she produced the first detailed map of the disease in South Africa. The same is true for malaria (R. Maharaj, pers. comm.) but this may be in part due to the control programme.

The geographic distributions of the invertebrate hosts under discussion are determined by their tolerances of environmental conditions and the availability of suitable habitats. The former also affect the occurrence of the relevant parasites' stages inside these hosts. However under certain conditions such as exceptionally high rainfall, malaria transmission may spread in the form of localized epidemics to the basins of the Molopo and Gariep (Orange) rivers in Northern Cape and Northwest provinces and the construction of irrigation schemes in non-endemic areas may result in the spread of schistosomiasis. Ranges may also retract as has happened for malaria in KwaZulu-Natal and urinary bilharzia in the Eastern Cape.

Human movement is another feature of the South African landscape and should be expected to facilitate outbreaks or epidemics of disease in previously unaffected areas. The southwards movement of infected labourers building the railway line down the KwaZulu-Natal south coast coupled with unusually high rainfall led to the area being colonized by vector mosquitoes (species uncertain) and the serious malaria epidemic of 1930 (le Sueur et al., 1993). Migrant fishermen from either KwaZulu-Natal or the former Transkei were thought responsible for the unpredicted outbreak of urinary schistosomiasis in the Kabeljous River at Jeffrey's Bay, Eastern Cape, in 2002 (C.C. Appleton, unpublished data).

The national Department of Health and the South African Medical Research Council have devised a risk map for malaria dividing the endemic area of the country into zones of high, moderate and low risk. This map can be found on www.malaria.org.za or www.doh.gov.za / www.health.gov.za. The distribution of both schistosomiases and their intermediate host snails are given in the *Atlas of Bilharzia* (Gear et al., 1980) (see below) and Appleton & Kvalsvig (2006) gave a preliminary estimate of risk zones for schistosomiasis.

Since malaria control programmes are in place in all affected provinces in South Africa, they will influence the occurrence of vector mosquitoes in waterbodies within the endemic area. There are however few, if any, proven cases of malaria vector mosquitoes being eradicated from even parts of their natural ranges by control programmes, and indeed their aim is to control rather than eradicate. Even if a species appears to have been successfully targeted (controlled), it may well reappear if the programme stops or is scaled down. Thus both *An. gambiae s.s*. and *An. funestus* were 'eliminated' from northeastern KwaZulu-Natal by indoor spraying of DDT but *An. funestus* reappeared from

Mozambique in 1999 (Attaran & Maharaj, 2000; Hargreaves et al., 2000) and contributed to the most severe epidemic seen for many years. Snail control is not practiced on more than a local scale in South Africa and has never been as successful as mosquito control (Appleton, 1985). It has not reduced the target species' numbers for longer than about six months.

Prediction of the presence/absence of the invertebrate hosts under discussion at a small scale is only realistic with a sound knowledge of their biology, habitat and breeding requirements. Some of these are discussed below. Even if a host does occur in a given habitat, it does not mean that the disease is being transmitted there.

8.2 Malaria

Analysis of the annual numbers of malaria cases reported in South Africa since 1971 showed a series of six epidemics approximately five years apart (R. Maharaj, pers. comm.) with the largest in 1996-2000. Predicting such epidemics is the aim of the MARA/ARMA programme, a major thrust of the Malaria Research Programme of the South African Medical Research Council in Durban. Models have been developed as has an early warning system but these are based on changes in weekly case numbers and not on entomological or ecological factors.

Surveying mosquito larvae in different habitats formed an integral part of larviciding programmes until the advent of DDT as an insecticide at the end of World War II and a shift in emphasis to controlling the adults. The biology and ecology of mosquito larvae thus lost its importance to the global malaria control effort and relatively little research has been done on larval ecology during the past 60 years. It has already been noted that anopheline larvae are restricted in their choice of breeding habitats and that those used by the members of the *An. gambiae* complex are different from those used by *An. funestus.*

The transmission of malaria in southern Africa is predominantly by *An. arabiensis*, a member of the *An. gambiae* complex, and is seasonal between October and May (DoH, 2003), with most cases reported between March and May – a pattern known as 'late season malaria'. While wetlands such as the perennial pans of the Pongolo River floodplain, particularly their vegetated edges, are known to serve as refuges for breeding by *An. arabiensis* over the dry winter months, most habitats used by this species during the summer rainy season are small, temporary and rely on rainfall, seepage or irrigation overflow water. Summer breeding sites are thus largely independent of wetlands, appear to be randomly selected and often lie at some distance from them. But for malaria transmission to occur, the resting and breeding sites for these vectors should be close to human habitation. Adult *An. arabiensis* are partially endophilic, resting both indoors and in outdoor sites such as pits, holes in river banks and animal burrows while both *An. gambiae s.s*. and *An. funestus* are totally endophilic.

Two very different types of breeding habitat thus contribute to shaping this 'late season' pattern and for predictive purposes it is useful to understand their roles. The winter refuges of *An. arabiensis* have not been well defined ecologically and it is therefore hard to assess their characteristics. The low autumn and winter temperatures slow larval development though the resulting adults are larger than those developing at the higher temperatures of spring and summer. The larger the adults the more robust they are with increased longevity (Maharaj, 1995). Although their fecundity is reduced, this greater fitness allows these large adults a flight range of up to 5 km enabling them to find rainpools when they become available in which to lay their eggs and so facilitate the annual spread into areas beyond the wetlands. Though relatively few in number, they are able to reproduce and transmit malaria for extended periods. Higher spring and summer temperatures increase adult fecundity and the rate of larval development resulting in high larval densities, i.e. crowded conditions involving hundreds of larvae in a single hoofprint pool (le Sueur, 1991). This leads to less efficient feeding so that the resulting adults have a smaller body size and reduced survivorship –

there are more of them than in winter but they are less fit. They transmit malaria for shorter periods than in winter.

Anopheles funestus is more closely associated with wetlands than *An. arabiensis* and can be expected to breed all year round in permanent streams and pools shaded by marginal or overhanging vegetation. Where *An. funestus* is present, transmission is likely to occur throughout the year as opposed to the seasonal pattern that results if the vector is *An. arabiensis*. Year-round transmission of malaria in an area is thus indicative of *An. funestus* being the main vector.

These two major species of malaria vector mosquitoes found in South Africa utilize very different types of freshwater habitat for breeding. *Anopheles funestus* on the one hand uses permanent, shaded waterbodies such as streams and pools and thus has a year-round association with wetlands. *Anopheles arabiensis* on the other hand shows a seasonal change in habitat usage. It uses refuge habitats in wetlands during winter and temporary sunlit rainpools during summer. The bionomics of this shift account for the seasonal transmission pattern that is characteristic of much of southern Africa.

