PROPOSITIONS / STELLINGEN

1. In the planning of irrigation systems, domestic use of water should be anticipated (this thesis).

2. Environmental disease control can contribute to sustainable irrigation only if inter-sectoral collaboration is institutionalized (this thesis).

3. In irrigation systems with rotational flow, length profile studies are much more effective in understanding snail ecology than cross-sectional surveys (this thesis).

4. Irrigation authorities should bear responsibility for the control of water-related diseases.

5. GIS-based simulation models generally demand high input of detailed data, whereas many applications can effectively be realised with good insight and creative thinking.

6. The requirement of funding agencies to include more than three partners in a research project may be politically correct, but is practically unworkable.

7. Het feit dat er in het Nederlands geen woord bekend is voor mensen die niet kunnen ruiken, toont de onderwaardering voor het reukorgaan aan.

8. Skieën leer je niet door vallen en opstaan.

Eline Boelee

"Irrigation ecology of schistosomiasis: environmental control options in Morocco." (26 January, 2000)

IRRIGATION ECOLOGY OF SCHISTOSOMIASIS:
Environmental control options in Morocco

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IRRIGATION ECOLOGY OF SCHISTOSOMIASIS:
Environmental control options in Morocco

Eline Boelee

PROEFSCHRIFT

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Voor mijn ouders

ABSTRACT

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The concept of *irrigation ecology* is introduced to study the transmission and the control of urinary schistosomiasis in Moroccan irrigation systems. By distinguishing a biological, a human and an irrigation environment, crucial interactions are identified in the overlap of these three environments. In the semi-arid Haouz plain in Central Morocco, schistosomiasis was introduced after the construction of the Tessaout Amont irrigation system in the early 1970s. The typical design of this canal irrigation system, with elevated semi-circular conduits as secondary and tertiary canals, is based on upstream control and the water is distributed in rotation. Inverted siphons, consisting of two square boxes connected by an underground pipe, have been constructed to convey the water under roads or tracks. The boxes contain stagnant water and provide excellent breeding sites for *Bulinus truncatus*, the intermediate snail host of schistosomiasis. A cross-sectional survey showed that especially inverted siphons on tertiary canals harbour high densities of *B.truncatus*. A length profile study along one secondary canal and four of its tertiaries showed that conditions near the tail end of canals, especially in the downstream siphon boxes, are most favourable to the intermediate snail host. The transmission of schistosomiasis in Tessaout Amont is concentrated at these siphons as, in the absence of other sources, water from the boxes is used for all kinds of agricultural and domestic purposes, inducing frequent water contact.

Three environmental control options have been studied. Regular emptying and cleaning of siphon boxes had a limited effect on densities of *Bulinus truncatus* snails and eggs. Creating a dark environment by covering siphon boxes with iron plates proved to be much more effective in reducing *B.truncatus* populations. Some of the covers were equipped with moveable lids to leave the water accessible to the villagers. The third control option concerned measures to increase the water flow velocity in siphons. Combining flow velocities with the duration of the flow results in a mean annual flow velocity. According to literature, above a critical value of 0.042 m/s, no *B.truncatus* snails are to be found in siphon boxes. In siphons with a lower mean annual flow velocity, this critical value can be obtained by reducing the inner dimensions of the siphon boxes, thus increasing the water flow velocity. However, in experiments with such smaller siphon boxes, the siphons were quickly repopulated with *B.truncatus*. Better results might be achieved by redefining the critical value. However, the small diameter siphons generate higher energy losses. Consequently, such siphons can only be applied in a layout where access to the fields is guaranteed through simple bridges over the drains, which significantly reduces the number of required siphons.

Key words
Bulinus truncatus, design, ecology, environmental control, irrigation, Morocco, schistosomiasis, siphon, snail, water management, water use.

PREFACE

In 1986, when I started my studies in Wageningen, one of the first courses we did consisted of group work on an interdisciplinary subject: health impacts of water resources developments. I was stunned to find out that projects intended to increase food supply and thus contribute to well-being of the farmers, could also make them literally sick. While over the years I learnt to see this phenomenon in a wider perspective, the initial feeling of indignation never left me and I decided to specialize on it. The late Jacques Slabbers was one of the first people in Wageningen who encouraged me to take this direction. While during my study, many doubts arose whether a study in medicine or vector biology would not be more appropriate, I became an irrigation engineer and never regretted that.

After graduation, when I wanted to put my knowledge into practice and work on environmental control of water-related diseases, there were no such jobs to apply to. Many friends and colleagues commented on my initial research proposal and it was Frans Huibers who got me into contact with Bruno Gryseels. He gave me the chance to contribute to a project proposal that received funding (grant CT93AVI0004) under the EU-Avicenne programme for research activities in the Mediterranean region. Bruno Gryseels has been a great inspiration to the team and I want to thank him for his trust.

In Morocco, I worked at the Institut Agronomique et Vétérinaire Hassan II, where the director, Dr. Sedrati has been most accommodating. Khalid Khallaayoune at the Department of Parasitology was the national coordinator of the project; without him the project would not even have been possible. If we could get hold of him, Abdelhafid Debbarh was always prepared for prompt and inspiring discussions. From the very beginning, Hammou Laamrani was more than a counterpart. The large contrasts in both our cultural backgrounds, disciplines and personalities made collaboration sometimes difficult, but always interesting and often very rewarding, both scientifically and personally.

The fieldwork in Attaouia was facilitated by the assistance of Mjid Laghroubi, Slimani and many students: Abdelilah, Aminatou, Asmae, Delilah, Edine, Hayat, Menno, Oumeima, Rajaa, Saddeq, Sakina and Timoté. Thank you all. People at the Irrigation Board, notably the chief engineer Samir and later Ghaoui facilitated our research activities in many ways, as did their colleagues at the ORMVAH in Marrakech. The local health centre provided us with working space and good reliable data.

In 1995 I returned to the Netherlands and found a stimulating working environment with André Deelder and other colleagues at the Laboratory of Parasitology in Leiden. *Later I continued the data analysis and finalized this thesis at the Irrigation* and Water Engineering Group in Wageningen University, where Linden Vincent and other occupants of the "Nieuwlanden" made me feel very welcome. Here I had the most fruitful discussions with Frans Huibers, who has been a great support to me throughout the years. In the last year of writing, the keen guidance of Reinder Feddes much facilitated me in composing a whole thesis out of many different papers.

Both in Leiden and Wageningen, I often shared my room. In chronological order I want to thank my room mates Seydou, Anthony, Katja, Lisette, Ria, Kiné, Djemila, Alexandra, Sergio, Joost, Esha, José, Andrea, Simon and Robina for being good company.

Some sections in this thesis (in Chapter 6 and 7) have been based on papers that were written with co-authors, whose respective contributions are much appreciated. Henry Madsen helped Hammou Laamrani and me in the statistical analyses for Sections 6.1, 6.2 and 7.2. The calculations in Appendix V have been applied together with Bert de Jager. In addition, others have given their comments on earlier versions of the chapters. In particular I am thankful to Katja Polman, Sake de Vlas, Wim van der Hoek and Flemming Konradsen for their comments on Chapter 1, to the Crump Weirdo's for tough but useful comments on Chapter 3, and to Paul van Hofwegen and Hugh Turral for comments on the paper for the Oxford Workshop that led to Section 5.2. In the final editing of the report, José Janssen familiarized me with Arcview and the scanner, contributing to a large extent to the present good looks of this thesis. Hugh Turral and Dini Pieterse corrected my English in the Summary & Conclusions and in the Abstract, while Hammou Laamrani took care of the French translation.

Finally I want to thank all my friends and family that I have not yet mentioned by name for their love and support. Most of all I want to thank Fred for always being there and slowing me down when I was trying to run faster than I could.

Eline

Colombo, November 1999

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IRRIGATION AND HEALTH: AN OVERVIEW

Irrigation aims at increasing or securing agricultural production and is very important for local and global food production. About 17% of all cropped land is irrigated world wide, with yields per hectare that are on average 2.2 times the yield of rain-fed agriculture. By providing 40% of the world's food, irrigated agriculture substantially contributes to human health by fighting malnutrition.

At the same time, irrigation systems are associated with increased spread of water-related diseases such as malaria and *schistosomiasis, that is also referred to as bilharzia or snail fever.* The enforcement of large state managed irrigation systems has upset social relations and equity of peasant irrigation in many regions (e.g. Mollinga 1998, Boelens & Dávila 1998). In other areas environmental damage through salinization or sodification turned out to be irreversible (e.g. Trouw 1994). Negative environmental impacts and social disruptions may even invalidate increased yields and other benefits of irrigation development.

Impacts of irrigation and water resources development on health have been extensively reviewed by researchers in different disciplines (e.g. Oomen et al 1988 & 1990, Weil et al 1990, Hunter et al 1993). With the publication of many case studies, the irrigation engineers who are responsible for design and water management become more and more aware of these impacts. However, there is insufficient knowledge of how exactly and to what extent the transmission mechanisms of water-related diseases are modified. As a result, it remains hard to predict the environmental impact of irrigation design and water management.

1.1. HEALTH IMPACTS OF IRRIGATION

1.1.1. Positive impacts: health benefits

Higher and more diverse food production in irrigated agriculture brings health benefits to farmer families in the newly irrigated areas. People may gain access to more varied and higher quality nutrition through increased income from cash crops. The construction or rehabilitation of irrigation systems has other positive impacts on the human environment through increased employment possibilities, which would raise income and subsequently increase access to health services and education. However, an increased income is not always spent on health care. Access to health services, water supply and sanitation can be facilitated if with the planning of a new irrigation system these additional services are included. Irrigation can also influence the wider physical environment in a positive way and thus increase human wellbeing. E.g. seepage from earthen irrigation canals improves the quality of ground water. In South Asia handpumps are installed along the canals to extract this sweet water for drinking.

Diseases may also be reduced with the development of water resources. Water-washed diseases like louse-borne infections and infectious eye and skin diseases may be reduced dramatically. The better availability of water, regardless of quality, enhances personal hygiene practices (Cairncross & Feachem 1993). This effect is especially widespread in arid and semi-arid regions, where irrigation systems may be the main source of water for all purposes (Section 1.3). In dry regions vector-borne diseases may be diminished, such as African trypanosomiasis, sleeping sickness (Hunter et al 1993). Tsetse flies prefer dry air and are probably chased away from the relative humidity of irrigated fields (Takken 1989).

1.1.2. Negative impacts: health hazards

A whole complex of factors associated with water resources development changes the environment and may eventually lead to negative impacts on human health such as water-related diseases (Section 1.2). Bad health has a negative influence on broader economic and demographic developments. Chronically sick people have lower economic output and a consequently lower access to food. Poorer nutrition, in turn, increases susceptibility to disease and a downward spiral is started.

The health hazards may result from the irrigation system itself or from accompanying phenomena such as (seasonal) migration (Birley 1995). In the development of new systems, the decision over the location will influence migration patterns. Large scale irrigation systems under construction lead to the aggregation of people. Seasonal labourers can bring different kinds of infective and non-communicable diseases into the region. The migrants may in turn come into contact with new diseases without having immunity (Tiffen 1991). Families of migrant labourers may choose to remain after the construction is completed and create new settlements without proper infrastructure, live in unsanitary conditions and contribute to disputes over land and common property resources (Birley

1995). Settlers often have a low social and economical status and cannot be expected to improve their living conditions on the short term, even with land and water. Several infective diseases are associated with these poor living conditions and linked to crowding and inadequate solid waste disposal (Cairncross & Feachem 1993).

Changes in the water availability through irrigation may alter the cropping pattern. The replacement of subsistence crops by cash crops could lead to malnutrition through micronutrient deficiencies (Birley 1995). On the other hand, human health may profit more from increased income and higher food availability than it would suffer from diseases or deficiencies. However, these impacts may reach different groups of people. Farmers who own land may benefit directly from increased yields while landless labourers only suffer from negative health impacts without being able to improve their well-being in any other way. Positive health impacts do not cancel out the negative ones if they affect different groups of people to various degrees. The extent as well as the importance of the total health impact of irrigation development is therefore extremely difficult to determine.

1.2. WATER-RELATED DISEASES IN IRRIGATION SYSTEMS

Most of the negative impacts of irrigation development on health consist of *water-related vector-borne diseases: parasitic diseases that are transmitted by a vector or that have an intermediate host that is dependent on water for its development. A vector is a blood-sucking insect that transmits disease when it feeds on a host, while an intermediate host does not transmit the disease directly but is necessary for the development of the parasite.* Many field studies have described the influence of irrigation on the spread of these water-related diseases (for complete overviews see e.g. Oomen et al 1988 and 1990, Bolton 1992, Hunter et al 1993, Steele et al 1997).

1.2.1. Spread of diseases with irrigation development

The construction of an irrigation system creates new water bodies in an area which may turn into breeding sites for vectors or intermediate hosts. Simultaneously people who use the irrigation system are exposed to breeding sites, vectors and disease agents. The association between irrigation and vector-borne diseases is probably as old as irrigation itself and has been systematically reported since the second half of the nineteenth century. Water-related diseases each have their own specific transmission cycle and relate differently to water and the irrigation system.

Breeding sites for malaria mosquitoes, *Anopheles* species, are found in clear surface water, well available in irrigation systems and an increase in vectors almost invariably leads to an increase in malaria (Box 1.1).

BOX 1.1 - Expansion of irrigated area leading to malaria increase

In the mid 19th century the building of irrigation canals in India was followed by large malaria outbreaks (Bradley 1995). More recent studies in India show malaria rates that are 6-9 times higher (depending on the season) in villages along irrigation canals than in villages 40 km away (Hunter et al 1993). In the Indus River Basin Irrigation Development Project in Pakistan 25 large and medium sized dams were constructed for irrigation, causing a sharp rise in malaria infections. The 38 000 ha Helmand River Irrigation Project in Afghanistan led to a similar increase in malaria (Diamant 1980).

Wet rice fields are notorious for providing almost ideal breeding sites and rice field breeding *Anopheles* account for a great deal of the malaria transmission in rice-growing areas of the world (Gratz 1988). Irrigation often facilitates double or even triple cropping of rice, allowing for year-round transmission. As a result, mosquito abundance and density increases while the mosquitoes may live longer, allowing malaria parasites to complete their developmental cycle in the adult insect so they can be passed on to another host. Mathematical modelling has shown that these two factors together with possible changes in feeding habits, determine whether epidemics break out. Or it could lead from a situation of low and irregular transmission to a situation with continuous high transmission that will put a heavy toll especially on young children, who have not yet build up any resistance (Bradley 1995). Only in cases where specific measures are taken, such as early diagnosis, prophylaxis, medication or bednets, does an increase in mosquito population not lead to increase in malaria.

The high incidence and wider spread of the infection resulting from an increase in vectors or intermediate hosts is observed for other water-related diseases than malaria too (Box 1.2). In some cases, the creation of favourable conditions for disease transmission may be caused by circumstances outside the irrigation system. For instance, soil erosion in the catchment area may lead to excessive sedimentation in irrigation canals and structures, that develop into suitable sites for aquatic weeds. This vegetation in turn can harbour large populations of vectors or intermediate hosts of water-related diseases.

BOX 1.2 - Spread of diseases after vector population increase

In Burkina Faso a rice irrigation system was started in the Tiao river valley in 1955 that very quickly became an intense area of onchocerciasis (river blindness), transmitted by small blackflies. Virtually the whole population was affected and 50% of people over 40 were blind by 1962 (Hunter et al 1993). In France and former Czechoslovakia the expansion of rice growing has resulted in a rise in various viral infections through the increase of vector mosquito populations (Mather & Trinh Ton That 1984).

In Cameroon a rice project brought almost 20 000 ha under irrigation. Infection rates of schistosomiasis rose from 15 to 40% in schoolchildren. In Madagascar, occurrence of schistosomiasis at schools within the irrigation system was 69%, while outside the scheme it was 7%. In Mali schistosomiasis is 5 times more common near irrigated rice fields of the *Office du Niger* than in traditional villages, while the rate of severe infection is 7 times higher (Hunter et al 1993). In the Caribbean Islands schistosomiasis has spread as well with water resources development. In Puerto Rico the shift from coffee production to sugar cane, supported by the development of irrigation systems, resulted in the spread of schistosomiasis in the 1930s (Oomen et al 1988).

Mostly the mechanisms that play a role in increasing transmission rates are very complex and dynamic. The farming system and subsequently the entire biological and human environment are often drastically changed with the introduction of irrigation. The process of mutual influences and interactions leading to disease transmission then becomes fundamentally different. Domestic animals may divert blood sucking insects (Samarasinghe 1986) but can also contribute to the spread of viral diseases (Box 1.3).