8.3 Schistosomiasis (bilharzia)

Suitability models have been developed using a variety of masks (e.g. temperature, rainfall, NDVI) to predict the likelihood of both the snail intermediate hosts of schistosomiasis and the disease occurring in several countries, viz. Zimbabwe (Mukaratriwa et al., 1999), Zambia (Simoonga et al., 2008), Uganda (Stensgaard et al., 2006) and South Africa (Moodley et al., 2003). These are however large scale models which assist in predicting a species' range or for guiding control programmes. They do not help decide whether or not a given waterbody within a snail's range is likely to harbour them or if it does, whether they will become infected and establish transmission.

Chemical analyses of water are of little use since the schistosomiasis snails are widely tolerant of many chemical variables (Appleton, 1978) so that most natural freshwaters lie within their tolerance ranges. Certain situations where for example the water has a pH below 6, is polluted, brackish, saline, anoxic or nearly so may be inimical to snails. The best we can do is look for three pre-requisites which should be satisfied in order for transmission to occur in a particular waterbody. These are (i) a stable body of standing or very slowly flowing fresh water, (ii) the presence of the snail intermediate hosts of the parasites and (iii) frequent contact by the same people. In respect of this last pre-requisite, it was shown in Lake Sibaya, KwaZulu-Natal, that only a few of the human contact sites along the shore were likely to support transmission (Appleton & Bruton, 1979) but it was difficult to identify these without some kind of parasitological assay.

The two major intermediate hosts of the parasites that cause schistosomiasis, *Bulinus africanus* and *Biomphalaria pfeifferi*, are common and occur widely, especially the former, in waterbodies of various types across the eastern half of South Africa. This distribution pattern correlates well with that of hard types of bedrock such as granite and basalt which erode unevenly where they form river channels to form the backwaters and detached pools that serve as refuges for these snails (Appleton, 1975; Appleton & Stiles, 1976). These snails should thus be expected to occur in waterbodies in this area, particularly those which are perennial and vegetated.

The distributions of the two species are plotted in detail on 1:250 000 trigonometrical survey maps in the *Atlas of Bilharzia in South Africa* (Gear et al., 1980; Moodley et al., 2003). Although this atlas is 28 years old and needs to be updated, there is no reason to expect that the presence/absence of these two species in individual river systems has changed much, if at all. They should thus be expected to occur along the lengths of these rivers below altitudinal or zonational limits and at and in permanent wetlands dependent on these rivers but their spatial distribution within individual habitats is likely to be aggregated. The limits referred to above lie at about 900 m in KwaZulu-Natal and Mpumalanga (Appleton., 1975; Gear et al., 1980).

High flow velocities due to floods or discharges from dams will decimate many of the more tenuous or temporary populations. Repopulation will depend on immigration from more persistent populations living upstream in refuges such as detached pools and protected backwaters. The availability of such permanent refuges is thus an important element in the epidemiology of schistosomiasis. It is worth remembering here that these pulmonate snails have higher intrinsic rates of natural increase than, say, prosobranch snails. They are opportunists capable of realizing their full potential in terms of growth, fecundity and survival in favourable situations and are able to recover rapidly from population crashes after catastrophes such as floods, droughts or molluscicide applications. They grow rapidly, live for 6 months to 1 year becoming reproductively mature after 4-12 weeks (depending on temperature) so that their reproductive life is relatively long, measured in months.

The occurrence of these snails in temporary wetlands is less certain. *Biomphalaria pfeifferi* does not aestivate as well as *B. africanus* which is on record as doing so for a year (Frank, 1964) but even *B. africanus* was classed as only a 'moderately successful' aestivator by Brown (1994).

There is truth in the 'old wives tales' that in South Africa schistosomiasis will not be contracted in flowing water or in westwards-flowing rivers. Host snails are indeed intolerant of flowing water (Appleton, 1978) since they are unable to feed or even remain attached to the substratum in velocities greater than 0.3 m/s but of course cercariae can be swept into the channel by flowing water after being shed from infected snails in calm habitats upstream. These cercariae can then infect people for a kilometre or more downstream. Host snails are absent from all westward-flowing rivers in South Africa except the Vaal and its tributaries, and so therefore is transmission. The reverse is of course also true, all eastwards-flowing rivers harbour snails and transmission is largely confined to the eastern half of the country.

Wetlands close to human habitation are prone to faecal pollution from people and/or animals. This is a common occurrence in South Africa and where it is severe, it is unlikely that snails will be found since invertebrate diversity has been shown to decline close to sewage outfalls (De Meillon et al., 1958; Malek, 1958; Hartland-Rowe & Wright, 1975). Low levels of pollution are however tolerated by some taxa and, importantly, may even lead to their greater abundance (Watson & Hawkes, 1984).

Observations in South Africa and Nigeria testify to *B. africanus, B. globosus* and *B. pfeifferi* being tolerant of low levels of faecal pollution. Bayer (1954) found schistosome-infected *B. africanus* and *B. pfeifferi* in a small dam in Durban contaminated with sewage discharge and Appleton (unpublished data) noted the colonization of the submerged lawn (*Hemarthria altissima*) of Rhodes University's Lake Sibaya Research Station by *B. globosus* after the rising lake level flooded the station's underground drains in the 1970s. No measurements of contamination are available for these cases but Smith (1975, 1982) investigated the faunal zonation below a sewage discharge point in a stream in Nigeria. He described a '*Chironomus* zone' immediately below the outfall followed by a '*Bulinus* zone'. The '*Bulinus* zone' was dominated by the pulmonate snails *B. globosus*, *B. pfeifferi* and *Lymnaea natalensis* and though the upper tolerance of faecal pollution by these species is not known, the levels of presumptive coliform bacteria in both zones were high, $>24 \times 10^4$/100 mℓ.

Another local example of decreased diversity associated with pollution is the replacement of the indigenous pulmonate fauna including *B. africanus* of the Msinduzi/Mgeni River by the invasive species *Physa acuta* – nicknamed, the "sewage snail"(Brackenbury & Appleton, 1993). Presumptive coliform levels here fluctuate from year to year but often exceed 20 000/100 mℓ (Appleton & Bailey, 1990).

Like other genera of the family Planorbidae, both *Bulinus* and *Biomphalaria* and the larvae of the midge *Chironomus pulcher* which characterized the *Chironomus* zone of Smith (1982) have haemoglobin as their respiratory pigment. With its high affinity for oxygen, the possession of haemoglobin equips these organisms to survive in oxygen-depleted water better than those with other pigments. This was illustrated by Frank (1964) who showed experimentally that *B. africanus* could survive in water with an oxygen saturation of only 7%.

Pollution from domestic rubbish may also be favourable for snails since it provides new substrata for the growth of the microflora on which snails graze. Empty fertilizer bags are well known as snail habitats and have even been used as traps!

The available suitability models do not help decide whether or not a particular waterbody harbours the schistosomiasis host snails. There is agreement (Mukaratirwa et al., 1999; Stensgaard et al., 2006; Simoonga et al., 2008) that while they are useful at large scales, they are simplistic and cannot adequately reproduce the combinations of environmental factors that must affect the snails' reproduction and survival as well as the intra-molluscan stages of the parasites in individual habitats. Until this deficiency is resolved, prediction at the habitat level must rely on more basic data such as known distribution ranges and tolerances of abiotic variables.