BOX 1.3 - The role of domestic animals in the spread of water-related disease

The establishment of large, modern pig farms in southern and eastern Asia has triggered the spread of japanese encephalitis, a viral disease transmitted by mosquitoes (Gratz 1988). In the Mahaweli rice irrigation system in Sri Lanka, pig production was deliberately and successfully promoted. The pigs provided a reservoir for Japanese encephalitis, that was then rapidly spread to the human population by the mosquitoes breeding in the rice fields (Service 1998, Steele et al 1997).

When draught animals are sold and replaced by tractors, mosquitoes may change their biting behaviour from cattle to men and cause an epidemic. The same may happen for ticks when wild animals disappear as vast areas of forest are cleared (Vitarana et al 1986). In other cases the simultaneous increase in suitable breeding sites for vectors or intermediate hosts and human migration together with an insufficient health system create the ideal circumstances for water-related diseases (Boxes 1.4, 1.5 and 1.6).

BOX 1.4 - Complex health hazards of irrigation development in northern Senegal

In the lower Senegal river basin, the replacement of traditional earthen dams by large concrete dams in the 1970s influenced the hydrological and ecological situation in the valley. At the same time, the sugar factory in the town of Richard Toll expanded. The meandering river transporting water from Lake Guiers to the sugar cane fields was replaced by a canal, that had stable and high water levels since the construction of the dams. In the old river bed dead arms with plenty aquatic vegetation provided excellent breeding sites, massively invaded by *Biomphalaria* snails, intermediate host of *Schistosoma mansoni*. The sugar factory attracted thousands of labourers from all over the country. In twenty years, the population in Richard Toll increased tenfold from 5 000 to 50 000, in 1994 over 60 000. Water supply and sanitation facilities for the booming population were inadequate and as a consequence, river and irrigation canals were the only sewers and the main sources of water for many people. The entire health situation has deteriorated. Malaria was the most important public health problem in this area before the construction of the dam and the irrigation system. Now schistosomiasis has become an increasing burden to the local health system, with almost the entire population infected with very high worm loads. Other health problems that have simultaneously increased are typhoid fever, cholera, rift valley fever, sexually transmitted diseases and malnutrition (WASH 1994, Kongs & Verlé 1994, Stelma 1997).

BOX 1.5 - Complex health hazards of irrigation development in Turkey

In Turkey a combination of poor water management and absence of maintenance in large irrigation systems in southern Anatolia led to silting up of canals and poorly drained ditches where large *Anopheles* populations prospered. The uncontrolled flux of migrant workers and simultaneous failure of the public health system led to malaria epidemics. With tens of thousands cases of malaria in 1976 and over 115 000 in 1977 national emergency was declared and massive funds had to be mobilized (Weil et al 1990, Hunter et al 1993).

BOX 1.6 - Complex health hazards of irrigation development along the Nile

Oomen et al (1988) give extensive details on the history of malaria and schistosomiasis in Sudan. Since the Gezira Irrigation System began in 1924, malaria has been closely linked to agricultural development. During the first 25 years reasonable malaria control was possible through good water management and larviciding. After 1950, when the irrigation system expanded and created more breeding sites, an intensification of cropping added water continuously to the larvae-producing minor canals. At the same time, large-scale applications of chemicals both against agricultural pests and for malaria control, had caused pesticide resistance in malaria mosquitoes. Together this led to severe malaria outbreaks in 1973 and 1974. Later in the 1970s the communications and control systems in the main canals broke down. Combined with heavy aquatic growth due to inadequate maintenance, all canals had to be fuller to deliver water to the crops. Without precise regulation they were prone to overflowing. An other complicating factor was the large labour force from malarious areas. These people were often outside health programmes and could easily bring infections into the area.

The Gezira irrigation systems have resulted in a similar increase of schistosomiasis. The same minor canals that favoured mosquito development, also stimulated high snail populations most of the year. These canals with clear water and dense vegetation, provided night storage and were close to villages, so water contact was high. Urinary schistosomiasis has increased from less than 1% before World War II to affecting almost a quarter of the adults and half of the children in the 1950s. Intestinal schistosomiasis rose even more from 5% in 1949 till 86% in 1973, in children of 7 to 9 years old, often the group with highest infection rates. An other vulnerable group consisted of the canal cleaners, who stayed daily for long hours in the infested water.

The Nile dams in Sudan added to the effect that the dams in upper Egypt already had on the transmission of schistosomiasis throughout the country. In the 1930s, the conversion from traditional flood irrigation to perennial irrigation after construction of the low Aswan dam led to high human population densities, intensive agricultural practices and frequent prolonged water contact. Infection rates of urinary schistosomiasis increased from 0-11 to 34-75 percent (Hunter et al 1993).

1.2.2. Analysis of health hazards

The complex and dynamic interactions between the irrigation system, people and water-related diseases make it difficult to analyze the mechanisms leading to increased health hazards. This is further hampered by methodological problems. In only a limited number of situations has it been possible to base the conclusions on a comparison of pre- and post-irrigation surveys. Most commonly, studies in an irrigation system are compared with data from nearby areas without irrigation, though adjacent regions may not be entirely similar (Weil et al 1990). Combined with a mono-disciplinary view on what often is a complex interdisciplinary situation, the exact cause of increase in disease remains indistinct, even in the case of epidemics. Sometimes this unclarity has led to cases where irrigation has been mentioned as the cause of an outbreak of water-related diseases without thorough proof.

Earlier analyses of case studies have led to the identification of certain key factors, characteristics of irrigation systems that foster the development of vectors or intermediate hosts (Speelman & Van den Top 1986, Weil et al 1990, Tiffen 1991, Hunter et al 1993, Slootweg 1994). Most of these key factors lead to the creation of water bodies with stagnant or slow flowing water, favourite breeding sites to most vectors and intermediate hosts.

When a region is characterized by an irregular topography with small depressions, these low-lying parts will often not be included in the irrigation system and may turn into water ponds. Soils with low permeability may cause water logging, especially when fields are uneven. In practice these soils are often considered very suitable for (rice) irrigation because losses of water and nutrients through percolation are prevented and water use efficiencies are high. The cultivation of certain crops, notably rice and sugar cane, requires continuous irrigation, resulting in permanently slow flowing water in canals and fields. Without a proper functioning drainage system the ground water table may rise, creating pools, while salinization or sodification may damage the soil permanently. Borrow pits created for ground works may fill up with water and provide deep vector habitats.

The construction material of irrigation systems is also important. Earthen canals allow for low flow velocities only, while poorly constructed or maintained canals may leak and create puddles alongside the canal or in the canal bed itself. Concrete hydraulic structures may have permanently standing water.

The characteristics of irrigation systems that stimulate the breeding of vectors and intermediate hosts might be manipulated for control purposes. However, the mechanisms leading to the spread of water-related diseases are much more complex, so many other biological and human factors and their interaction with irrigation need to be identified as well.

1.2.3. Environmental control recommendations

In the literature it has been argued that negative health impacts of irrigation could be prevented by designing an irrigation system without the characteristics that foster the development of vectors and intermediate hosts. This is referred to as *environmental management for vector control*, defined as:

> "Planning, organization, carrying out and monitoring of activities for the modification and/or manipulation of environmental factors or their interaction with man, with a view to preventing or minimizing vector propagation and reducing man-vector-pathogen contact" (Phillips et al 1993).

In this definition, the term *vector* includes intermediate hosts as well. Modification refers here to physical transformation of land, water or vegetation that is permanent or long-lasting while planned recurrent activities are called environmental manipulation. Thus, it is argued, the irrigation system becomes an environment that is, in theory, permanently hostile or at least not favourable to vector breeding.

Measures for environmental control have been applied for ages in many countries till the first half of this century (Box 1.7). With the introduction of DDT in the 1940s, environmental management seemed no longer necessary. Excessive spraying of fields, bushes, houses and even people replaced the inter-disciplinary cooperation and at that time almost eradicated malaria in some countries. In a similar approach, the snail host of schistosomiasis was attacked with molluscicides. As a consequence, augmenting resistance of vectors to pesticides and unwanted effects in *non-target organisms* occurred. More efficient drugs have been developed, but the distribution is difficult, reinfection is not prevented and parasites become resistant to the treatment.

BOX 1.7 - Environmental control in colonial Indonesia

In Indonesia the so-called "hygienic exploitation" was developed at the beginning of the 20th century by civil engineers together with medical specialists and entomologists. The efforts were directed mainly against malaria. First the local vector was identified and then the habitat of this particular *Anopheles* species was dealt with. All kinds of measures were experimented with in order to diminish vector populations in canals, ponds and rice fields. In a lot of cases vector density and malaria infection rates decreased significantly. A good example is the management of marine fish ponds that could sustain large populations of vector mosquitoes. The hygienic exploitation in this case involved frequent drying of the ponds to reduce floating algae that provide shelter to larvae against fish. It led to strong reductions in malaria occurrence (Takken et al 1990).

Nowadays the health sector has come to rely on environmental management again as a part of integral disease control approaches. However, these measures are usually based on a logical reversal or elimination of the factors determining the breeding of vectors and intermediate hosts rather than on a systematic approach based on full understanding of at least the local mechanisms that lead from irrigation development to the spread of water related diseases. As a result, the recommendations are mostly limited to preventive measures that can be incorporated into the design of new irrigation systems.

Preventive environmental control

Apart from avoiding the characteristics that foster the development of vectors and intermediate hosts, the siting of villages and drinking water supply appeared to be important factors (Box 1.8). The distance between irrigation infrastructure and habitation may determine how often and how intensely the population is exposed to vectors or infested water. For several mosquito species, the flight range is known and when houses are located at a larger distance from the breeding sites, people will be less exposed to possibly infective bites. However, the benefits of having a canal nearby the house, may be numerous too, as will be discussed in Section 1.3.

BOX 1.8 - Design for schistosomiasis control in Zimbabwe

In Zimbabwe schistosomiasis control determined to a large extent the final design of small holder irrigation systems in Mushandike. Villages were located as far as possible from potentially infected water. Boreholes with handpumps were constructed near each village, but hardly used for laundry as the borehole water was too hard for washing clothes. The latrine-programme, consisting of building instructions and the provision of cement for latrines, was not very successful because of the hard bedrock. Consequently, the main environmental control measures consisted of interventions in the concrete lined irrigation system. Hydraulic structures such as sluice gates, weirs and field inlets had an adapted design to avoid standing water. In the operation of the system, regular drying of canals, water level fluctuation in night reservoirs, regular maintenance and routine cleaning contributed to continuous control of the intermediate snail host. A uniform cropping pattern of maize and cotton in summer, followed by wheat and vegetables in winter, maximized uniformity in water usage. Infection rates were monitored and people received medication. Snail hosts remained present but in low populations, apparently enough to substantially reduce the transmission potential. Despite continuing water contact and failing sanitation, the reduction in schistosomiasis was more than in villages where only treatment was given (Draper & Bolton 1986, Bolton 1988, Chandiwana et al 1988, Chimbari et al 1993).

Good construction practices are crucial in the implementation of a new irrigation system. Fields that are evenly laid out, require less water than poorly prepared lands, while puddles and other breeding sites are less likely to form. Canals with the right elevation, size and slope will be less prone to erosion and can convey water at higher velocities without overtopping. During the construction works, when all the equipment is in the field, last minute adjustments to the design can be made and additional provisions like bridges and fences can be included in the works. Unfortunately, the preventive measures that are proposed in the literature can hardly be tested in practice, as extension of the area under irrigation is only possible in a few regions around the world. Most environmental control of water-related diseases would have to take place in existing irrigation systems.

1.2.4. Environmental control in existing irrigation systems

There appears to be little systematic experience in environmental management for vector control in existing irrigation systems. The main reason for this is that most design or construction characteristics cannot be modified without hindering the functioning of the irrigation system. The system may be several months out of production for redesign and construction works, which requires a lot of investments. Actually most proposed environmental measures against breeding sites and the transmission of water-related diseases can only be implemented when an irrigation system needs important renovation or rehabilitation. This may occur several decades after the first implementation of the system for several reasons, such as overdue maintenance, change in land use patterns, increase or decrease in population, or inadequate construction. On the other hand, the rationale behind design decisions often still holds true at the time of a rehabilitation. E.g. when night storage reservoirs were opted for, these may not easily be eliminated or in a later stage modified for disease control purposes only. The lining of earthen canals to allow higher flow velocities and the replacement of structures generally is too costly, even for large scale rehabilitation.

The only remaining options for manipulation of system characteristics to control vector breeding and water-related diseases seem to be in maintenance and water management. Good cleaning and preventive maintenance of all irrigation infrastructure such as canals, structures and drains will reduce the breeding of vectors and intermediate hosts, while also improve irrigation performance. The periodic removal of aquatic weeds from canals reduces friction and thus increases conveyance efficiencies, while it can have a significant impact on vector mosquito larvae and aquatic snails (Box 1.9).

BOX 1.9 - Improved weed removal for vector control

In the Philippines frequent weeding resulted in increased yield through higher availability of water, while snail densities diminished. In Egypt and Sudan weed control in canals has been applied as an effective method of vector control. On the other hand, routine cleaning work can be a health hazard as such. In Gezira, Sudan the special canal cleaning personnel became the most infected group and maintained the transmission of schistosomiasis (Fenwick et al 1982). In other regions attempts have been made to prevent this effect and adapt the time of cleaning activities to the cycle of the parasite. In the Fayoum oasis in Egypt different types of weed removal were evaluated. The use of fish, grass carp, to control aquatic weed and mechanised bucket mowing were most efficient against the intermediate snail host of schistosomiasis. Simultaneously, alternative hand tools were developed to reduce water contact during cleaning work (Euroconsult 1993). An opposite strategy has been advised too. Pollution of drains and field canals with sisal and sugar cane wastes has been used with success against malaria mosquitoes in Sri Lanka and the Philippines. In India decaying matter from palm leaves or toxin-containing plants caused a shift in mosquito fauna from vector anophelines to various culicines. This could be a problem when the new mosquitoes are man-biters, but in most cases *Anopheles* are considered the greater danger (Rajagopalan et al 1990).

Adapted water management has often been suggested in bio-medical studies as an easy and cheap measure for vector control. Contrastingly, very few examples can be found in the literature of experiments with this type of environmental manipulation, because in practice it is not so easy nor cheap to change established water management patterns.

Water management interacts not only with vector breeding or disease transmission, but also with the irrigation system itself. Changes in the water distribution often require modifications in the design, notably the sizing of canals and type of structures. If e.g. continuous delivery is replaced by rotation of the water flow to disrupt breeding sites, the discharge in the canals alters from constant low flows to intermittent high flow, requiring large size canals. At the same time the wider human environment is influenced. With water flowing in the canals continuously, farmers can use it to irrigate their crops whenever they want. With rotation, the flow has to be divided over time between (groups of) users, demanding a high level of organization. Water scheduling for meeting crop water requirements is complicated, especially when conflicting interests between higher water use efficiencies and farmers demanding flexibility have to be taken into account. If disease control measures have to be observed as well, scheduling becomes an almost impossible task.

In particular cases in Asia where vectors are restricted to rice fields, a locally adapted farm water management system has been shown to reduce mosquito and snail populations. With this so-called intermittent irrigation method exact water quantities are applied at field level (Box 1.10). This requires accurate water deliveries from the canals and influences the organization of water management up to system level.

BOX 1.10 - Intermittent rice irrigation for vector control in Asia

In China the so-called intermittent irrigation method has been developed in close cooperation between agronomists, entomologists and irrigation workers. Instead of providing a continuous water layer on the rice fields, the water is drained off 10-15 days after transplanting, when the plants turn green. The fields are then filled with a shallow layer of water that disappears through absorption, percolation and evaporation within 48 hours. This is repeated every 4-5 days. The intermittent irrigation method effectively controlled mosquitoes, vectors of malaria and lymphatic filariasis. Experiments showed that the method contributed to higher yields and water savings. As a result, farmers adopted the method on over 10 000 ha in 1980 (Luh 1984). In the Philippines a local adaptation of this method was developed for the control of intermediate snail hosts. In addition to intermittent irrigation, weeds were cut and the fields were ploughed and harrowed twice a fortnight before planting. Till harvesting there were two more weedings, while water control was improved by building small dikes around the plots. Snail populations were reduced and rice yields were almost twice as high under improved methods (Pike 1987).

Another suggestion for the control of mosquito or snail populations in irrigation canals is to periodically flush canal sections between check structures. The high water velocity not only removes vector populations by washing them away or leaving them stranded high on the canal banks, it scours out silt deposits too. This is only possible under certain conditions, when the canal is large enough and special structures can be installed in the canal bed (Box 1.11).

BOX 1.11 - Flushing for vector control

In the Philippines, Sri Lanka, Puerto Rico and India malaria mosquitoes and schistosomiasis snails live primarily in irrigation canals. Intermittent flushing with automatic self-starting and self-arresting siphons was successful in vector control as early as the 1930s (Krusé & Lesaca 1955, Hunter et al 1993). An intervention like this can hardly be installed in earthen canals. Perhaps comparable to a large earthen canal was the small river in Tanzania, where a special weir was installed. Snail populations were flushed away, stranded on the river banks and could not repopulate the river bed (Fritsch 1993). In Mauritius flushing through rubble masonry for malaria vector control also reduced snail populations (Pike 1987).

1.3. MULTIPURPOSE USE OF WATER IN IRRIGATION SYSTEMS

Health is also influenced by irrigation development when the water, destined at agricultural crops, is used for other purposes. This may have positive and negative health impacts as well and is influenced by the availability of other water resources.

The different environmental control measures often require high levels of irrigation water management and depend on reliable water supplies. In many irrigation systems around the world however, insecurity and instability of water availability are more common than water-related diseases. Farmers have often responded to this situation by accumulating water. As a result, many environmental control measures loose their effect (Van de Laar 1993).

1.3.1. The use of irrigation water for non-agricultural purposes

Few open canal irrigation systems exist were the water is used solely for agricultural purposes. Generally the water in the canals is, in addition to irrigating main crops, used for all kinds of agricultural, domestic, municipal, industrial and recreational purposes. These activities may influence the water quantity, the quality or both.

At river basin level the allocation of water resources to different sectors in an approach of integrated water management is becoming common practice (e.g. Berkoff 1994, Heathcote 1998). Water from large dams and reservoirs is often used for the generation of hydropower, for industry, for municipal water supplies, as well as for irrigation. In intersectoral negotiations over water, irrigation often comes after energy, municipal water supply and industrial supply, because of the low expected revenues from irrigated agriculture. This could change if all actual uses of water would be included (Meinzen-Dick 1997).

The different uses of water within irrigation systems are poorly documented; what really happens after the intake structure, at farm or household level, how much water is used in what way for what purpose, is hardly studied. One of the reasons for this is that the water use is often scattered. Another reason is that the quantity of water withdrawn from the irrigation system for domestic uses generally is a very small fraction of the total irrigation water (Yoder 1983). But perhaps the most important reason for the lack of information is that this multipurpose use of irrigation water is not formally recognized and, for water quality reasons, perceived as sensitive matter.

An irrigation board or water users association may ignore or even deny the ad hoc or systematic use of irrigation water for not planned purposes. E.g. the watering of home gardens is often explicitly forbidden in areas of water scarcity. Other activities such as fishing in canals, are hardly ever considered a problem because these normally would not interfere with the functioning of the irrigation system. The use of canals for laundry is usually tolerated too or even facilitated through special provisions that prevent damage to the existing infrastructure (Box 1.12).

BOX 1.12 - Adaptations of irrigation infrastructure

Steps may be constructed in canals to provide easy access to the water for washing and livestock watering, while protecting the banks, e.g. in Egypt. In Northern Portugal water mills form an integrated part of small-scale farmer managed irrigation systems and have their own intake structure. The canal water also flows constantly through washing tanks and cattle troughs (Boelee 1992). These provisions are as old as the system itself and widely accepted, though sometimes pollution with soap and sewage causes problems downstream (Stam 1993).

In semi-arid and arid countries, where irrigation systems are often the only available source of water for all purposes, tanks for community water supply may be fed directly from the irrigation system. In many villages in the Punjab of Pakistan and in Central Morocco such tanks may be the only available source of water. The water taken from these tanks is sometimes treated at home, but often it is used for drinking, cooking or other household uses without any treatment or precaution.

1.3.2. Health impacts of multipurpose use of irrigation water

Benefits

The availability of water from irrigation systems often enhances hygiene and may thus have a direct benefit for health by reducing water-washed diseases. The use of irrigation water for cooking and consumption, despite its often questionable quality, may even diminish hygiene related diarrhoeal diseases. as water quantity is believed to be more important than quality (Konradsen et al 1997).

In areas where separate drinking water supply is available, irrigation canals and structures are often considered more practical for bathing and washing clothes, animals and household utensils. The waste water can be returned to the canal instead of soiling mud houses without sewerage. Besides that, it is more ergonomic to take laundry and utensils to a canal close by than to carry home large amounts of water. An additional advantage is that irrigation canals and the roads alongside can be used for transportation and thus add to energy savings (Yoder 1983). With such water-related activities, canals and structures develop into centres of social contacts and the irrigation system becomes part of the human environment the same way that houses do.

Irrigation canals can also be sources of high quality protein and micro-nutrients in the form of aquatic plants, fish, crustaceans and mollusca. The presence of an irrigation system enables people, often women, to divert water to their home gardens. These gardens may have trees bearing nutritious fruit, giving shade and providing wood for fuel. Live stock rearing, be it cattle, sheep, goats or chicken, may depend directly on water from irrigation systems, in addition to profiting from the higher availability of fodder from crop stubble. E.g. in India and Pakistan milk production is significantly better when irrigation water is available than when saline groundwater is the only source (Meinzen-Dick 1997).

Water from irrigation canals can also contribute to the development of local economic activities, be it small scale and informal such as butchers, car washing or market places, or medium scale with formal water rights such as ice factories in Pakistan. These rural industries may contribute to regional income generation. Hardly qualifying under health benefits, but definitely contributing to better health through disaster prevention is the use of irrigation water by fire brigades in southern Europe to help extinguish forest fires.

Hazards

When irrigation water is used directly for human consumption, without any treatment, faecal-orally transmitted diseases such as diarrhoea, dysenteries, poliomyelitis and hepatitis A may spread. Eggs or larvae of intestinal parasites are, in the absence of sanitation facilities, often excreted with faeces close to irrigation canals, especially when people use water for anal cleansing. Crops may be contaminated during irrigation or the water may be used further down the system for washing, cooking and drinking. The faecal contamination of irrigation water can be intentional. E.g. in Indonesia, latrines are often built directly over canals. Generally people do not use this water and prefer wells for drinking, rivers for laundry and both for bathing. But contact with this water in land preparation, rice planting and weeding is inevitable and when wells or rivers are too far, many people have no other alternative than to use the contaminated canal water for bathing and even drinking (Yoder 1983). Water contamination with excreta followed by water contact increases exposure to schistosomiasis (Box 1.13).

BOX 1.13 - Water contact in irrigation canals in Egypt

In the Egyptian Nile delta, all villages are situated next to canals or drains, that form an integrated part of rural daily life. The canals are used for e.g. laundry, bathing, washing of household utensils, swimming, watering animals, bathing animals, ablutions before prayer, washing grains, making dough, cooking and washing vegetables, while the same water courses are used for untreated sewerage and disposal of garbage and dead animals. Especially women and boys are, through their activities, highly exposed to diseases such as schistosomiasis (Talaat 1996).

Irrigation development is sometimes associated with high levels of agro-chemicals: fertilizers and pesticides. The chemicals applied to field crops may leak into the drains. In some parts of Asia small fish, crabs and snails that served as a source of nutritious protein to the local population, now have gone down in numbers because of the use of pesticides in upstream irrigation systems. Pesticides may also contaminate the water if the equipment used for spraying or mixing is washed in the canals. When the water is used for animal or human consumption downstream, the low concentrations may still be harmful to health. The chemicals can seldom be removed by cooking and not much is known about long term effects (Van der Hoek et al 1998). Pesticides are also applied directly into canals, for chemical control of aquatic weeds and occasionally against the intermediate snail hosts of schistosomiasis. The used products are often not very specific and may kill all organic life in the canal system.

1.3.3. Implications of multipurpose use of water

The assessment of health impacts of drinking water supply projects is hampered by methodological problems (e.g. Blum & Feachem 1983, Hoddinott 1996). The diverse character of multipurpose use of irrigation water and the lack of quantitative data, makes it even more difficult to estimate its overall effect on human health. Besides, as with health impacts of irrigation as such, it remains to be seen whether the positive and negative health impacts of multipurpose water use affect the same people.

Modification of the irrigation system

Still, it seems that for the whole of multipurpose uses, there are more health benefits than health hazards. The safe use of irrigation water for health improving activities, could be further encouraged by the provision of adequate facilities. Especially in arid and semi-arid regions, separate drinking water supply may not always be feasible. In those cases it could be considered to acknowledge and incorporate other water uses in irrigation systems. Unfortunately, multipurpose use might then even become a threat to irrigated agriculture. In parts of India, new rural water supply systems are being considered that incorporate irrigation tanks. In Northern Maharashtra an irrigation tank was proposed as a source for two large rural water systems. The total domestic demand plus evaporation loss, would be up to 50% of gross storage and thus seriously hamper the irrigation of crops (Vincent 1997). An additional problem to the integration of domestic and other water uses in irrigation systems is that drinking water supply often is the responsibility of other sectors and generally planned independently.

Whether multipurpose use of irrigation water is stimulated or not, certain water use activities will take place anyhow and special accommodations are required to avoid damage to existing infrastructure and to prevent the pollution of irrigation water. Provisions for bathing, laundry or the washing of household utensils and agricultural equipment would then have to be well constructed and properly drained to avoid the creation of puddles that attract mosquitoes. A major disadvantage of the stimulation of water use activities along canals is that water contact is enhanced, possibly increasing people's exposure to schistosomiasis. Therefore, additional sanitation and solid waste disposal facilities should be available and correctly used to avoid contamination of (irrigation) water sources. Pollution control should not only consider drainage, but also the use of pesticides and water use activities in upstream canals.

Water management

Contrary to the recommendations for vector control, continuous water flows in canals or intermittent flow with short rotation cycles are most suitable to facilitate access to irrigation water and maximize health benefits of multipurpose water use. Interruptions in the canal flow, suggested to reduce vector breeding sites, jeopardize the survival of home gardens or livestock and disrupt social patterns of water use activities. Flexible water distribution with special water rights for other activities than irrigation[1] might be needed. In existing systems constructed for supplementary irrigation, both system capacity and the availability of water resources may already allow for the development of multipurpose water management systems. In Hungary, modelling has made it possible to estimate

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[1] Not all irrigation systems have allocation and distribution based on water rights.

both amount and uncertainties of water resources available for other uses in the irrigation system (Dávid 1982).

The control of aquatic weeds is an important part of regular cleaning. In addition to maintaining the hydraulic shape and allowing for high(er) water velocities, it clears hiding places for mosquitoes and eliminates food for fresh water snails. Chemical weed control methods however, may kill all aquatic flora and fauna that could play a crucial role in the local diet or in income generating activities.

1.4. CONCLUSIONS

The examples from over a century of documentation of health impacts of irrigation show that insight into the mechanisms of increased disease transmission is restricted to the identification of the characteristics of irrigation systems that foster vector breeding or enhance human exposure. As a result, the number of projects where control measures have been designed and evaluated in a scientific way is limited. More attention to the actual use of irrigation water for all kinds of purposes will contribute to a complete overview of the diverse positive and negative health impacts of irrigation. *An overall analysis should consider the irrigation system as an integral part of the environment, interacting with people, vectors or intermediate hosts and parasites.*

2

OUTLINE OF THE THESIS

Relevance

In Chapter 1 it has been shown that human health can be harmed as well as enhanced with the introduction of irrigation. *Health impacts may thus limit or increase the sustainability of irrigation.* However, health is only one of the factors determining sustainable irrigation, while the definition of sustainable development is even wider:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations" (WCED 1987).

It is not obvious to achieve sustainable development through irrigation. An irrigation system has to be planned, designed and managed in such a way that it avoids adverse environmental impacts and ensures long term benefits and social equity (Roelofs 1998). One of these benefits would be improved health, which will be influenced by and have consequences for social, institutional, technical, financial and economic sustainability as well. The contribution of irrigated agriculture to sustainable development would be seriously restricted by water-related diseases or other health hazards and other environmental impacts. E.g. the changed hydrology, possible pollution of water and soil, erosion and sedimentation influence the ecology both in the irrigated area and in the downstream area and all have consequences for social, economic and cultural development. The environmental and health impacts appear to be linked in a complicated way. The complexity of mutual influences may lead to a chain of events and processes that is hard to predict. Many examples of such processes have been given for health impacts in Chapter 1.

Research theme

The study of these complex interactions needs an overall view, which in this thesis will be conceptualized as *irrigation ecology*. In order to obtain a better understanding of imbalances leading to problems such as health hazards, the concept of irrigation ecology will be focussed on a particular problem, the transmission and control of schistosomiasis in open canal irrigation systems in Morocco. This water-related disease is linked with irrigation in many different ways. *With the concept of* irrigation ecology, *crucial links and interactions between people and the irrigation system will be identified that lead to the spread of schistosomiasis.*

Background

Data discussed in this thesis have been collected in a research project entitled "Environmental control of schistosomiasis in irrigation schemes of the Mediterranean regions", funded by the European Commission under the Avicenne Programme, grant CT93-AVI-0004. The project was coordinated by the University of Leiden/Institute of Tropical Medicine Antwerp in collaboration with the Institut Agronomique et Vétérinaire Hassan II, the Danish Bilharziasis Laboratory, Wageningen Agricultural University and the Egyptian Ministry of Public Health. In addition to data from this research project, other primary data on irrigation aspects in the present thesis have been collected during earlier field studies in Ivory Coast and Portugal and during later missions to Morocco, Egypt, Senegal and Pakistan.

Thesis outline

In Chapter 1 the overview of health impacts of irrigation and multipurpose use of irrigation water showed that negative health hazards may be substantial. In the absence of a systematic approach, the characteristics of irrigated agriculture that have been identified as determinants of disease transmission have led to mostly ad hoc interventions with environmental disease control, without taking water use for other purposes than irrigation into consideration.

In Chapter 3 the concept of *irrigation ecology* will be introduced, providing an overall view for the identification of mechanisms in the interaction between the human, biological and irrigation environment, that lead to the transmission of diseases. The transmission cycle of schistosomiasis will be described in Section 3.2 in relation to irrigation. Strategies to control schistosomiasis will be discussed in Section 3.3. Current research and control approaches will be compared to the approach that would follow from the application of the concept of *irrigation ecology* on schistosomiasis transmission and control.

From Chapter 4 on, the thesis will be focussed on the transmission and control of urinary schistosomiasis in Morocco. In Section 4.1 rural water supply and the expansion of schistosomiasis following developments in the national irrigation environment will be discussed. This will be followed by an investigation of the schistosomiasis control and elimination programmes from the Moroccan health sector. In Section 4.2 the oasis of Akka in the South of Morocco will be presented. After a description of the sources of water for agricultural and domestic purposes, the water contact patterns and consequences for the transmission of schistosomiasis will be analyzed. Some recommendations for control measures, as proposed by the residents of Akka oasis, will be discussed. Section 4.3 will provide a short history of irrigation in the Haouz region in Central Morocco, introducing the Tessaout Amont irrigation system. Additionally some regional figures on schistosomiasis occurrence will be given.

In Chapter 5 the irrigation environment of Tessaout Amont will be investigated as well as the overlap with the human environment in relation to the water use that is exposing people to schistosomiasis. In Section 5.1 the technical irrigation design and water management characteristics of the modern open canal irrigation system of Tessaout Amont in Central Morocco will be dealt with. In Section 5.2 the multipurpose use of water and water contact patterns will be discussed, considering the availability of water from different sources in the region and criteria for water use.

In Chapter 6 the overlap between the irrigation environment and the biological environment will be investigated to analyze the distribution of the intermediate snail host of schistosomiasis, *Bulinus truncatus*, in the Tessaout Amont irrigation system. First, an inventory in Section 6.1. will determine the distribution of *B.truncatus* and other fresh water snail species over canals, structures and drains in the system. The link to irrigation design, water management and water use will be studied in more detail in Section 6.2, where one entire secondary canal and some of its tertiaries in Tessaout-Amont will be analyzed to obtain an ecological length profile.

In Chapter 7 the options for environmental control in the Tessaout Amont irrigation system will be investigated. In Section 7.1 the hydraulic considerations for inverted siphons will be analyzed in detail in order to identify alternative designs. These alternatives will be elaborated for increased water velocities. In Section 7.2 three interventions on inverted siphons in the Tessaout Amont irrigation system will be discussed: cleaning, covering and reduction of the physical dimensions. Finally recommendations will be formulated for environmental control of schistosomiasis in the Tessaout Amont irrigation system and in new Moroccan irrigation systems.