8.4 Fascioliasis (liver fluke disease)

Transmission of *Fasciola* spp. depends on encysted cercariae (metacercarial cysts) on emergent or floating vegetation being eaten by herbivorous animals and, in some parts of the world, by people. It should thus be expected wherever people eat aquatic vegetation. This is however uncommon in South Africa and human infections are correspondingly rare.

Three lymnaeid species serve as intermediate hosts for *Fasciola* spp. in South Africa. Predicting the occurrence of one of these, *Lymnaea natalensis* which carries *Fasciola gigantica*, is subject to the same prediction problems as the schistosomiasis snail hosts. The other two, *Lymnaea truncatula* which carries *F. hepatica* and *L. columella* whose parasitology is not known in South Africa but is widely thought to be susceptible to both *Fasciola* spp., are amphibious and often found out of the water on damp mud in habitats such as shaded river banks and irrigation furrows as discussed in an earlier chapter. The newly introduced *Radix rubiginosa* is, like *L. natalensis*, completely aquatic and its habitat requirements are probably similar. Its spread should be monitored.

9. Change in infection risk profile in relation to the provision of water services

9.1 Malaria

Despite the fact that most malaria transmission occurs close to dwellings, it is not transmitted to people via contact with water. The provision of water services to households or communities in malarious areas is therefore unlikely to impact the transmission of the disease. Neither will the provision of a water supply to communities affect the breeding of vector mosquitoes. This is unless of course poor water management provides *An. arabiensis* with suitable breeding habitats close to human habitation in the form of leaks, seepages and overflows.

9.2 Schistosomiasis (bilharzia)

Transmission of schistosomiasis is also found close to human habitation – in either natural or artificial waterbodies. Kloos et al. (2001) demonstrated in rural Brazil that *Biomphalaria* spp. were being dispersed to a variety of domestic habitats (outdoor baths, storage tanks, drains, seepage areas, fishponds and rice paddies) in water led from natural streams via canals. Snails in several of these waterbody types were infected with *S. mansoni*.

Similar studies have not been done in southern Africa but reducing the reliance of people on such habitats for their water supplies must lead to less frequent and less intense transmission. In the South African context, a suite of simple and inexpensive control measures collectively called 'rural management' was designed for this purpose in the 1960s by Dr RJ Pitchford to target agricultural developments in the rural Mpumalanga lowveld where schistosomiasis transmission was increasing in parallel with the human population on these farms (Pitchford, 1966, 1970a&b). These measures aimed at interrupting transmission by preventing people having contact with infested water prior mass chemotherapy. They included a clean, piped water supply for standpipes, laundry facilities and swimming pools, bridging and/or fencing streams and siting dwellings below irrigation canals (rather than above them) and at least 30 m away from them. After eight years of this environmental control, *S. haematobium* and *S. mansoni* prevalences had dropped by 45% and 28% respectively. Such modest success eight years after installation indicates the long term nature of environmental control, i.e. without chemotherapy. Covering irrigation canals near human habitation to prevent contamination was part of this package and contributed to the decrease in transmission by reducing the numbers of *S. mansoni* detected by sentinel rodent immersions in the storage dam fed by the canal by 99%, from 4.2 worms/rodent to 0.03 worms/rodent.

The impact of more substantial (but more expensive) measures, namely the provision of piped water and water-borne sanitation, on schistosomiasis transmission in an urbanized community was illustrated by Evans et al. (1987) in the Mpumalanga lowveld. Seven years after the installation of in-house water supplies and water-borne sewerage, prevalences of *S. haematobium* and *S. mansoni* in children were 8 and 4% respectively compared with 48-88 and 43-67% for these same parasites in four nearby communities without these facilities and where residents relied on stream water. Indeed, prevalences as low as those recorded in the serviced community probably suggest that the parasites had been eliminated and simply reflect infections acquired elsewhere (Pitchford & Schutte, 1967).

On the Caribbean island of St Lucia a suite of water supply improvements similar to those used by Pitchford (1966, 1970a&b) and also designed to keep people away from contaminated water led to a significant decrease in the incidence of new *S. mansoni* infections from 19% to 4% (Webbe & Jordan, 1993). These authors stressed that it was not sufficient to simply install standpipes; to be effective as an anti-schistosomiasis intervention these had to be supplemented with laundry and shower facilities.

9.3 Discussion

In terms of the control of diseases such as bilharzia, the provision of water supplies/services cannot be seen in isolation. For it to be effective as an anti-schistosomiasis measure, it cannot be divorced from other types of intervention (chemotherapy and health education). Current thinking (WHO, 2002) is that chemotherapy should accompany the provision of water services with the expectation that the immediate reduction in worm burdens and morbidity to a low level following treatment would be maintained by longer-term interventions such as safe water supplies, sanitation and health education.

10. Conclusions

10.1 Study objectives

The objectives of this project are firstly to establish the current knowledge base regarding the relationship between regulated river flow and the invertebrate hosts of malaria, schistosomiasis (bilharzia) and fascioliasis (liver fluke disease), and secondly, to investigate the theory that manipulation of regulated flow may provide a mechanism for control of these invertebrates and the transmission of the diseases that they carry.

10.2 Species-specific conclusions

10.2.1 Malaria

Although a significant body of literature exists surrounding *Anopheles* mosquitoes and their relationship with rivers, many of these studies concerned species found around the world, and few focused on the two main species of malaria mosquito in South Africa, *Anopheles funestus* and *An. arabiensis*.

Anopheles funestus may well utilise the quiet backwaters of rivers in which to breed. It has however been established that the current distribution of *An. funestus* has been significantly reduced in South Africa largely through the indoor residual spraying programme, though its exact spatial range is unknown. This particular species is endophilic, meaning that it rests indoors, and is thus particularly susceptible to indoor spraying. Due to the success of the spraying programme, it appears as if *An. funestus* has become significantly less responsible for malaria transmission in recent years. The introduction of flow related control is unlikely to make more of an impact on this species than the spraying programme. *Anopheles funestus* is thus considered a poor candidate for flow related control.

Anopheles arabiensis is an opportunistic breeder which utilises temporary sunlit pools of rainwater in which to breed. This fact makes their link with rivers an extremely tenuous one. Le Sueur (1991) showed that they sometimes do breed alongside rivers, but only in areas where suitable temporary water bodies had formed, such as cattle hoof prints where the animals had come down to drink. In general, the majority of breeding sites recorded in his study were away from rivers in areas where shallow pools of rainwater had formed. Because of their particular breeding habits, *An. arabiensis* is also considered to be a poor candidate for flow related control.

In addition to the factors discussed above, the short duration of the larval stage of the mosquito life cycle would mean that flow related control events would need to be repeated several times a season, each within a 10 day cycle. This would be especially impractical due to the scarcity of water resources in this country. In conclusion, it is considered that flow related control mechanisms would not significantly impact the incidence of malaria in South Africa.