The thesis will be concluded with Summary and Conclusions.

3

IRRIGATION ECOLOGY AND SCHISTOSOMIASIS

3.1. THE CONCEPT OF IRRIGATION ECOLOGY

Irrigation ecology is a dynamic concept that provides an overall view for the analysis of health impacts in irrigation systems. By distinguishing three overlapping environments, complex interactions can relatively easy be identified in the overlap between the human, biological and irrigation environments (Figure 3.1). These interactions determine whether a situation can develop that is favourable to the transmission of water-related diseases. Irrigation systems are considered as very particular ecosystems, where the man-made physical environment generates a changing biological environment of crops, animals and (aquatic) weeds. Both the irrigation environment and the biological environment interact in a very specific way with the human environment of management and behaviour.

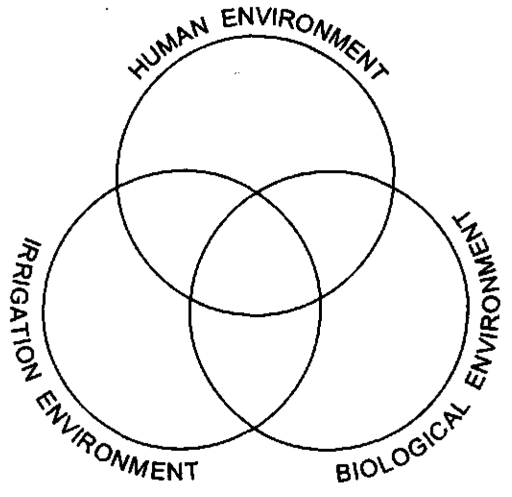


Figure 3.1. The overlapping human, biological and irrigation environments in irrigation ecology.

The term *irrigation ecology* has been used before in a different context. The ecological approach in social sciences attempted to explain "relations between selected human activities, biological transactions and physical processes by including them within a single analytical system, an ecosystem" (Geertz 1970).

Kraus (1992) applied the term *irrigation ecology* to irrigation systems as "a feature of adaptive social systems". In this thesis the concept is further developed to contain distinct overlaps between the separate human, biological and irrigation environments. As such the concept may be used not only to analyze the transmission of water-related diseases, but *irrigation ecology* could also be applied to other health hazards, environmental impacts or even totally different problems, such as crop pests or soil degradation.

The three environments in irrigation ecology

The *irrigation environment* has two dimensions: the *physical infrastructure*, resulting from conscious design, and *water management*. In this thesis irrigation is restricted to *surface systems with open canals, structures and drains* that use water from a deliberately mobilized surface or subsurface source (Figure 3.2). Irrigation with drainage or waste water is excluded, as well as sprinkler and drip irrigation with completely closed systems and pumps.

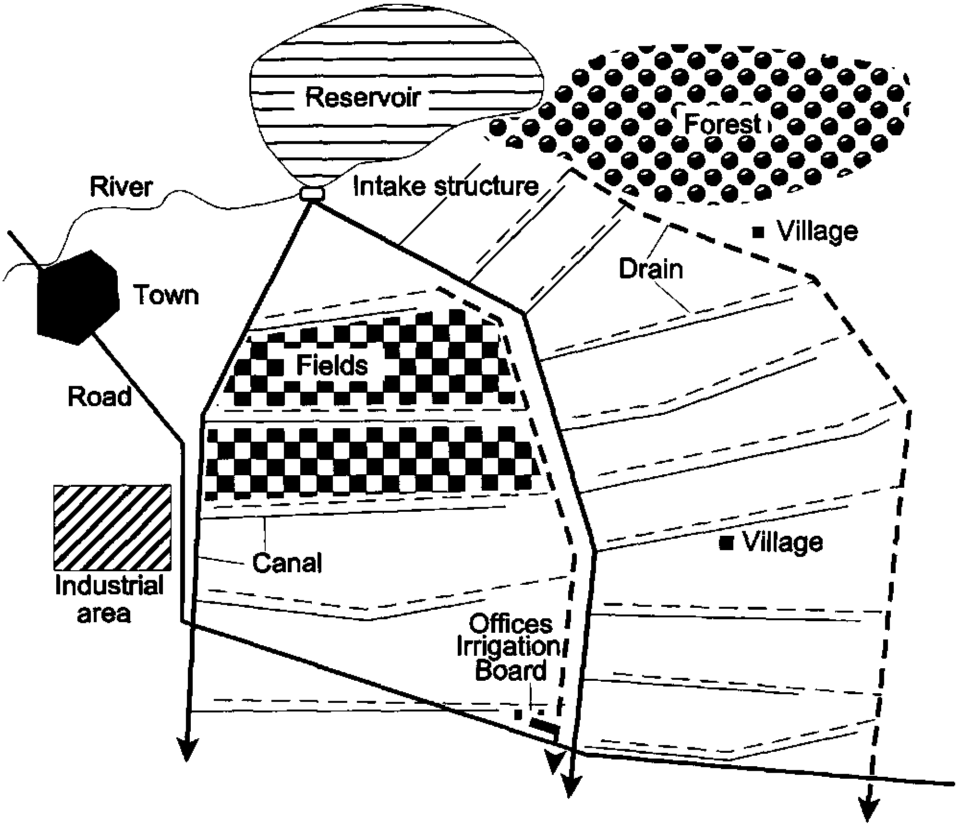


Figure 3.2. Elements in the irrigation environment of an open canal irrigation system (not to scale).

Water management takes place in the overlap with the human environment and *consists of the (organization of) operation of the irrigation infrastructure. In more* general terms it is the purposeful manipulation of water from a source to its destination and its facilitation through cleaning and maintenance of the system. This manipulation of water flows is determined by crop water requirements, system infrastructure, water rights, people operating the systems, institutions and more location-specific elements, that all mutually interact. Water management is very dynamic and changes over time as it is influenced by the wider human environment (Box 3.1).

BOX 3.1 - Interaction in irrigation ecology: the example of crop selection

The interaction and interdependence of the human, biological and irrigation environment can be illustrated for the choice of a crop. Local or international market mechanisms can make the cultivation of certain crops very profitable. However, the crop selection is limited by the type of soil and the quantity of available water. In turn each crop prefers a certain water management that requires more or less frequent operation of the distribution structures by the farmers.

The *human environment* includes individual people as well as society. Man behaves in a certain way to interact with the environment. E.g through water management actors in the human environment manipulate the physical environment, that may then provide different conditions in the overlap with the biological environment. People in an irrigation environment are exposed to positive and negative health impacts, directly or indirectly through the presence or use of irrigation. Benefits and hazards to health may be strengthened or weakened by social behaviour such as sanitary habits, water use and medication.

The *biological environment* comprises all flora and fauna in the irrigation scheme. The biological elements can be brought into the area intentionally, such as agricultural crops and livestock, but may also flourish unintentionally under the new circumstances, such as aquatic weeds, crop pests, vector organisms and parasites.

3.2. TRANSMISSION CYCLE OF SCHISTOSOMIASIS

Schistosomiasis, also known as Bilharzia or snail fever, continues to be a major health problem in irrigated areas around the world. It is a chronic, debilitating *parasitic disease caused by a trematode worm of the genus* Schistosoma, *with freshwater snails acting as intermediate hosts*. World wide some 200 million people in 74 countries are infected, of which probably two thirds show symptoms. The disease may cause damage to the bladder or intestines and lowers the resistance of the infected person to other diseases. Sixteen different species of *Schistosoma* are known, of which five are infective to man: *S.mansoni, S.haematobium, S.intercalatum, S.japonicum* and *S.mekongi*. The various species differ according to their snail intermediate host, final location of the adult worms in the human body, resulting symptoms and geographical distribution (Doumenge et al 1987).

Final hosts, i.e. people and animals, get contaminated during water contact when *Schistosoma* cercariae penetrate the skin (Figure 3.3). After migrating through the portal veins to the liver, where they mature and mate, the worm pairs move to the veins around the intestines (intestinal form) or the bladder (urinary form), where they continually produce eggs. It is the passage of these eggs through the walls of vein and bladder or intestines that causes the disease with inflammation and bloody urine or diarrhoea with bloody stools. Acute schistosomiasis or Katayama fever is associated mainly with *S.japonicum* infections. In severe chronic cases serious complications such as fibrosis and calcification of urinary tractus and bladder may occur with *S.haematobium* infections and fibrosis and enlargement of liver and spleen with portal hypertension in the case of *S.mansoni* (WHO Expert Committee 1993).

Schistosoma eggs are excreted with urine or faeces and hatch in surface water, where the larvae, miracidiae, stay alive for 24 to 48 hours to search and enter the intermediate hosts, *Biomphalaria* or *Bulinus* snails. Activity and infectivity of the miracidiae decrease rapidly after 4 to 6 hours. In the snail the larvae multiply asexually and develop into cercariae. This multiplication continues till the snail dies, so infected host snails shed cercariae for the rest of their lives. The cercariae that leave the snail must find a final warm blooded host within 48 to 72 hours, whose intact skin they are able to penetrate. Carried away with streaming water the cercariae, like miracidiae, do not feed, so after a few hours their infectivity drops considerably (Sturrock 1993a). When these larvae enter a human being, the cercariae can develop into adults and the cycle starts again.

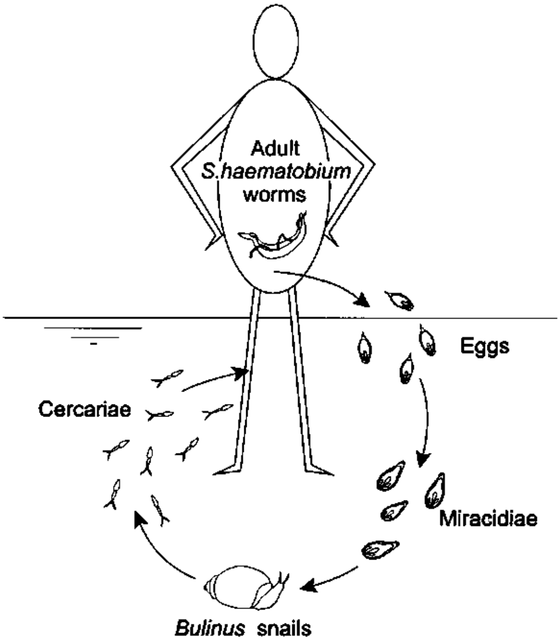


Figure 3.3. Transmission cycle of urinary schistosomiasis.

The intermediate snail host of schistosomiasis may find breeding sites in the irrigation environment (Figure 3.4). Canals, drains and hydraulic structures with slowly flowing or stagnant water may provide suitable snail breeding sites. In absence of adequate sanitary facilities or during recreational activities, people may urinate or defecate in irrigation water. When infected, they thus bring *Schistosoma* eggs into the water, where the hatched miracidiae may find an abundance of *Biomphalaria* or *Bulinus* snails. When the conditions in the irrigation system are favourable, the miracidiae can complete their developmental cycle in snails and multiply into cercariae. During irrigation or other water use activities, people may get into contact with the infested water where cercariae may penetrated their skin and infect them.

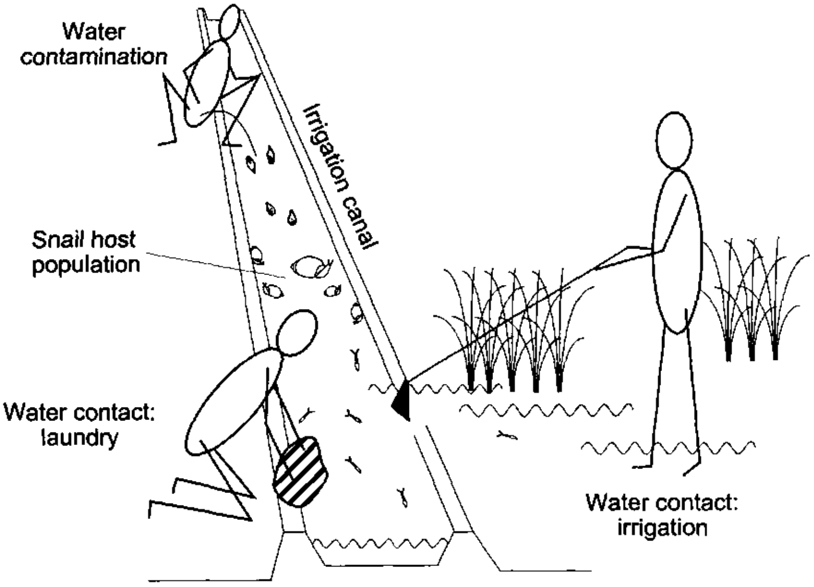


Figure 3.4. Transmission cycle of schistosomiasis in the irrigation environment.

3.3. IRRIGATION ECOLOGY OF SCHISTOSOMIASIS TRANSMISSION AND CONTROL

Approaches to schistosomiasis control

Monitoring and control of parasitic diseases is considered to be a prime responsibility of the public health sector. Three partly overlapping public health objectives for the control of schistosomiasis can be distinguished: morbidity, infection and transmission control (Gryseels 1998).

Morbidity control seeks to reduce disease symptoms through medication, so is mainly aimed at people who are suffering from the disease schistosomiasis. The introduction of safe and effective drugs such as Praziquantel in 1987, combined with the development of simple and rapid diagnostic techniques, has facilitated this approach (Gryseels & Polderman 1991). Symptoms have indeed been dramatically reduced in a number of countries, while infection rates dropped to a low level.

Infection control is aimed at the reduction of the number of people infected with schistosomiasis, either with or without clinical symptoms. By minimizing the infection rate in the population, the output of schistosomiasis eggs into the environment is also reduced. As people without disease symptoms do not seek medical treatment, screening campaigns have to be organized to detect and treat all infections. In a lot of countries it is not feasible to organize an adequate case detection system for targeted medication, so often the entire population is treated in a so-called mass treatment campaign.

Transmission control is aimed at the reduction or elimination of transmission, either by weakening the transmission cycle at as many points as possible or by aiming all efforts at the most vulnerable link in transmission. Mathematic modelling has recently provided more insight in the quantification of transmission mechanisms. However, in practice it still appears very difficult to identify crucial weaknesses in the cycle and many uncertainties continue to exist. This is reflected in different models of schistosome population dynamics, each with other consequences for transmission control. At the one extreme, a model of gradual dilution of the transmission potential implies that a reduction of any transmission factor would always result in reduced transmission and low infection rates. This model would plead for multi-targeted transmission control. A model at the other extreme distinguishes expansion points such as the multiplication of larvae in the snail, followed by bottlenecks such as the low number of cercariae that develop into adult worms inside a person. The rate of transmission would in this model be determined by the size of the bottlenecks, human immunity being the crucial one (Gryseels 1996).

In any case, if schistosomiasis control is restricted to case detection and treatment, people can get reinfected through water contact. Infective cercariae-shedding snails are capable of continuing the transmission for years and the human population has to be treated again. Transmission can only be interrupted by medication if it is supplemented by the elimination of all water contact till the last infective snails have died out (Engels 1997). As this is rarely feasible, supplementary measures are required that weaken the other links in the transmission cycle by reducing water contamination and controlling snail populations (Figure 3.5).

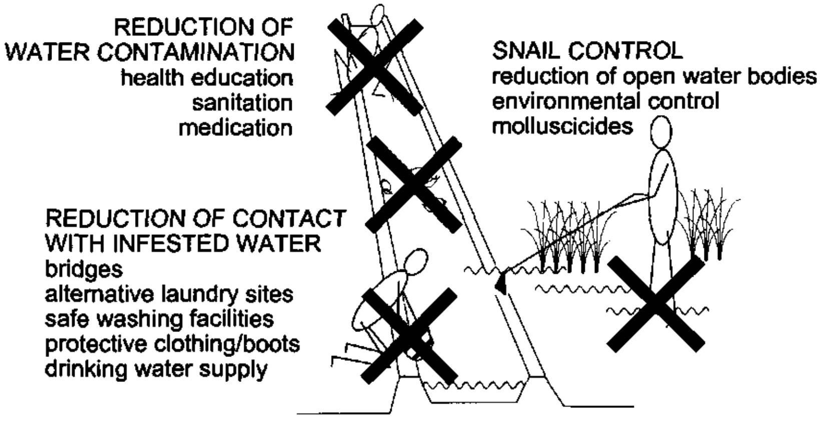


Figure 3.5. Options for schistosomiasis control in the irrigation environment.