10.2.2 Schistosomiasis (bilharzia)

According to the outcomes of the project workshop (see appendix 1), the majority of freshwater snails prefer permanent, still to slow moving water bodies and habitat stability is a key factor contributing to a population's success. According to Woolhouse and Chandiwana (1990), the most important limiting factors in the population ecology of freshwater snails in rivers are temperature and extreme variations in flow. They have documented the enormous impact natural flood events have on populations of *Bulinus globosus* in a stream on the Zimbabwean highveld. These accounts suggest that flow variability is key to limiting snail population growth in rivers. If by regulating a river's flow, variations in flow are removed, it would appear that this does provide freshwater snails with favourable conditions in which to flourish.

This conclusion can be taken further. Given the snail's inability to withstand flow velocities greater than approximately 0.3 m/second (Appleton, 1978), and given that it has been shown that they are poor aestivators and are susceptible to desiccation following stranding, it is suggested that snails make extremely good candidates for flow related control measures. Indeed, Fritsch (1993) has proven that the flushing of a stream is an effective method of eliminating *Bulinus globosus* from a small stream. This conclusion should however be viewed in terms of the limited number of people who might benefit from this form of control.

10.2.3 Fascioliasis (liver fluke disease)

No significant conclusions could be reached regarding flow related control of *Lymnaea truncatula, L. natalensis,* and *L. columella,* the invertebrate hosts of *Fasciola hepatica* and *F. gigantica*. This is largely due to the lack of information in circulation surrounding the parasites. The habitat choices of the host snails are rather vaguely described in the literature, and it is assumed that their relationship with rivers will be similar to that of the *Bulinus* and *Biomphalaria* species (see above). The exception is perhaps *L. truncatula*, which is known to be amphibious and to be a good aestivator (De Kock et al*.,* 2003) and is likely to be found out of water on damp mud. This factor reduces its candidacy for flow related control, especially for attempts which utilise reductions in flow in an attempt to desiccate the river bed.

Note should be made of the lack of information available concerning the economic impact of these parasites in South Africa. Anecdotal evidence of farmers and veterinarians depict fascioliasis as having a significant financial impact on the beef and dairy industries especially. It is estimated that the parasite costs the UK agricultural sector R322 million per year, and in Australia it is estimated to be R520 million per year.The costs associated with this parasite in South Africa have however never been assessed.

10.3 Implementation – context and efficacy

Based on the species-specific conclusions presented above, the disease most likely to be impacted by flow related control mechanisms is bilharzia. The implementation of flow related control of this disease should be seen in the light of the following conclusions.

2.5 million people are estimated to be infected with bilharzia nationwide (Moodley et al. (2003), reported by Appleton et al. (2006)). Costs of treatment and loss of earning potential are estimated to amount to approximately R250.00 per case, and a national annual estimate of approximately R625 million. The provision of water services is thought to be an effective method of reducing contact with transmission sites, however, despite the high numbers of infections, there is currently no national programme aimed at controlling the invertebrate hosts of bilharzia. Some local mollusciciding has been carried out in the past (Appleton, 1985), though efficacy appears to have been extremely limited.

Approximately 18% of people living in bilharzia endemic areas live within walking distance (5 km) of rivers that are thought to be candidate rivers for flow related control. This suggests that, should flow related control be implemented successfully against bilharzia snails, at the most, 18% of the people living in endemic areas may benefit from a reduction in the risk of transmission. This is not to say that 18% of infections will be eliminated. Many people living within this area will face transmission in any number of water bodies other than candidate rivers. Also, many of the people living in these areas are supplied with household water, and are in fact not 'at risk' since they do not generally come into contact with possible transmission sites. It is worth considering however that according to this estimation, 82% of people living in endemic areas will see no benefit from this method of control. The rationale behind calculating this value is to put the idea of flow related control into perspective in terms of what proportion of people 'at risk' from bilharzia in South Africa may potentially benefit from it.

The merits of flow related control must be closely considered in respect of the overall health of the aquatic ecosystem in which it is proposed to be implemented. Unnatural flow variation can be extremely damaging to ecosystem functioning as has been shown in the case of hydropower dams. Increasingly, river health is being seen as of paramount importance in maintaining the quality of water resources, and the introduction of the Ecological Reserve in the near future will seek to ensure that flows released from dams will best approximate natural flow conditions. The concept of manipulating the release of water in order to control invertebrate hosts of disease will need to be evaluated against this setting, given that any control measure implemented will also affect other elements of riverine ecosystems. Additionally, given the scarcity of water over much of the country, the feasibility of a proposal to utilize stored resources it in an effort to control bilharzia will have to be very carefully assessed and the implementation of such a proposal strongly motivated for.

11. Identified research requirements

During the course of this project gaps in existing knowledge concerning this particular subject have been identified. These are laid out below as recommended research requirements that will develop the broader body of knowledge concerning the invertebrate hosts of malaria, schistosomiasis (bilharzia) and fascioliasis (liver fluke disease) and their relationship to river flow, flow regulation and flow manipulation.

11.1 Over-arching subjects

The impact of different flow regulation scenarios on invertebrate host assemblages (specifically invertebrate hosts) in South Africa.

The impact of flow regulation on invertebrate hosts is not specifically documented in this country. Dam construction has been shown to affect distribution of diseases around the world, but the downstream impact is less well documented, if at all in the case of South Africa. This work should emphasise the changes in vector supporting habitat that result from flow regulation

The response of riverine ecosystems to manipulated flow scenarios with specific reference to invertebrate host populations.

Various flow manipulation mechanisms have been proposed as invertebrate host control mechanisms in this report (such as flushing and desiccation), and the possible effects of such manipulation have been debated. It is however essential that these impacts are assessed before implementation is considered.

The distance downstream over which a manipulated flow regime remains effective in disrupting snail and mosquito lifecycles.

It has been shown that flow manipulation can prove effective in reducing snail populations. The distance downstream from the impoundment that this remains effective is however unknown. It is also unknown whether snails dislodged from one point augment populations downstream or indeed if they start new populations which may create new transmission sites.

11.2 Disease specific subjects

11.2.1 Malaria

The breeding habits of the malaria vector mosquitoes of South Africa in relation to rivers and their floodplains.

With the exception of the work carried out by le Sueur, very few studies have been carried out characterising the breeding cycles of the malaria vector mosquitoes in South Africa (especially in the last 60 years). The potential for slow flowing rivers to provide over-wintering habitats for *Anopheles arabiensis* should be specifically considered. Additionally, the changes in riverine vegetation brought about by the regulation of rivers should be considered in terms of providing additional potential breeding habitat.

The current distribution of *Anopheles funestus* in South Africa

The indoor residual spraying programme has effectively targeted *An. funestus* and succeeded in shrinking its distribution. It is thought it may have been driven out of RSA altogether. This is unconfirmed. It is suggested that the current distribution of this important malaria vector be established.

11.2.2 Schistosomiasis (bilharzia)

National infection statistics

In general, schistosomiasis is well researched, however there exist gaps in the body of knowledge which would contribute enormously if filled. The most obvious gap is national infection statistics. Since this is not a notifiable disease, it is understandable why such a gap exists, but an accurate, up-to-date assessment of the number of diagnosed infections would help greatly with the understanding of the impact of this disease on South African people.

The distribution of bilharzia parasites

The distributions of the parasites causing this disease have not recently been defined. The distribution map used in this project is drawn from the Atlas of Bilharzia which was published in 1980

The effect of flow regulation on the distribution and abundance of freshwater snails

Although this is a topic already mentioned above, schistosomiasis is the most likely candidate for control by way of flow manipulation. It is thus singled out here as a potential individual study.

The population dynamics of bilharzia snails in South Africa

Studies of this nature have been carried out in tropical climates elsewhere in the world but few studies have documented snail population dynamics under South African conditions.

11.2.3 Fascioliasis (liver fluke disease)

Fascioliasis as a subject is extremely poorly documented in South Africa. This is not surprising in terms of human infections since cases are rare in this country. It is surprising however, considering the enormous costs associated with it in other countries (R322 million per year in the UK, R520 million per year in Australia), that almost no literature is available concerning this parasite as an agricultural pest, and the economic impact it has on the agricultural sector in this country.

The distribution and biology of both *Fasciola hepatica* and *F. gigantica* in South Africa*.*

Both species of parasite are poorly understood in the South African context. Basic information such as parasite distribution is not available.

The economic impact of fascioliasis on the agricultural industry in South Africa.

As mentioned above, the economic impact of this important agricultural parasite has never been assessed in this country.

The respective roles played by *Lymnaea truncatula, L. natalensis* and *L. columella* in the transmission of liver fluke disease among livestock in South Africa.

The respective roles played by these three invertebrate hosts in transmitting fasciola parasites are uncertain, especially in the case of the invader snail *L. columella*.

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13. Appendices

Appendix 1 – Synthesis of the available knowledge that describes the relationship between river flow and the invertebrate hosts of Malaria, Schistosoma and Fasciola.

The relationships between regulated river flow and the invertebrate hosts of Malaria, Bilharzia and Liver Fluke Disease

Bilharzia

Introduction

- Two types of bilharzia parasite infect people in South Africa – Urinary bilharzia (*Schistosoma haematobium*) and Intestinal bilharzia (*Schistosoma mansoni*).
- *S. haematobium* uses *Bulinus africanus* and *Bulinus globosus* as its invertebrate hosts, while *S. mansoni* uses *Biomphalaria pfeifferi*.

Snail habitat preferences

- All of the above species of snail prefer a firm **substrate** with very few snails found living on sediment. The substrate should be firm enough to allow egg laying and should support periphyton. This is usually hard rock or vegetation such as grasses and floating vegetation mats. Surprisingly, very few snails are found in *Phragmites* beds. No explanation for this was known.
- A snail's **food** is generally epiphyton. Not higher plants and not filamentous algae. Snails do appear to enjoy high protein foods such as fish food, while sediment coming out of suspension and covering food presents a real problem.
- **Water quality** appears to have an effect on snail distribution. Snails are not encountered below 2 mg/l O_2. Snails appear to be at home in mildly polluted rivers though they are more sensitive to heavy metals. Acidic water below pH 6 limits the ability of the snail to form shells, thus appears limiting. Change in water quality below dams appears to have an effect on snails. Aswan dam changed temperature, clarity and lack of sediments. Salinity is limiting although snails can survive in water up to 3.5 ppt. Hatchlings however require fresh water to survive. Turbidity is not thought to be limiting in itself, though it may be associated with high flow levels which will be limiting. Sediment falling out of suspension may cover food. It is not known what level of turbidity would limit snails.
- **Competition** is not considered to be a major limiting factor. Normal competition with other grazing invertebrates is expected. **Predation** is likely to be more limiting. Birds, fish, invertebrate larvae, and species of freshwater crayfish all eat snails.
- **Ideal river flows** are rivers which flow steadily over hard bed-rock (which erodes erratically and creates pools and backwaters which are important refugia). Habitat stability is all-important, with constant slow flows providing ideal conditions, and

erratic flows being least suitable. Flooding is thus considered detrimental to populations, but may however be important as it will recharge isolated pools and backwaters, providing fresh habitat.

Impact of Dams on Habitats

Reduced Flow

- Impacts due to reduced flow during the **summer / rainy season** are generally that the variability of flow and the flooding frequency are reduced. This has the effect of providing a more stable habitat. This will also allow an increase in the amount of vegetation growing along the margins, providing more suitable substrate and refuge from predators. Slower, steadier flow will allow greater in-stream heating, which depending on the climatic situation of the dam, may prove beneficial or detrimental to snails. Dam release water is less variable in temperature than natural flows, which increases the stability of the habitat. Less flooding means people generally live closer to the water's edge. This may mean more contact with the water and increased infection is likely. People may also remove riverside vegetation, reducing shaded area and changing habitat.

- Reduced flow during **the winter / dry season** may result in elevated water temperatures, which may benefit snails. It may also result in a loss of important habitats such as isolated pools and backwaters. In some instances, streams may stop flowing altogether resulting in almost total loss of habitat.

Elevated Flow

- Elevated flows during the **summer / rainy season** would result in increased water velocities. This would be detrimental to snails. Also however, more water in the river may result in lateral expansion of the river and more habitat creation. Stability of this flow is important to snails, erratic flow is detrimental. Greater current speed may carry snails downstream to re-colonize areas. Snails may be carried out of impoundments on floating vegetation during periods of high flow.

- Elevated flows during the **winter / dry season** could result in more breeding habitat being made available, therefore potentially more snails. Limiting cold water temperatures may be moderated by warmer isothermal dam releases. Increased temperatures may result in increased breeding.

Control mechanisms

Flushing (through flooding)

- Case study does exist, though impacts on other aquatic biota were not considered.

- Snails are sensitive to increased flow velocities and are unable to resist flows greater than approximately 0.3 ms^{-1}. Thus increased flows may be effective in reducing snail densities in certain areas.
- Flushing may be made impossible by the shortage of water in SA, however floods released as part of the Reserve allocation may be timed to assist with snail control.

Desiccation (through extremely low flows)

- If habitats dry out, the majority of snails will die, though some may survive through aestivation. Snails are not known to seek out the best habitat for aestivation, and it is not known how long it takes a snail to begin to aestivate.
- Possibly drop the level of a river to kill snails. Some will survive in pools but this is only a partial survival. However some reduction in population is better than none.
- A combination of flushing and desiccation should be investigated.

Other flow related ideas

- Fish are effective in places, flows could be managed to benefit fish.
- Vegetation control seemed effective in Durban. Perhaps manage flows to reduce vegetation, though the volumes of water required for this are unlikely to be available in South Africa. Releases to coincide with natural flooding could be seen as an option.
- The relationship between flooding and snail breeding should be studied.