Schistosomiasis control in the health sector

Control strategies are not always based on clear objectives or on a certain transmission model. More often pragmatical choices are made for a so-called vertical or horizontal operational control approach.

A vertical approach is aimed at one single disease and specifically addresses the particular problems of its transmission and symptoms (Box 3.2). Often vertical control programmes have been established on external initiative. These programmes then depend on continuous external inputs and are only too often incompatible with existing local health services (Gryseels 1998).

BOX 3.2 - Examples of vertical schistosomiasis transmission control

Vertical control of schistosomiasis in Indonesia is based on mass examination and treatment of positive cases, supported with mollusciciding, community water supplies and latrines (Hunter et al 1993). In the Philippines the new schistosomiasis control strategy is based on case finding and treatment, safe water supplies and toilets, snail control through drainage of water logged areas, the construction of foot bridges, and public health education (WHO Expert Committee 1993). In Iran a broad vertical approach against schistosomiasis combined drugs, chemical snail control and the modification of snail habitats. The prevalence dropped from 20 to 2% in 8 years, despite extension of the irrigation system. Now after revolution and war, no hard currency is available for drugs and chemicals, and health services have diminished. The only restraints left to schistosomiasis transmission are the permanent modifications made to snail habitats by filling and drainage (Oomen et al 1988).

A horizontal approach does not consider specific infections but is aimed at general disease prevention, hygiene education and stimulation of good health at the local level. The horizontal or primary health care approach is carried out by decentralized health services and includes the propagation of safe drinking water supply and environmental sanitation. Schistosomiasis morbidity control can be incorporated into these existing health services, which makes it highly cost-effective and sustainable. Primary health care can also contribute to schistosomiasis transmission control, because sanitary facilities help to reduce water contamination and health education makes people aware of the risks of water contact.

Current research

Researchers tend to study aspects related to the transmission cycle from their own disciplinary background in much detail. Epidemiological studies for infection control usually cover whole communities, while reliable results require good quality but often expensive field diagnostics (Engels 1997). Specific options for snail control can only be identified by specialized vector-biologists after extensive studies on the ecology of the intermediate host (Madsen 1992a). Elaborate water contact studies are carried out to determine transmission sites, important water-related activities as well as exposed age groups (Kloos et al 1983, Stelma 1997). Most of these mono-disciplinary studies provide detailed information on parts of the human or the biological environment only.

Separate studies on irrigation design and water management on the other hand, seldom cover the transmission of water related diseases. Analyses by engineers often focus on the performance of irrigation systems, measured in terms of water use efficiencies, crop yields or social sustainability. These data are not very relevant to the irrigation ecology of schistosomiasis either. On the contrary, the data show that while investments in irrigation generally have to be paid back with increased agricultural production, policy decisions tend to prioritize water use efficiencies within the system. Non-productive elements such as the use of irrigation water for other purposes or the potential creation of vector breeding sites are hardly considered.

Hence it is the overlap of the human and biological environment with the irrigation environment that determines the transmission cycle of schistosomiasis in irrigation systems. Therefore interdisciplinary studies are inevitable to identify crucial mechanisms in transmission.

Perspectives for control in irrigation ecology

In the overlap of the human, biological and irrigation environment relevant elements in the transmission cycle of schistosomiasis can be identified in their interdependence at a particular location, without being limited by disciplinary boundaries. Detailed local studies may still be important, as the epidemiology of schistosomiasis is characterized by an uneven distribution of infection over the population. But by looking at the interaction between the human, biological and irrigation environment, separate studies and subsequent interventions can be much more targeted. The irrigation system would then not be considered as a static part of the physical environment, but as a dynamic and regulating environment characterised by irrigation design and water management. This irrigation environment influences the suitability of breeding sites for the snail host of schistosomiasis and provides possibilities for as well as limitations to water contact only in interaction with the human and biological environment. Schistosomiasis control in irrigation systems can then be aimed at the overlap with the human environment instead of being limited to one environment only.

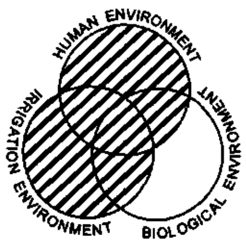
3.4. CONCLUSIONS

In irrigation environments, life is to a large extent concentrated around irrigation. Transmission of schistosomiasis takes place in the overlap of the human, biological and irrigation environment. The concept of *irrigation ecology*, applied to schistosomiasis, provides the overall view that is needed to identify critical links in transmission. Supported by interdisciplinary studies on interactions between elements in the three overlapping environments, specific options for the control of schistosomiasis can be determined.

4

SCHISTOSOMIASIS AND WATER SUPPLY AT NATIONAL AND REGIONAL LEVEL IN MOROCCO

In this Chapter, a number of case studies will be introduced. Morocco is a country where the relation between water supply and schistosomiasis is obvious (Section 4.1). In the irrigation ecology of schistosomiasis transmission, water supply includes agricultural water supply (irrigation), as well as domestic and drinking water supply. The schistosomiasis control efforts by the Ministry of Health had different effects on the traditional and new transmission sites. In the oasis of Akka in southern Morocco, transmission of schistosomiasis continues with the traditional water contact patterns in the river bed (Section 4.2). However, the residents of Akka have recommended many measures to control schistosomiasis. The Tessaout Amont irrigation system in the Haouz plain is a typical situation where urinary schistosomiasis has spread with the introduction of modern open canal irrigation (Section 4.3).



4.1. MOROCCO

In this section the main characteristics of irrigated agriculture as well as rural water supply in Morocco will be discussed. It will be explained how the Moroccan open canal type of irrigation system created a new irrigation environment that led to the expansion of urinary schistosomiasis. The Ministry of Health reacted to that with National Control and Elimination Programmes. These programmes will be assessed with respect to the need for environmental control.

4.1.1. Agricultural and domestic water supply in rural areas

Morocco is located in North-West Africa, bordered by the Atlantic Ocean and the Mediterranean Sea. Large mountain chains give the country a wide diversity in geography and climate, dividing it into four distinct climatic areas (Table 4.1).

Agriculture is a very important sector in Morocco. Together with animal husbandry and fisheries it provided employment to more than 40% of the population in 1991. Most of the employment is provided in traditional small scale agriculture, aimed at self-sufficiency. This is reflected in the contribution of the agricultural sector to the Gross National Product, which was only 16% in the same year (Bennis & Bennouna 1995).

Table 4.1. Distinct climatic zones in Morocco (ANAFID 1991).

TYPE	REGION	ANNUAL RAINFALL (mm)	CHARACTERISTICS
Mountains	High and Middle Atlas, parts of Rif	700-2000	Arable area limited
Atlantic Plain	North Western coastal zone	300-800 5-6 months dry	Good soils
Highlands	Eastern uplands	200-300, 9 months dry	Moderate soils
Sub-Sahara, Sahara	South-East and South desert	< 200	High temperatures, oases

In the semi-arid and arid climate of Morocco, irrigation plays a vital role in agriculture. In 1961, five years after independence, the National Irrigation Office ONI[1] was created to stimulate irrigated agriculture. In the years that followed, plans were formulated to develop irrigation systems and major investments were made with support from international organizations such as UNDP, FAO and World Bank, as well as from bilateral donors. The central objective of the Moroccan government was to increase the level of national self-sufficiency for products like sugar and wheat (Popp 1984). As part of these efforts since independence, 13 large dams have been constructed for irrigation by the Ministry of Public Works, 8 of these also for (urban) drinking water supply (ANAFID 1991). Annual investments for irrigation and drinking water supply continue to increase (Table 4.2).

Table 4.2. Average annual Moroccan investments in water resources development (million Euro, with 1€ = 10 MAD), as adapted from Benazzou (1994).

PERIOD	AGRICULTURE (INCL. DAMS)	DRINKING WATER SUPPLY	TOTAL
1981-85	158.8	68.1	226.9
1986-87	190.6	58.5	249.1
1988-92	214.1	115.3	329.4

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[1] ONI: *Office National d'Irrigation.*

Irrigation

The total irrigated area has increased from 41 000 ha in 1956 to 1 200 000 ha in 1997 (ANAFID 1991). Figure 4.1 shows Morocco's large and medium modern irrigation systems, covering two third of the total area under irrigation. The design and construction, as well as operation and maintenance of these modern irrigation systems is supervised by the Regional Offices of the Ministry of Agriculture ORMVA[1], with a special division for the management of irrigation and drainage systems SGRID[2], further referred to in this thesis as Irrigation Board.

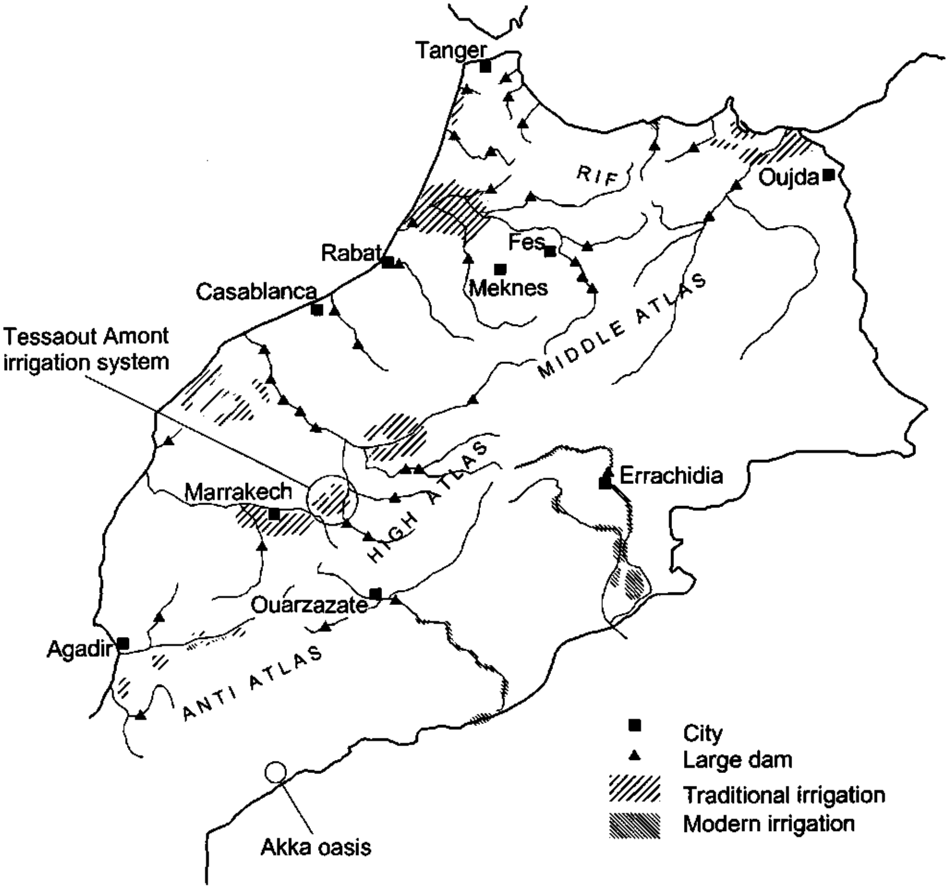

Figure 4.1. Major dams and large and medium traditional and modern irrigation systems in Morocco (after ANAFID 1991).

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[1] ORMVA: *Office Régional de Mise en Valeur Agricole.*

[2] SGRID: *Service de Gestion des Réseaux d'Irrigation et du Drainage.*

In the medium and large systems, sprinkler irrigation is used at 9 % of the irrigated area while wet rice constitutes only 1% of the total irrigated area. Trickle and drip systems are applied on an experimental scale at less than 0.5 % of the irrigated surface (Benazzou 1994). *About 90% of the modern irrigation environment consists of surface systems with open canals and drains.* Such irrigation systems have a typical design that can be found in other North African countries and France as well. This design offers the possibility of rapid construction of canals under uniform slopes without seepage losses and with a low flow resistance. Water is led from a large dam and storage lake into trapezoidal concrete lined primary canals (Figure 4.2). From these, half round raised concrete conduits constitute the secondary and tertiary canals (Figure 4.3) that supply water to earthen quaternary canals. A complementary drainage network consists of earthen open field ditches, tertiary drains and secondary drains leading any surplus of water into large open masonry lined collector drains. Leakages from the elevated canals can be seen easily, although the cost of replacing damaged stretches of canals is relatively high. The elevated canals require special provisions to give access to fields and villages, for which generally inverted siphons are constructed (Figure 4.4). These structures lead the water under the road or track.

Figure 4.2. Typical trapezoidal concrete lined primary irrigation canal in Morocco: primary canal West in the Tessaout Amont irrigation system.

Figure 4.3. Typical elevated half-round concrete secondary irrigation canal with tertiary branch in Morocco: secondary canal D3 in the Tessaout Amont irrigation system.

Figure 4.4. Typical inverted siphon with square boxes, connected by an underground pipe (not visible). The sides of the canal upstream of the siphon (right) have been heightened with cement to avoid overtopping of the water. Downstream of the siphon (left) the first canal element is of a larger diameter for the same reason.

Rural drinking water supply

Till 1976 the Ministry of Agriculture has been responsible for the drinking water supply in rural areas. After that year the responsibility was transferred to the Local Authorities. The local Community or Village is supposed to organize itself and to apply for financial support to the regional representative of the Ministry of Interior, mostly being the Governor. However, several services of the Ministry of Agriculture remained involved in drinking water supply, especially where integrated rural development projects were planned and implemented.

According to Benazzou (1994), who gives detailed information on the water sector, the development of rural water supply received little attention as compared to urban water supply. He states that in 1990 only 14% of the people living in rural areas of Morocco had access to drinking water from a public source (i.e. a functioning safe water supply within 100 m from the house). In the same year 23% of the population had private wells. Almost two third of the population depended on other supplies including rain water collection and the purchase from private water sellers. Many of them used surface water of sometimes questionable quality.

In 1990 a Master Plan for the development of the drinking water supply of rural populations has been established. Within 20 years, 80% of the rural population had to be provided with drinking water, mostly through communal water points, assuming that daily water consumption per capita remains constant (Table 4.3). The Plan depends mainly on the additional exploitation of groundwater and to some extent on rain water harvesting, using small earthen dams. Surface water is deliberately excluded as a potential water source for drinking water because of its low quality (Benazzou 1994).

Table 4.3. Actual and projected coverage (% of rural population) of drinking water supply in rural areas in Morocco, according to Benazzou (1994).

LEVEL OF SERVICE	1990 (ACTUAL)	2010 (OBJECTIVE)
Collective pumps	6.3	30
Public taps (network)	5.7	40
Individual connections	2.3	10
Total	14.3	80

4.1.2. Spread of schistosomiasis and its control

Urinary schistosomiasis, caused by *Schistosoma haematobium, is the only form of schistosomiasis present in Morocco*, with the freshwater snail *Bulinus truncatus* as the intermediate host. This snail lives in natural habitats in southern oases, where schistosomiasis has probably been transmitted since the middle ages (Doumenge et al 1987). Migrant labourers from these regions were hired for construction of modern irrigation systems in the late 1960s. They may have been infected with schistosomiasis and thus might have brought the disease into a new environment: the man-made irrigation ecosystems that the intermediate snail host had colonised in large numbers.

Data on schistosomiasis infections from local health posts are collected and summarized for the whole country since the late 1960s by the Ministry of Health. The number of cases of schistosomiasis per year shows considerable fluctuations over time (Figure 4.5). After the construction of new irrigation systems and the extension of existing systems, an intensive case detection campaign yielded a high number of 13 416 people with urinary schistosomiasis infections in 1973. This was quite a peak when compared to the annual average of around 2600 infections in the ten preceding years (Mahjour 1993). The year after that, in 1974, only few people were diagnosed and as a result, cases were found only sporadically.