Malaria

Introduction

- Two species of mosquito are primarily responsible for the transmission of malaria in South Africa, *Anopheles arabiensis* and *An. funestus*.
- Very little is documented concerning either species breeding habitats in South Africa

Malaria Mosquito breeding habitat preferences

- In terms of **water body type**, *An. arabiensis* prefers temporary sunlit pools, with no vegetation such as rain-filled cattle hoof prints or those found at the edge of larger water bodies. They overwinter in larger water bodies protected by aquatic vegetation, e.g. Pongola river pans. Here they mature much slower. *Anopheles funestus* prefers larger bodies of water often shaded by vegetation, e.g. stream margins.
- **Water quality** appears to affect larvae only in that they mature best in clear water. Anoxic conditions are not problematic since the larvae breathe air. The relationship

to nutrients is unknown, though no fixed relationship is believed to exist between nutrients and malaria.

- Fish and Belastomatids are major **predators** of the larval stage. No examples of **competition** are known.

- **Beneficial natural river conditions** that would be suited to the breeding of malaria mosquitoes would be rivers with well vegetated back-waters or areas of still water (out of the current). The relationship between malaria mosquitoes and rivers is a tenuous one.

<u>Impact of Dams on Habitats</u>

- **Reduced flow** would make more stable pools outside of the current available as habitat, however less water means less habitat overall. Increased vegetation on margins means less favourable habitat for *An. arabiensis*, however this may favour *An. funestus* which is less widespread (possibly exterminated from South Africa). This marginal vegetation may also provide resting places for adults after feeding, though little of this is known. Flow gauging weirs may provide more habitat especially since they provide stiller waters and assured inflow, though this type of habitat is not favoured by *An. arabiensis*.

- **Elevated flow** might provide additional habitat if the geomorphology of the river channel was suitably diverse, though higher flows, especially if slightly variable, would most likely flush the streamside pools of larvae and increased velocity would limit habitat availability.

- Although not strictly flow related, new habitat may well be created **within the dam** itself. Farm dams make excellent mosquito breeding habitat. This includes marginal vegetation in the dam and seepage pools below the dam wall, though it is questionable if *An. arabiensis* would utilise this type of large water body.

<u>Control mechanisms</u>

Flushing

- Case studies do exist in Sri Lanka, though unlike *An. arabiensis*, the species of malaria mosquito which occurs there is a known river breeder.

- Mosquito larvae have no way of combating current, and therefore can be swept out of shallower pools and vegetated areas. However, changing the water level risks creating more streamside pools and thus increasing breeding potential.

- The larval stage of the life cycle lasts little more than a week, and this means that any flushing control mechanism would need to be repeated many times at least at weekly intervals to be effective.

Desiccation

- It is thought that desiccation may impact portions of the population living in stream bodies. However, it is also thought that it is not possible to dry out isolated pools.
- As with flushing, the short period of the larval stage means that pools will need to be dried out very quickly. This will not always be achievable.

Other

- Water turbidity may be able to restrict mosquito habitat.
- A rapid draw down rate of dams releasing water may prove effective in stranding and thus eliminating larvae living along the margins of dams.

Liver fluke

Introduction

- Very little is known about this parasite or its invertebrate hosts as it very rarely infects humans in South Africa. The Nile delta and areas of Peru are known infection hotspots. In Europe, where water cress is consumed in large quantities, it is also a problem.

Snail habitat preferences

- *L. truncatula* is amphibious and thus its preferred **substrate** is generally mud or vegetation at the edges of marshes and bogs. *L. natalensis* and *L. columella* are aquatic species and can be found on similar substrates to *Bulinus africanus*. One difference is though that they are often found on mud, and thus may occur at the bottom of pools or dams.
- As with *Bulinus* species, c**ompetition** is not considered to be a major limiting factor. Normal competition with other grazing invertebrates is expected. Similarly, **predation** is likely to be more limiting. Birds, fish, invertebrate larvae, and species of freshwater crayfish all eat snails. In addition, rodents may be predators of the amphibious *L. truncatula* while it is out of the water.
- As with *Bulinus* species, **ideal river flows** for the aquatic *Lymnead* species are where rivers flow steadily over hard bed-rock. Habitat stability is all-important, with constant slow flows providing ideal conditions, and erratic flows being least suitable. Flooding is thus considered detrimental to individual populations, but may however be important overall as it will recharge isolated pools and backwaters, providing fresh habitat. *L. truncatula* is less likely to be associated with rivers and ideal conditions would be marshy bogs and muddy edges of almost stagnant pools.

Impact of Dams on Habitats

- It is expected that the impacts of **reduced flows** on the aquatic *Lymnaead* species would be the same as those experienced by the *Bulinus* species. The most important of which is the stabilising of river habitats with a reduction in flow variability and fewer and less severe floods. Temperature variations attributable to dam release mechanisms may favour or disfavour snails depending on local climatic conditions.

- Similarly, the impacts of **elevated flows** are expected to be the same as for the *Bulinus* species. The most significant of these is the fact that elevated flows are likely to be accompanied by increased velocities, which are likely to disfavour snails. Habitat area may however be increased by the lateral expansion of the river.

Control mechanisms

- Desiccation is considered less of an option for *L. truncatula*, since they are an amphibious species and ordinarily occur out of the water in any case.

- Since very little is known about this disease and its invertebrate hosts in South Africa, it was suggested that European literature should be consulted to inform the suggestion of possible control mechanisms. Liver fluke disease is a great deal more common there and control is likely to have been assessed in more detail.

5. Summary of key findings

1. Very little is known in general about the relationship between flows and invertebrate hosts of these three diseases. Liver fluke disease in particular is poorly understood, while there appears to be no knowledge of a significant relationship between malaria mosquitoes and rivers in South Africa.

2. In South Africa, the nature of regulation of flows varies considerably from dam to dam. This is due mainly to the manner in which the dam is operated and the mechanisms by which water is released. Both of these will have an impact on the habitats created below the dam. It is difficult to thus come to generalised conclusions regarding their impact on biota below the dam

3. Habitat stability is of key importance to snail species’ breeding success. Regulated flows (whether they are elevated or reduced) introduce increased levels of stability both in the form of flow as well as temperature and thus favour snail populations.

4. Areas of refuge are important for snail population continuity. These are areas where the current is reduced such as back-waters, isolated pools and areas of dense emergent or aquatic vegetation.

5. Regulated **elevated flows** due to dam releases in the summer/rainy season will probably result in increased snail habitat area, increasing breeding opportunities. Greater flow velocities may be detrimental to snail abundance, though snails may be washed downstream to colonise areas. **Reduced flows** during the summer/rainy season will result in less flooding / flow variability and therefore greater habitat stability. Less flow may also mean an increase in the water temperature, which may be beneficial to snails in colder areas. Reduction in flood events and flow variability will also allow more marginal vegetation growth, providing more habitat.