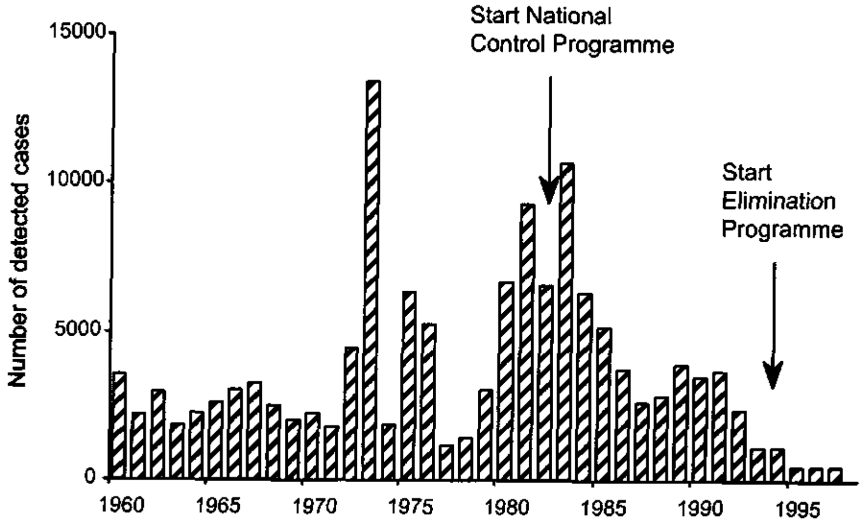

Figure 4.5. Number of detected infections of urinary schistosomiasis in Morocco from 1960 onwards. Also indicated are the years the Ministry of Health started the national schistosomiasis programmes (Mahjour 1993, SMP 1995 & 1998).

The alarming situation of 1973 motivated the Moroccan Ministry of Health to initiate a National Schistosomiasis Control Programme, which was fully implemented in 1982. The Programme was based on transmission control, using selective and mass case detection with treatment of positive cases (Laaziri & Bennouna 1982). Routine checking of urine samples at local health posts was supplemented by mass campaigns by mobile teams. In addition, the snail population was monitored systematically to identify foci for molluscciding by local health workers responsible for the Control Programme.

Prevalence, the rate of infected people over the exposed population, decreased with the National Schistosomiasis Control Programme. Medical treatment of schistosomiasis infections was especially successful after the introduction in 1987 of the single dose drug Praziquantel (Mahjour 1993). However, transmission still occurs in several provinces, with abundant breeding sites holding large populations of the intermediate host *B.truncatus*. The snail prospers in the many open water bodies of the irrigation systems and since the 1970s *S.haematobium* is present in most modern open canal systems in Morocco (Figure 4.6). *Field studies have identified inverted siphons, which holding stagnant water almost permanently, as the ideal breeding sites* for *B.truncatus* (Camerlynck et al 1974, Khallaayoune & Laamrani 1992). The main transmission season is summer, when children play in the cool water of irrigation canals and structures. High snail densities then coincide with high intensities of water contamination and water contact.

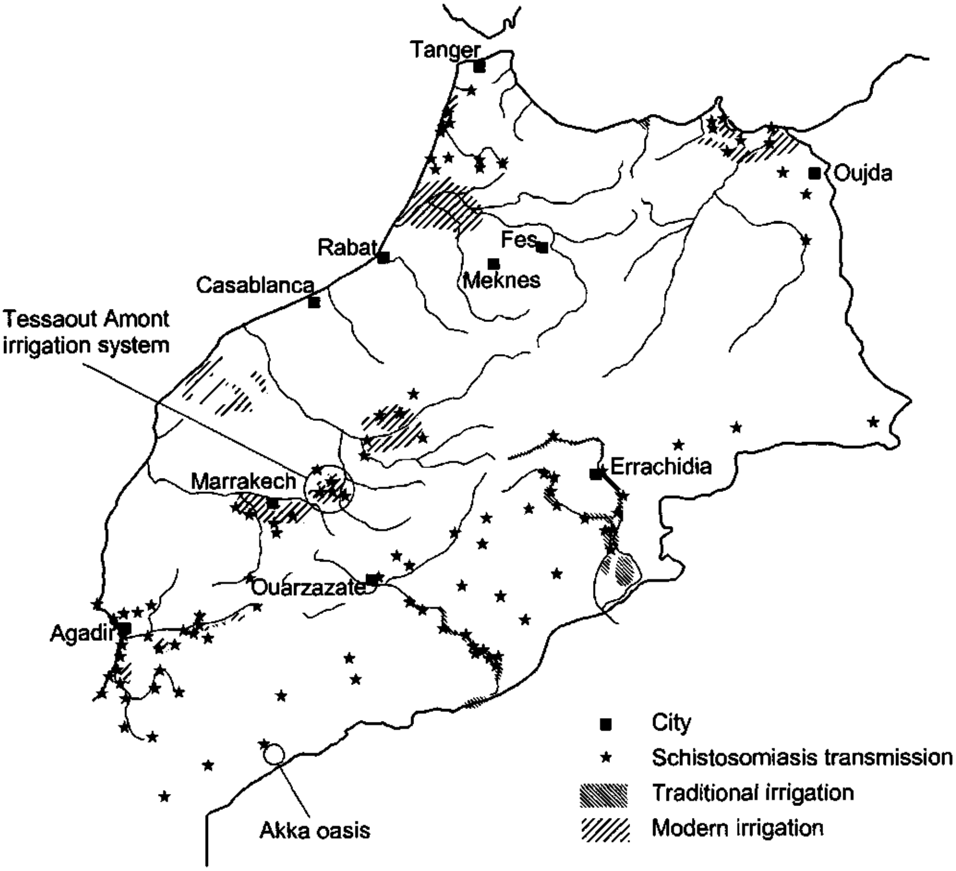

Figure 4.6. Irrigated areas and sites of schistosomiasis transmission in Morocco (after ANAFID 1991 & Doumenge et al 1987).

4.1.3. *From schistosomiasis control to elimination*

In 1992, after ten years of systematic control activities, prevalence of schistosomiasis had dropped below 1%. With this low prevalence and the well-established integration into local health services, conditions were fulfilled to intensify the transmission control and strive for eradication of the disease. The Ministry of Health, supported by the World Health Organization, defined as its new and ambitious goal the *elimination*[1] *of urinary schistosomiasis from Morocco by the year 2004.* The new Schistosomiasis Elimination Programme was launched in 1994. It depends on intra- and intersectoral collaboration with other departments and ministries (Appendix I) and is based on the following operational strategies (SMP 1993):

1. Large scale case detection and treatment of schistosomiasis with more sensitive techniques covering a larger part of the population in endemic areas to find all cases;
2. Education of people in endemic areas to prevent contamination of water;
3. Environmental snail control.

Ad 1. Intensified case detection

In the Schistosomiasis Elimination Programme, transmission has to be interrupted completely and permanently, each infected person being one too many. Therefore the mass campaigns have as main goal to find all infected people, including those with light infections. These light infections can only be detected by means of very sensitive diagnostic tools. Each year in autumn and winter, a few months after the main transmission season, mass case detection campaigns are launched at primary and secondary schools in endemic areas, followed by village wide surveys around positive cases. The Ministry of Health's field teams use sedimentation of urine samples to find excreted schistosome eggs (Laaziri & Bennouna 1982). Sometimes this is supplemented with the use of reagent strips to detect micro-haematuria, as the presence of microscopic blood in urine is a sign of irritation of the urinary tract that can be caused by the passage of worm eggs.

More sensitive diagnostic techniques for the detection of low infections are available but appear to be too time consuming and expensive for use in the field. Recent studies have shown that repeated large volume filtration of urine samples may find a few extra infections. Still, the routinely and accurately applied sedimentation by the Ministry of Health's field teams does not underestimate the true epidemiological situation. *Convincing more people to submit their urine for diagnosis may be more important than increasing the sensitivity of the diagnostic technique to achieve elimination of schistosomiasis* (Tiemersma et al 1997). Mass screening campaigns have so far often been aimed at school children because they had the highest infection rates. Over the last years however, this seems to change and now young men aged 15-25 years show the highest infection rates

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[1] The word "elimination" is used here to indicate zero prevalence. "Eradication" means that no cases have been found for a number of years, reason for the Ministry of Health not to use this term.

(SMP 1995). As most of this group is missed in school-based campaigns, retargeting is imperative.

Ad 2. Health education

Health education may play a vital role in motivating people to attend mass case detection campaigns. It could be aimed at the prevention of water contact, but practice has shown that water use habits are difficult to change. *Good health education can only be expected to lead to results when sufficient safe water is available.* Education campaigns to raise awareness of schistosomiasis transmission could be planned by the Ministry of Health in rural areas simultaneously with the construction of new facilities for domestic water supply. In some provinces international non-governmental organizations that work in drinking water supply and sanitation have already developed education material in collaboration with the Ministry. If no alternative facilities are planned, an adapted message could be formulated and spread, encouraging people to use the water at certain sites only, where no *Bulinus truncatus* snails are found and the risk of schistosomiasis transmission is minimal. In addition, information on water related diseases may be included in agricultural extension (PEEM 1995). All these education activities may be beneficial to schistosomiasis control, but the final effect remains unreliable.

Ad 3. Vector control

One of the consequences of increasing control efforts to achieve elimination of schistosomiasis, is that the costs per case become very high. On the other hand, a *neglect of control may result in a resurgence of the disease, as with the presence of large populations of the intermediate host the transmission potential remains high.* Even if all infected persons could be traced and treated effectively, reinfection may occur easily if water contact habits persist. Infected snails continue to shed cercaria till they die, so *B.truncatus* breeding sites remain the focus of infection from which the transmission cycle may start again. Present breeding sites could be made less favourable to *B.truncatus* and less accessible for water contact by environmental control.

If a modification or manipulation of any part of the irrigation environment is desirable for disease control, then design and water management have to be considered as well as the multipurpose use of irrigation water. For any environmental measure, the Ministry of Health therefore depends on collaboration with national and local representatives of other sectors such as Irrigation Boards and Local Authorities. *Preventive environmental control strategies are urgently needed against the intermediate snail host as an 80% expansion of the area under* *modern large scale surface irrigation is planned for 2010* (ANAFID 1991). A combined effort of the agricultural, public works and health sectors could perhaps prevent a resurgence of urinary schistosomiasis in Morocco.

4.2. AKKA OASIS

Akka is one of the southern oases in Morocco that are known to be ancient transmission sites for urinary schistosomiasis. In this section the use of different sources of water and its implications for schistosomiasis transmission will be discussed. The case of Akka will be completed with recommendations for the control of schistosomiasis.

4.2.1. Sources of water in Akka

The oasis of Akka is situated south of the Anti-Atlas mountains, 170 km south-east of Agadir. The region has a desert climate with hot dry summers and short but cold winters with very little rain (Figure 4.7). Several villages are located along the River Akka, surrounded by palm gardens (Figure 4.8). Ten springs well up in the river bed with discharges up to 35 l/s (Table 4.4). Occasionally floods and inundations occur. Water from the springs is kept behind dams in small ponds and divided through a network of earthen canals with a total length of 50 km. In addition to the springs in the bed of River Akka, hundreds of shallow private and communal wells in the oasis provide water, mainly for domestic uses.

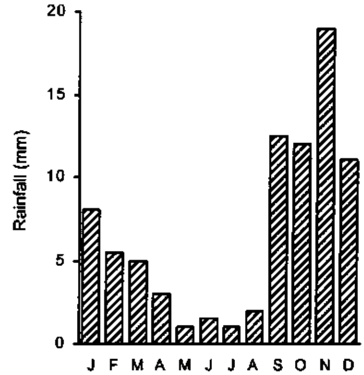

Figure 4.7. Mean monthly rainfall at Akka over the period 1937 to 1990 (unpublished data of MAMVA).

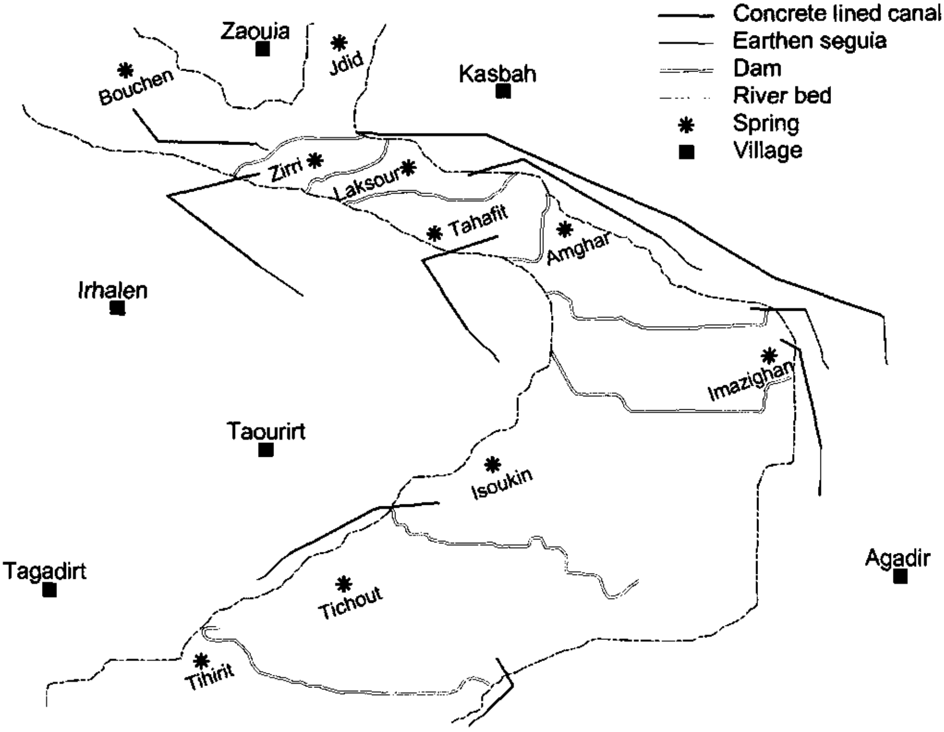

Figure 4.8. Springs, ponds and canals in the Akka river bed.

Table 4.4. Springs and irrigation canals in the Akka river bed (unpublished data MAMVA 1996). The range of discharges has been based on 12 measurements taken between 1939 and 1993.

SPRING	DISCHARGE (l/s)	LENGTH OF MAIN CANALS (m)	ROTATION PERIOD (days)
Jdid	0 - 53	3811	44
Bouchen	9 - 96	3250	44
Zirri	0.5 - 30	2146	19
Laksour	8 - 100	3836	44
Tahafit	3 - 14	2841	18
Amghar	18.6 - 100	4675	22
Imazighan	20.7 - 61	5005	18
Isoukin	2.5 - 27	4150	26
Tichout	3.1 - 36	3750	14
Tihirit	0 - 1.25	2865	18

Some of the canals, totally about 16 km, have been lined during a rehabilitation project. This project has been limited deliberately to the protection of sources, the reinforcement of dams and the lining of first parts of canals only. The ponds have been maintained as they were, allowing the water to seep through the dam and the bottom of the pond to downstream springs (Figure 4.9). In this way the yield of the springs has hardly been affected and water rights of the communities over the springs could be respected. The distribution of water from each spring to its right holders is arranged by an elected Spring Committee. Individual water rights are based on labour contributions to the construction or maintenance of the canal or dam, expressed in terms of time shares. Water rights are thus not linked to land.

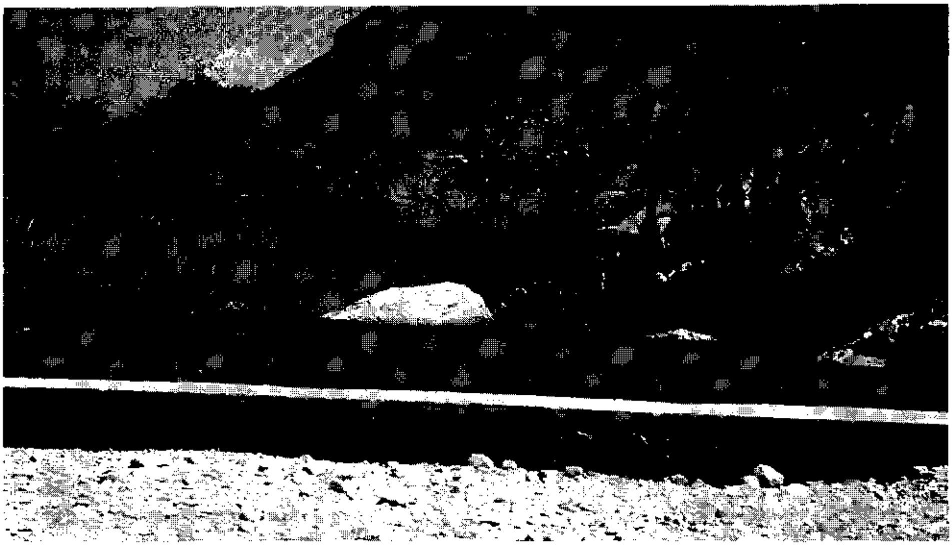

Figure 4.9. Reinforced dam creating a small reservoir for irrigation in the Akka river bed.

Main crops in the oasis are date palms and some food crops. In addition, a few people are herdsmen with flocks of mainly sheep and goats. However, the main source of income in Akka consists of money sent by relatives working as shop keepers in Western and Central Morocco.

4.2.2. Schistosomiasis transmission in Akka

Despite efforts in the National Control Programme since 1982, prevalence and incidence in Akka have dropped only slowly since 1990. When the Schistosomiasis Elimination Programme was launched in 1994, a mass treatment campaign was planned, without prior individual diagnosis. The entire population of the villages surrounding Akka received medication against schistosomiasis in 1995. However, less than one year later, new cases emerged (Table 4.5).

Table 4.5. Infection rate in May 1996 in 5 villages in Akka oasis (Laamrani et al 1997).

VILLAGE	POPULATION	INFECTION RATE	NUMBER OF WELLS
Kasbah	929	0.36	81
Zaouia	446	0.46	37
Irhalen	1820	2.68	111
Taourirt	1851	1.74	13
Tagadirt	1830	0	0[1]

[1] Tagadirt has public standposts.

Water use

People probably had been reinfected with schistosomiasis in the river bed ponds, where large populations of the intermediate snail host *Bulinus truncatus* prosper (Laamrani & Lhayati 1996). People cross the river several times a day to get to their fields or to visit relatives at the other river bank. Some of the diversion dams can be used for crossing, but at other sites people simply wade, till their knees through the water.

Apart from irrigation and crossings, the springs with their respective small dams, ponds and streamlets are used for all kinds of domestic and recreational activities such as fishing. At several places, laundry facilities have been constructed during the rehabilitation project of the springs and canals. Though the washing of clothes itself is usually done in small basins with soap (that kills cercariae), the lined irrigation canals at the river side provide excellent opportunities for rinsing. At some places, the water flow velocity in these canals is high, so *Schistosoma* cercaria can hardly survive, let alone enter the human host through the skin. These laundry sites at the canals constitute a meeting place and centre of social life for women of all ages. Other women do their laundry directly in the ponds behind the dams. This means that they are standing submerged to the hips in the water and are exposed to cercaria for prolonged periods of time.

The ponds also constitute a favourite playground to children. Especially young boys like to play, swim and fish in the ponds. Agricultural equipment and sometimes even cars, are also washed near the springs.

Despite the presence of the numerous wells, the ponds in the river bed are favourite sites for water collection as well. This water is then used at the house for all kinds of purposes such as washing of (household) utensils and brick making. Some people depend on the springs and ponds in the river bed to provide them with all domestic water, e.g. because their house is built on rock so they have no private well. The water may be consumed without treatment, as the springs are perceived to be clean sources that do not cause health problems. The schistosomiasis transmission risk may be linked to the availability of water supply though, as the data from Tagadirt would suggest. It is the only village in the sample with piped water supply and no cases of urinary schistosomiasis were detected in May 1996.

4.2.3. Recommendations for schistosomiasis control

In spring 1997 a rapid rural appraisal has been carried out in the oasis of Akka. The main objectives of the study were (Laamrani et al 1997):

- The identification and elaboration of strategies for the elimination of schistosomiasis, that are supported by the local population;
- The testing and further development of a methodology for rapid appraisal and possibly monitoring of schistosomiasis control options.

The study was focused on the three villages of Irhalen, Taourirt and Kasbah. In the appraisal the following methodological tools were used: informal interviews and discussions, direct observations, consultation of archives and key informants as well as a focus group discussion (Potten 1985, Bolton et al 1990, Chambers 1992, Dawson et al 1993, Liebler 1994). Several multi-disciplinary recommendations for the control of urinary schistosomiasis in Akka have been formulated by the residents of Akka (Table 4.6). Apart from some costly (fencing the river bed) and environmentally harmful (molluscíciding) suggestions, all other recommendations seem feasible with more or less efforts by the local community or other sectors.

The wide variety in the recommendations and the preparedness of the Village Committees to take responsibility for many of those, show that the residents felt committed to the problem of schistosomiasis transmission. Some of the ideas were very original and more adapted to the local human, biological and irrigation environment in Akka than any national measure proposed by the Ministry of Health could ever be. Furthermore, it was suggested by the Village Committees to look for funding of some interventions by stimulating emigrants from Akka to invest in their village of origin.

Table 4.6. Recommendations for schistosomiasis control, as proposed by inhabitants of the villages of Irhalen, Taourirt and Kasbah in the Akka oasis. The suggestions marked with * were put into practice less than a year after being formulated.

TYPE OF INTERVENTION	ACTIONS
Reduction of water contact	- Fence the river bed - Warning signs at infested sites (design provided through school contest) - Appoint a guard - Penalty system for children playing in the water - Installation of convenient obligatory passages over the river - Symbolic fine for crossing elsewhere after construction of new passages - Installation of taps - Construction of safe laundry sites - Installation of safe recreation basins in the villages
Snail control	- Reconstruction of the springs - Chemical snail control (despite noxious effect on frogs and fish) - Mechanical weed removal in transmission sites* - Reinforce collaboration between Village Committees and Spring Committees*
Health education	- Make a video documentary in local language with local images - Plan education campaigns in summer, when water contact and contamination risk are highest - Campaigns at schools, as children can pass the message to the household better than adults - Make village leaders aware of their responsibility to inform the parents - Target information at women as they are more exposed to schistosomiasis and less reached by regular campaigns - Explain that after several negative screenings it is still worthwhile and important to participate in case detection campaigns the next year - Involve other sectors than health and interior in education
Other Ministry of Health activities	- Check urine at each visit to the health post - Add a nurse to the schistosomiasis elimination team - Install a medical doctor in Kasbah health post* - Integrate schistosomiasis control activities with trachoma control programme - Assure implementation, monitoring and evaluation of interventions - Involve local leaders and authorities in this evaluation

Meanwhile, the first recommendations have been put into practice. The Ministry of Health complied with the request of the residents and indeed appointed a medical doctor at Kasbah health post. In 1998 the field health technician who was one of the team members, discovered that the Village Committees collaborated with the Spring Committees in regular cleaning of irrigation canals and ponds in the river bed. Without any interference of health or local authorities, the community had thus taken the responsibility for planning and execution of intensive weed removal for snail control.

4.3. HAOUZ PLAIN

The Haouz plain in Central Morocco has depended on irrigated agriculture for ages, but urinary schistosomiasis was introduced in the region only with the construction of a modern open canal irrigation system.

4.3.1. Traditional irrigation in the Haouz plain

The Haouz plain lies between the eroded hills of Jebilet and the High Atlas mountains in the Highlands climatic zone (Table 4.1) in Central Morocco (Figure 4.10). The plain has a semi-arid climate, characterized by low and irregular rainfall during the year, as well as from year to year. Annual precipitation in Attaouia, at the centre of Tessaout Amont irrigation system, varies from 170 - 400 mm, with the main rainy season from January till April (Figure 4.11). In summer practically absolute drought prevails while temperatures may reach 50°C with the hot Saharan Sirocco wind. Mean annual temperature is 20°C, in summer 37.7°C and in winter 4.9°C. Mean relative humidity is 54% and the reference evapotranspiration rate 2300 mm/year, according to Blaney-Criddle (Comité Technique 1990). Under these climatic conditions, rain-fed agriculture is marginal: irrigation has been practised in the Haouz plain for ages.

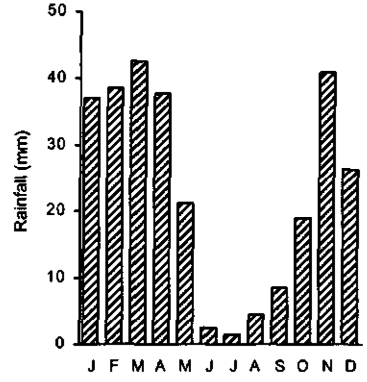

Figure 4.11. Mean monthly rainfall at Attaouia over the period September 1968 to August 1994 (unpublished data of SGRID).

In the twelfth century the strategy of water mobilization for irrigation shifted from the individual exploitation of ground water by animal powered pumps to more elaborate systems. One of the successful works from this era was a 20 km long canal to bring water to the royal gardens in Marrakech and to provide drinking water for the town. This canal is still functioning today. By the thirteenth century, some 20 000 - 25 000 ha were irrigated in the Haouz plain by major canal systems called *seguias*[1] (El Faiz 1994). Successive local chiefs mobilized water higher up

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[1] *Seguia*: traditional earthen canal.

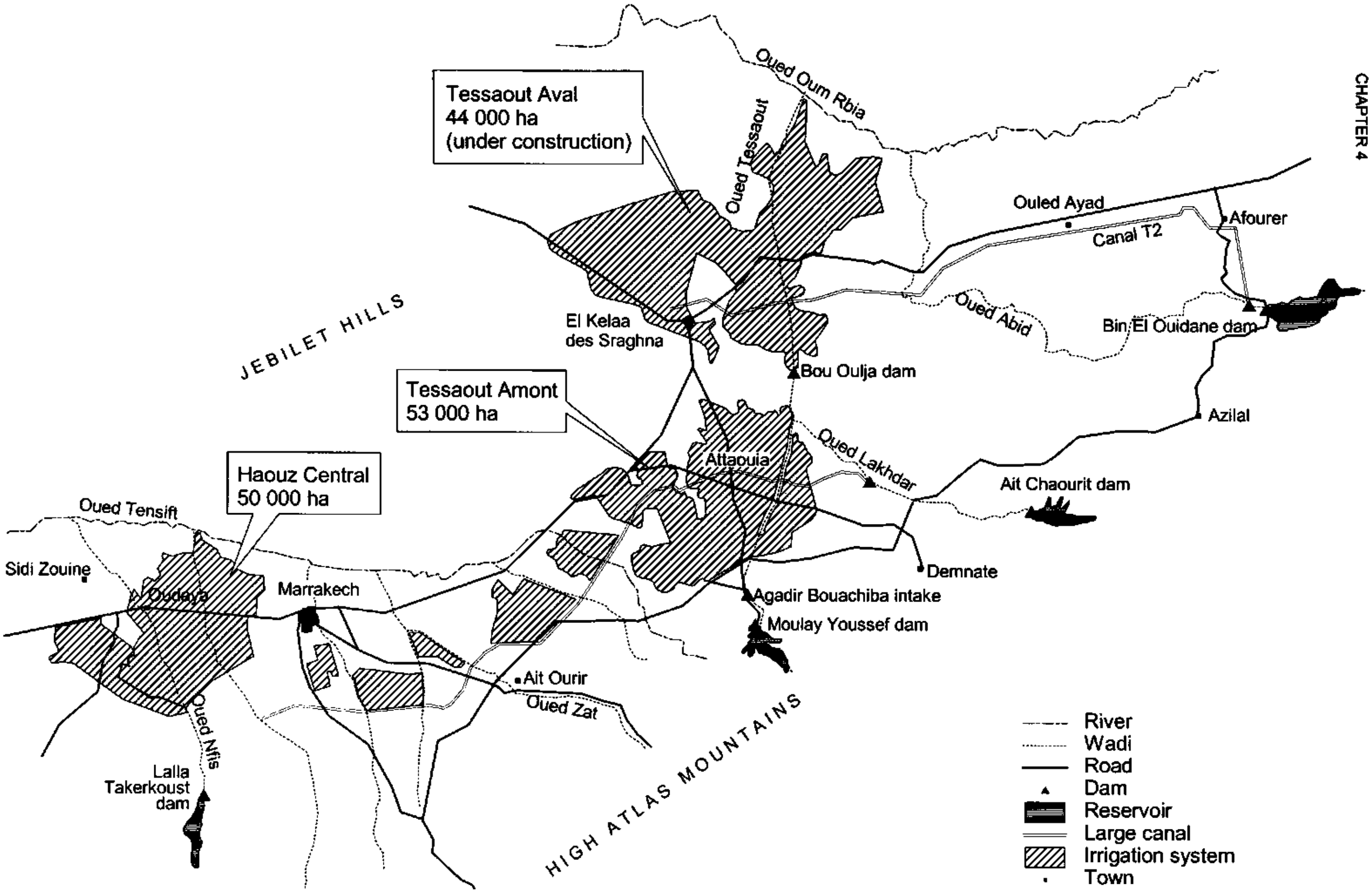


Figure 4.10. Modern open canal irrigation systems in the Haouz plain (after ANAFID 1991).

the river in order to ensure water supply when flows were low. Only leaders who had sufficient military strength, political stability and financial means were able to guarantee successful construction and operation (Pascon 1983).

Before implementation of the modern systems, 31 *seguias* with a total length of 84 km took water from the River Tessaout. Water rights are traditionally linked to the labour input in canal construction and maintenance and thus independent from the land ownership. Groups of water users usually live in the same settlements and are bound by strong ties, which facilitates the organization of construction, operation and maintenance of the *seguia*. In order to profit from local expertise and traditional organization structures, the design of the modern irrigation system Tessaout Amont preserved the location of the old *seguias*. While the siting of the intake structure and primary canals was based on rational topographical and economical grounds, secondary canals were superimposed on the seguias, following the old courses as closely as possible. In this way, existing water users groups could continue their task of distributing the water among them, as they had been doing for centuries. In a way, the design of Tessaout Amont can thus be considered as a modernisation of the traditional structure, rather than the creation of a new irrigation system (Ducrocq & Pascon 1973). The increased water availability from the dam made extension of the irrigated area possible beyond the command area of the original *seguias*.

4.3.2. Schistosomiasis in the modern Tessaout Amont irrigation system

The Tessaout Amont irrigation system is provided with water from the Moulay Youssef dam. Tessaout Amont has the typical layout of modern open canal irrigation systems in Morocco and is entirely gravity-fed. Open trapezoidal primary canals have been constructed around 1970 and supply water to elevated semi-circular concrete secondary and tertiary canals. As in other open canal systems, many inverted siphons have been constructed at road crossings. The concrete siphon boxes hold large populations of *Bulinus truncatus*, the intermediate snail host of schistosomiasis (Khallaayoune & Laamrani 1992).

During the centuries of traditional *seguia* irrigation, no schistosomiasis occurred in the Haouz plain. In Tessaout Amont the first cases of urinary schistosomiasis were detected in 1976, a few years after the first operation of the modern irrigation system started. The disease was probably brought into the area by migrants from the South of Morocco. Since then, the local health posts that serve the population in the Tessaout Amont irrigation system classified 24 000 - 27 000 persons as being exposed to schistosomiasis, on a total population of 120 000 - 125 000. "Exposed" implies that the people live in an area where transmission takes place and that they are regularly in contact with irrigation water. The case detection and treatment campaigns were supplemented by chemical snail control in the standing water of hydraulic structures. Till the mid eighties this rather costly measure was applied in high incidence areas in the Tessaout Amont irrigation system only.

In 1981, 16.2% of the exposed population in the region was infected with urinary schistosomiasis. All infected persons were treated. From 1985 to 1991 between 5500 and 9500 urine samples were examined annually, detecting some 350 cases each year (unpublished data Attaouia Health Centre). In 1991 a small epidemiological survey was carried out in the village of Lamyayha near Attaouia. In this study 18 out of 85 samples (21.2%) were positive, while 36% of the children aged 7 - 14 years were infected (Khallaayoune & Laamrani 1992). In the same period, the regional infection rate was 5.8%. Subsequently, in an intensive campaign in April and May 1992, 16 665 samples were analyzed, representing three quarters of the exposed population. The 450 detected cases gave an incidence rate of 2.7% (unpublished data Attaouia Health Centre). During the mass school campaign in spring 1995, no positive cases were detected (Hafid & Tiemersma 1995). In 1995, 1996 and 1997 less than 0.5% of all examined urines were positive (Nhammi 1997).

4.4. CONCLUSIONS

Irrigated agriculture is very important in Morocco. However, with the development of modern open canal irrigation systems, the transmission of schistosomiasis has increased. The Ministry of Health has been able to counteract this expansion with an effective National Schistosomiasis Control Programme. However, the risk of transmission is still present with the abundant breeding sites for the intermediate snail host *Bulinus truncatus* in traditional and modern irrigation systems. Therefore, efforts to achieve transmission control and eventually eliminate the disease from the irrigation environment need to be continued in spite of the increased cost per detected case. Options for environmental schistosomiasis control need to be identified in the overlap of the irrigation, human and biological environment. With ever increasing investments in both agricultural and drinking water supply, joint investments could also be more cost-effective.