6. Regulated **elevated flows** during the winter/dry season may result in warmer water temperatures due to isothermal dam conditions, which may increase breeding. Larger volumes of water may also provide an increase in the area of suitable habitat. **Reduced flows** during the dry season / winter period may result in elevated water temperatures which may benefit snails. It may however mean the drying out of pools, and a loss of important back-water habitat.

7. In South Africa, malaria is transmitted primarily by *Anopheles arabiensis*. This species prefers temporary sunlit pools as breeding habitat, and is not known to use larger water bodies such as rivers. *Anopheles funestus* is the other major vector and may use larger shaded water bodies. Its distribution has been drastically reduced in South Africa by pesticide spraying, and may well no longer occur here at all.

8. Rivers with large areas of out-of-current, vegetated back waters potentially could provide breeding habitat. The extent to which this applies in the South African context is unknown.

9. **Reduced** flows will result in less habitat overall, but may provide more vegetated pools, which *An. funestus* may exploit. It is thought though that this species is largely exterminated from South Africa. **Elevated** flows may provide additional habitat areas, though the accompanying increase in current will mitigate this effect as larvae have no method of combating current.

10. Snails and mosquito larvae are both vulnerable to desiccation. There is potential to attempt to control populations, by lowering river levels sufficiently to strand larvae and snails which will die.

11. Mosquito larvae will however be difficult to target using reduced flows due to their preference for temporary water bodies and the short period of their larval stage. Snail populations may survive in isolated pools and re-colonise the river once normal flow resumes.

12. Both snails and mosquito larvae are also vulnerable to increases in current velocity. There is potential to exploit this by using increased flows over short periods of time to 'flush' rivers. This has been demonstrated by case studies in other countries.

13. Control mechanisms involving the release of water from dams will however be difficult to realise given the scarcity of water in South Africa. Mosquitoes' short larval stage (about 10 days) also limits the practicality of this possibility as flush event would need to be repeated frequently in order to control mosquito populations. Also the impact of such flush events

(especially during the dry season) on other biota would in all likelihood make this method ecologically unacceptable.

14. It was suggested that the relationship between flooding and snail breeding should be more closely studied to determine if snail breeding could be negatively affected by the timing of floods. These floods, it was suggested, could form part of the legislated reserve releases. It was also suggested that a combined approach of flushing and desiccation should be investigated.

Appendix 2 – Workshop attendance list

Workshop Attendees

Name	Affiliation
Dr Chris Dickens	Institute of Natural Resources (Project team / Workshop facilitator)
Prof Chris Appleton	University of KwaZulu-Natal (Project team)
Mr Leo Quayle	Institute of Natural Resources (Project team)
Dr Stanley Liphadzi	Water Research Commission
Dr Jenny Day	Freshwater Research Unit / University of Cape Town
Dr Helen Dallas	Freshwater Research Unit / University of Cape Town
Dr Heather Malan	University of Cape Town
Dr Peter Ashton	Council for Scientific and Industrial Research
Ms Christa Thirion	Department of Water Affairs and Forestry
Dr Neels Kleynhans	Department of Water Affairs and Forestry
Mr Ian Bailey	Umgeni Water
Dr Steve Mitchell	Water Research Commission

Appendix 3 – Candidate dams

DAM NAME	TOWN	RIVER
ALBASINI DAM	LOUIS TRICHARDT	LEVUBU RIVER
ALBERTFALLS DAM	NEW HANOVER	UMNGENI RIVER
AVALON DAM	MAGUOU	
B5 9 DAM	NEWCASTLE	
BLYDERIVIERSPOORT DAM	HOEDSPRUIT	BLYDE RIVER
BOSKOP DAM	POTCHEFSTROOM	MOOI RIVER
BOSPOORT DAM	RUSTENBURG	HEX RIVER
BRAMHOEK DAM	VAN REENEN	BRAAMHOEKSPRUIT
BRONKHORSTSPRUIT DAM	BRONKHORSTSPRUIT	BRONKHORST SPRUIT
BUFFELSPOORT DAM	RUSTENBURG	STERKSTROOM RIVER
CORONATION DAM	VRYHEID	RIETSPRUIT
CRAIGIEBURN DAM	GREYTOWN	MNYAMVUBU RIVER
DA GAMA DAM	WITRIVIER	WITWATERS RIVER
DAMANI DAM	THOHOYANDOU	MBWEDI RIVER
DE HOOP DAM	STEELPOORT	STEELPOORT RIVER
DOORNDRAAI DAM	POTGIETERSRUS	STERK RIVER
DREADNAUGHT DAM	EMPANGENI	NSELENI RIVER
DRIEKOPPIES DAM	MALELANE	LOMATI
DUMFIRMLINE HOUSE DAM	NEWCASTLE	
EBENEZER DAM	TZANEEN	GRT. LETABA RIVER
EMPANGENIMEER	EMPANGENI	MHLATUZE RIVER
FLAGBOSHIELO DAM	MARBLE HALL	OLIFANTS RIVER
GLENALPINE DAM	TOLWE	MOGALAKWENA RIVER
GOEDERTROUW DAM	ESHOWE	MHLATUZE RIVER
GOODENOUGH BIG DAM	UMKOMAAS	MKOMAZI RIVER
HARTBEESPOORT DAM	BRITS	KROKODIL RIVER
HAZELMERE DAM	VERULAM	MDLOTI RIVER
HEYSHOPE DAM	PIET RETIEF	ASSEGAAI RIVER
HLUHLUWE DAM	HLUHLUWE	HLUHLUWE RIVER
HUGOMOND LS 118 DAM NO. 2	DENDRON	HOUT RIVER
INANDA DAM	HILLCREST	MGENI RIVER
INJAKA DAM	HAZYVIEW	MARITE RIVER
JERICHO DAM	AMSTERDAM	MPAMA RIVER
KENNEDYS VALE DAM	STEELPOORT	DWARS RIVER
KETTINGSPRUIT DAM	TZANEEN	KETTINGSPRUIT
KLIPDRIF DAM	POTCHEFSTROOM	LOOP SPRUIT
KLIPFONTEIN DAM (W4)	VRYHEID	WIT-MFOLOZI RIVER
KLIPKOPJES DAM	WITRIVIER	WHITE RIVER/WITRIVIER
KLIPVOOR DAM	KLIPVOOR	PIENAARS RIVER
KOSTER DAM	KOSTER	KOSTER RIVER
KWENA DAM (BRAAM RAUBENHEIMER DAM)	LYDENBURG	KROKODIL RIVER
LAKE MZINGAZI	RICHARDS BAY	MZINGAZI RIVER
LAKE NHLABANE	RICHARDS BAY	LAKE NHLABANE
LEBEA DAM	DUIWELSKLOOF	KOEDOES RIVER
LEPELLANE DAM	MALIPSDRIF	SEBATWANE RIVER

LIMA LOWER RESERVOIR	ROOSSENKAL	DE HOOP DAM
LIMA UPPER RESERVOIR	ROOSSENKAL	DE HOOP DAM
LINDLEYSPOORT DAM	SWARTRUGGENS	ELANDS RIVER
LOSKOP DAM	GROBLERSDAL	OLIFANTS RIVER
LUPHEPHEDAM	MESSINA	LUPHEPHE RIVER
MAKULEKE DAM	GIYANE	MPHONGOLO RIVER
MARICO-BOSVELD DAM	ZEERUST	GRT. MARICO RIVER
MARLOTHI	KOMATIPOORT	NGWETI
MBAMBISO DAM	BOSFONTEIN	M'ZINTIRIVER
MBWEDI DAM	KHUBVI	MBWEDI RIVER
MEARNS WEIR	MOOI RIVER	MOOI RIVER
MHLATHUZE WEIR	RICHARDS BAY	MHLATUZE RIVER
MIDDELBURG DAM	MIDDELBURG	LIT/KLN OLIFANTS RIVER
MIDDEL LETABA DAM	GIYANI	MIDDEL LETABA RIVER
MIDMAR DAM	HOWICK	MGENI RIVER
MOKOLO DAM (HANSSTRIJDOM)	ELLISRAS	MOKOLO RIVER
MOLATEDI DAM	MADIKWE	MARICO RIVER
MORGENSTOND DAM	AMSTERDAM	NGWEMPISI RIVER
MTATA DAM	UMTATA	MTATA
MUTSHEDZI DAM	THOHOYANDOU	MUTSHEDZI RIVER
NAGLE DAM	PIETERMARITZBURG	MGENI RIVER
NANDONIDAM	THOHOYANDOU	LUVHUVHU RIVER
NCANDU RIVER DAM	NEWCASTLE	NCANDU RIVER
NEVADA DAM	BABERTON	LOUWS CREEK RIVER
NGODWANA DAM	NELSPRUIT	NGODWANA RIVER
NGOTWANE DAM	LOBATHLENG	NGOTWANE RIVER
NGWADINI DAM	UMKOMAAS	NGWADINI RIVER
NOGATSHA DAM	MTUBATUBA	NOGATSHA RIVER
NOOITGEDACHT DAM	CAROLINA	KOMATI RIVER
NSAMI DAM (HUDSON NTSANWISI)	GIYANI	NSAMA RIVER
NZHELELE DAM (NJELELE)	MESSINA	NZHELELE RIVER
OHRIGSTAD DAM	OHRIGSTAD	OHRIGSTAD RIVER
OLIFANTSNEK DAM	RUSTENBURG	HEX RIVER
ONTEVREDE DAM	VRYHEID	MPEVANA RIVER
PATAGONIA DAM	MACHADODORP	BLOUBOSKRAAL RIVER
PHIPHIDI DAM	THOHOYANDOU	MUTSHINDUDI
PONGOLAPOORT DAM	PONGOLA	PHONGOLO RIVER
RHENOSTERKOP DAM	MARBLE HALL	ELANDS RIVER
RHENOSTERKOP DAM 4	MARBLE HALL	ELANDS RIVER
RICHMOND DAM	STEELPOORT	KLEIN-DWARS RIVER
RIETVLEI DAM	PRETORIA	HENNOPS
RIETVLEI DAM	TZANEEN	NWANEDZI RIVER
ROODEKOPJES DAM	BRITS	KROKODIL RIVER
ROODEPLAAT DAM	PRETORIA	PIENAARS RIVER
ROOIKOPPIES DAM	TZANEEN	POLITSI RIVER TR.
ROY POINT DAM	NEWCASTLE	iNGAGANE RIVER

RUSTDEWINTER DAM	PRETORIA	ELANDS RIVER
SCHOEMAN(LOMATI)STU-DAM	MALELANE	MLOMATHI RIVER
SLANGDRAAI DAM (WATERFALL)	LADYSMITH	SUNDAYS RIVER
SOUTHHILLSDAM	HIGH FLATS	MKUMBENI RIVER TR.
SPIOENKOP DAM	LADYSMITH	TUGELA RIVER
STERKSPRUIT DAM	MACHADADORP	KROKODIL RIVER
TZANEEN DAM (FANIEBOTHA)	TZANEEN	GRT. LETABA RIVER
VAALKOP DAM	RUSTENBURG	ELANDS RIVER
VONDO DAM	THOHOYANDOU	MUTSHINDUDI RIVER
VYEHOEK DAM	TZANEEN	VYEHOEK RIVER
VYGEBOOM DAM	BADPLAAS	KOMATI RIVER
WAGENDRIFT DAM	ESTCOURT	BUSHMANS RIVER
WALDA WEIR	NTUNDA	N'KOMATI RIVER
WATERVAL DAM	LADY SMITH	SUNDAYS RIVER
WESTOE DAM	AMSTERDAM	USUTU RIVER
WITBANK DAM	WITBANK	OLIFANTS
WITBANK DAM	WITBANK	OLIFANTS RIVER
WITKLIP DAM	SABIE	SAND RIVER
WITKLIP DAM	NELSPRUIT	-
ZAAIHOEK DAM	WAKKERSTROOM	SLANG RIVER

Appendix 4 – Candidate rivers

RIVER NAME	Length (km)	RIVER NAME	Length (km)
Assegaai	70.0	Moretele	31.1
Blyde	52.8	Mpama	12.4
Bronkhorstspruit	31.8	Mpambanyoni	69.2
Buffels	209.3	Mphongolo	76.9
Crocodile	573.2	Msunduzi	19.9
Elands	263.3	Munywana	2.2
Ga-Selati	13.0	Mutshedzi	9.1
Great Letaba	197.9	Mzingazi	6.2
Groot-Marico	56.5	Ndlamyane	2.5
Gwathle	18.1	Nels	6.6
Hennops	57.0	Ngotwane	26.3
Hex	80.0	Ngwempisi	71.9
Hluhluwe	41.4	Nhlabane	3.6
Hout	35.9	Nkongolwana	27.6
Klein-Olifants	38.2	Nseleni	8.2
Kolope	1.0	Nwanedi	53.2
Komati	217.2	Nzhelele	101.1
Kranspoortspruit	2.5	Ohrigstad	84.2
Letaba	98.3	Olifants	682.5
Limpopo	568.5	Palmiet	1.2
Little Letaba	132.6	Phongolo	128.7
Lomati	67.4	Pienaars	147.9
Luvuvhu	213.5	Politsi	10.2
Madikwene	28.9	Puleng	2.1
Mahitse	0.9	Sabie	118.0
Makhutswi	47.8	Sand	175.5
Marico	171.9	Shingwidzi	27.4
Mdloti	26.6	Steelpoort	135.2
Mfolozi	77.0	Sterk	64.1
Mhkondvo	27.6	Sterkstroom	37.8
Mhlatuze	107.1	Thukela	277.4
Middel Letaba	29.1	uMngeni	174.6
Mkomazi	28.3	uSuthu	71.7
Mkuze	305.6	White Mfolozi	313.8
Mogalakwena	267.7	Wilge	81.1
Mokolo	118.7	Zibayeni	4.3
Mooi	80.1	Unknown	1309.8
		Total length	**8732.7**