Akka is one of the southern oases in Morocco that are known to be ancient transmission sites for urinary schistosomiasis. The river bed with its various springs exploited for irrigation is the central axis of daily life in the oasis. Despite the availability of other water sources, many water use activities result in contact with snail breeding sites in the river bed. Consequently, transmission of schistosomiasis still occurs today, be it at a low level. In this region, environmental control combined with health education might be the best schistosomiasis control strategy, as is reflected in the suggestions by the residents of three villages. The fact that the Village Committees in Akka oasis have already taken the initiative to implement some of their own recommendations (Table 4.6), shows that a rapid rural appraisal can increase and activate the awareness of schistosomiasis.

The semi-arid Haouz plain has a long history of irrigation using *seguias*, traditional earthen canals. The implementation of large modern open canal irrigation systems was based on the existing *seguias* and the organizational structures around these. With the construction of the Tessaout Amont irrigation system, urinary schistosomiasis was introduced in the region. The detection and treatment of infected people through the local health services led to a decrease in the infection rates. While in 1981 16% of the exposed population was found positive for schistosomiasis, since 1995 this has been less than 0.5%. In earlier studies inverted siphons have been identified as the main breeding sites of the intermediate snail host. However, more research is needed on water contact habits and distribution of *B.truncatus* snails in relation to characteristics of the irrigation system.

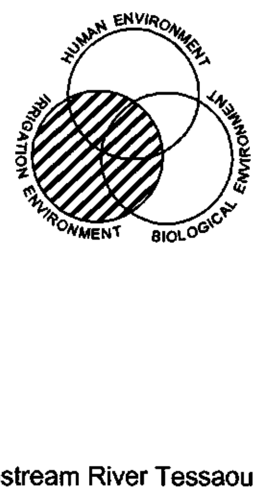
5

IRRIGATION AND WATER USE IN THE TESSAOUT AMONT IRRIGATION SYSTEM

In order to obtain a better insight into the irrigation ecology of schistosomiasis transmission in modern Moroccan irrigation systems, the Tessaout Amont irrigation system will be further studied. Technical characteristics of the irrigation system (Section 5.1) will be followed by an investigation of multipurpose use of water in the region (Section 5.2).

5.1. IRRIGATION DESIGN AND WATER MANAGEMENT IN THE MODERN OPEN CANAL IRRIGATION SYSTEM OF TESSAOUT AMONT

In this section the Tessaout Amont irrigation system will be described in detail. A good understanding of the reasons behind the layout of the system and the consequences of upstream flow control for the different types of hydraulic structures will contribute to the comprehension of the irrigation environment as an ecosystem. The process of water allocation and distribution determines the flow regime in the canals that is an important factor in snail dynamics (Chapter 6).



5.1.1. General layout

In 1969 the Moulay Youssef dam has been constructed upstream River Tessaout in the foothills of the High Atlas mountains (Figure 4.10). The dam has a reservoir capacity of about 200 million m^3 intended for irrigation of the Tessaout Amont irrigation system (Figure 5.1) as well as for power generation. A quantity of 0.05m^3/s is delivered to the water treatment plant of the provincial capital El Kelaa des Sraghna. Another part of the water is planned to be used to supplement the Tessaout Aval irrigation system, under construction. In 1981, another dam, Timinoutine with a capacity of 5.5 million m^3, was constructed downstream of the

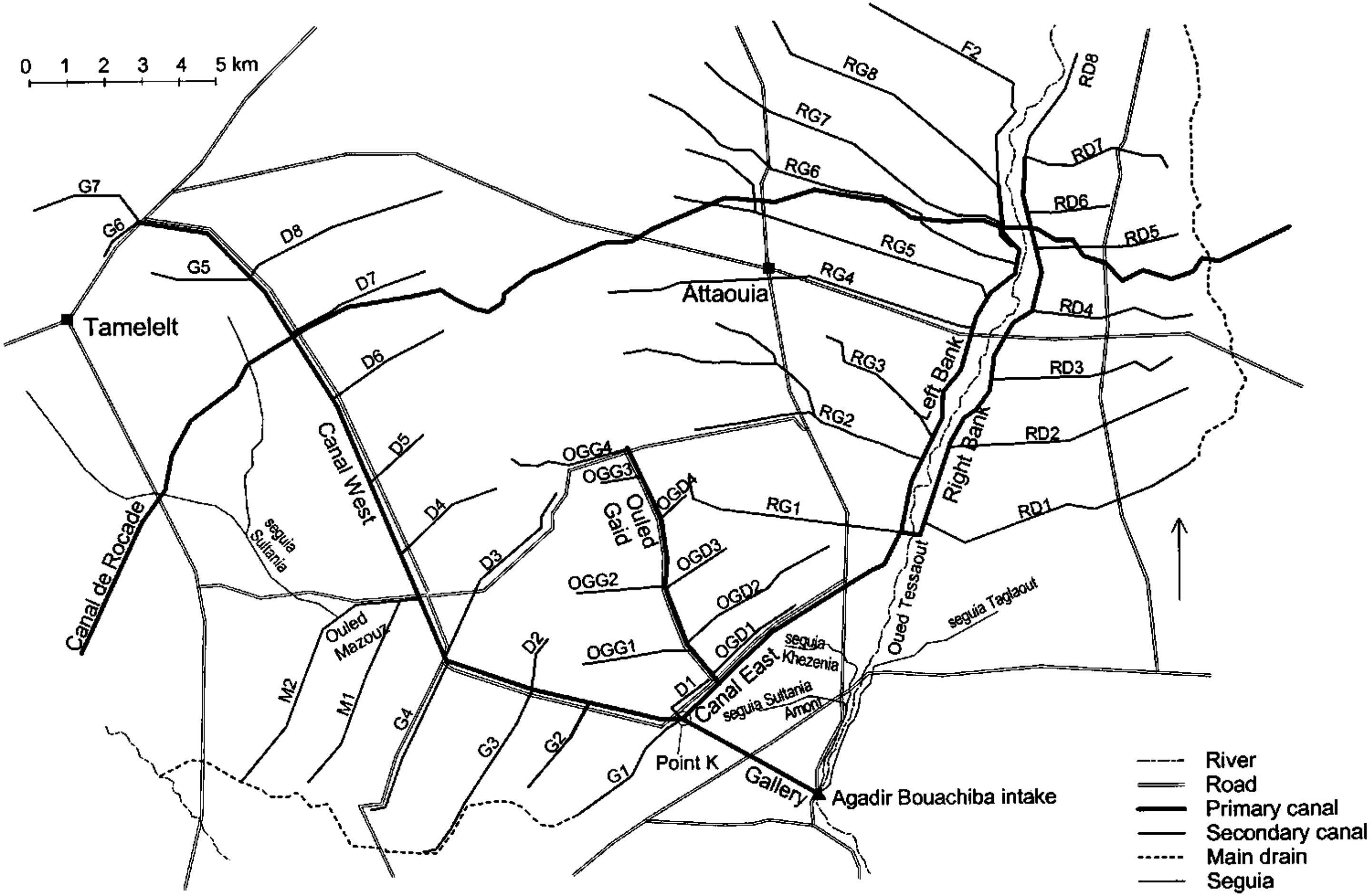


Figure 5.1. Primary and secondary canals as well as some *seguias* in the Tessaout Amont irrigation system.

Moulay Youssef dam to capture the water after energy generation. Now water is available for irrigation, independent from the requirements for the electricity plant (ANAFID 1991).

The 53 000 ha Tessaout Amont irrigation system starts from the system intake of Agadir Bouachiba . The intake is equipped with an AVIO gate and Neyrpic distributors (Figure 5.2). It is the first structure that is under the exclusive responsibility of the Tessaout Amont Irrigation Board of the ORMVAH[1]. From Agadir Bouachiba the water is led into a 4 km underground gallery. After a sand trap the water is regulated at "Point K" by an AMIL gate into the eastern and by Neyrpic distributors into the western primary canal and into two secondary canals.

Figure 5.2. Agadir Bouachiba intake with AVIO gate and Neyrpic distributors seen from the bend before the underground gallery.

The entire irrigation system is supplied by gravity force, which means that no pumps are used to get the water to the fields. The canals, drains and structures are all laid under a slope to get the water from the lake to the crops, that may be as far as 30 km away. Canals and hydraulic structures create resistance losses so the water has to be given sufficient (energy) head. In Tessaout Amont irrigation system water flow velocities change along the length of the canals with varying discharge, canal diameter and slope.

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[1] ORMVAH: *Office Régional de Mise en Valeur Agricole du Haouz*, the Ministry of Agriculture's Office for Agricultural Exploitation in the Haouz region. ORMVAH's command area stretches over parts of three provinces: those of Marrakech, Azilal and El Kelaa des Sraghna. Tessaout Amont irrigation system lies entirely in the latter province.

Primary canals have been constructed in trapezoidal sections of in-situ reinforced concrete following the topography (Figure 4.2). The canals have slopes between 0.1 and 1%, resulting in high water flow velocities of 1.5 - 3.5 m/s. The Primary Canal East has a separate primary branch called "Ouled Gaid" and is further downstream split in a left bank canal and a right bank canal, west and east of river Tessaout. Primary Canal West has a primary branch "Ouled Mazouz". The primary canals supply a total of 39 secondary canals of precast concrete half round conduits of maximum 1850 mm diameter (Figure 4.3). The secondary canals have replaced most of the traditional *seguias* in the region. The slope of the secondaries depends for some of them on the original location of the *seguia* and may vary from 0.1-3% (Table 5.1).

Table 5.1. Total lengths and maximum discharge capacities of canals in the Tessaout Amont irrigation system (Comité Technique 1990). The maximum discharges are given for the head ends of the canals, as the discharges and consequently the sizes of the canals are reduced downstream, in the direction of the water flow.

CANALS	TOTAL LENGTH (km)	MAXIMUM DISCHARGE CAPACITY (m^3/s)
Gallery	4	17
Primary Canal West	22.2	8
Primary Canal East	8.3	11
Ouled Gaid	6.9	2
Left Bank	9.0	4
Right Bank	11.9	5
Secondary canals	170	0.75
Tertiary canals	720	0.12
Primary drains	82	-
Secondary drains	190	-
Tertiary drains	720	-

All secondary canals are numbered systematically according to their location in the scheme (Figure 5.1). Secondaries on the Primary Canal West are numbered G1 - G7 (G = *Gauche* = left side), D1 - D8 (D = *Droite* = right side), and those on the Ouled Mazouz branch, M1 and M2. Secondaries on the primary canal East are numbered RG1 - RG8 (RG = *Rive Gauche* = left bank), RD1 - RD8 (RD = *Rive Droite* = right bank), and those on the Ouled Gaid branch OGG1 - OGG4 (OGG = *Ouled Gaid Gauche* = left side of Ouled Gaid) and OGD1 - OGD4 (OGD = Ouled Gaid *droite* = right side of Ouled Gaid). Additionally, the primary Left Bank feeds the lined *seguia* F2, in the Freita area.

On the total area of 53 000 ha, 33 000 are equipped with modern concrete irrigation canals up to the tertiary level and managed on the basis of crop water requirements. From the secondary canals the water flows into branches, tertiary canals, that are similarly constructed with elevated semi-circular concrete conduits of 400, 500 and 600 mm in diameter. The tertiary canals are numbered consecutively from the start of the secondary canal (e.g. D5T7 is the seventh tertiary canal on the secondary D5). The tertiary canals in turn provide water to quaternary or field canals, made of earth (Figure 5.3). The other 20 000 ha are provided with water from the modern system into (lined) *seguias*, following traditional water rights. An extensive network of earthen drains exists complementary to the irrigation network. Main collector drains are partly masonry lined.

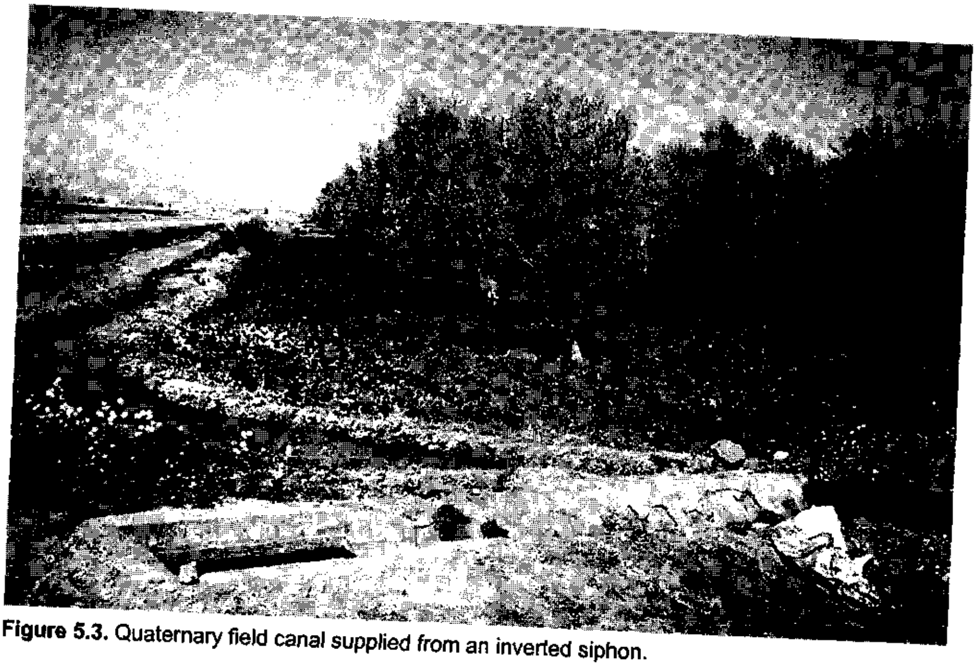

Figure 5.3. Quaternary field canal supplied from an inverted siphon.

The Tessaout Amont irrigation system has been constructed in phases between 1968 and 1978 (Figure 5.4). Some *seguias* were replaced by lined secondary canals in the early 1990s.

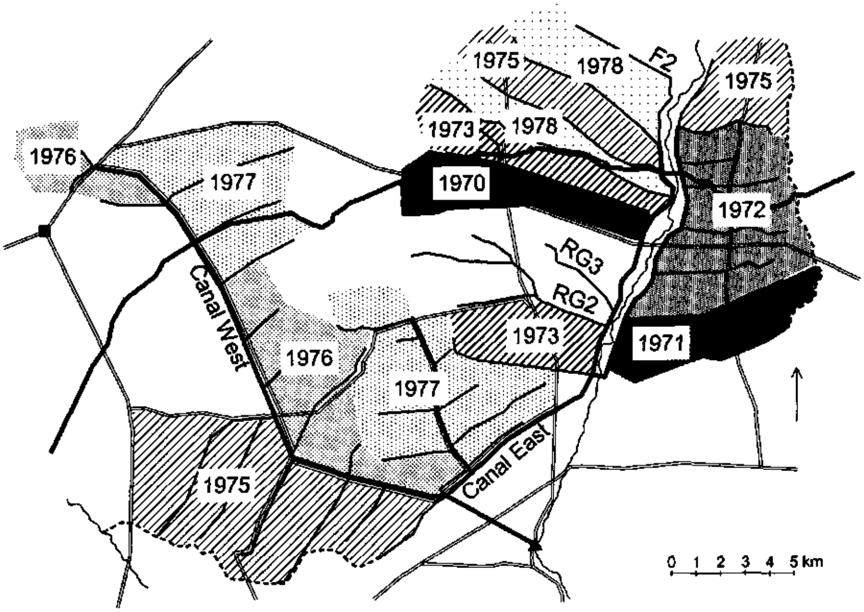

Figure 5.4. Year of first operation of secondary units in the Tessaout Amont irrigation system (El Yadouni 1995). The sectors served by the secondary canals RG2, RG3 and F2 are managed according to traditional water rights.

Flow control

Water discharges in the gravity-fed irrigation system are regulated by upstream control, which means that the downstream outlet discharge is constant, with a deviation of plus or minus 10 %, regardless of fluctuations in the upstream supply (Figure 5.5). Measurements in 6 secondary canals in the Tessaout Amont irrigation system showed that indeed the discharge measured did not differ more than 10% from the discharge set (Jones 1993). Upstream control is the most suitable regulation in systems where water supply does not meet the demand (Kraatz & Mahajan 1975). As a result, *water is supplied intermittently* with rotation periods that vary from 1 to 3 weeks. Major disadvantage of this method is the long time it takes for changes in the upstream part of the irrigation system to become effective downstream. From the system intake to a tertiary canal this may take several hours.

In the primary canals, with relatively high discharges, fixed weirs or automatic upstream water level regulators, AMIL gates, provide the right water level for the secondary outlets. At some canal stretches downstream of an AMIL gate, sometimes AVIS gates are used to obtain a constant downstream water level. For tertiary outlet structures, generally a diagonal or duckbill weir is constructed in the

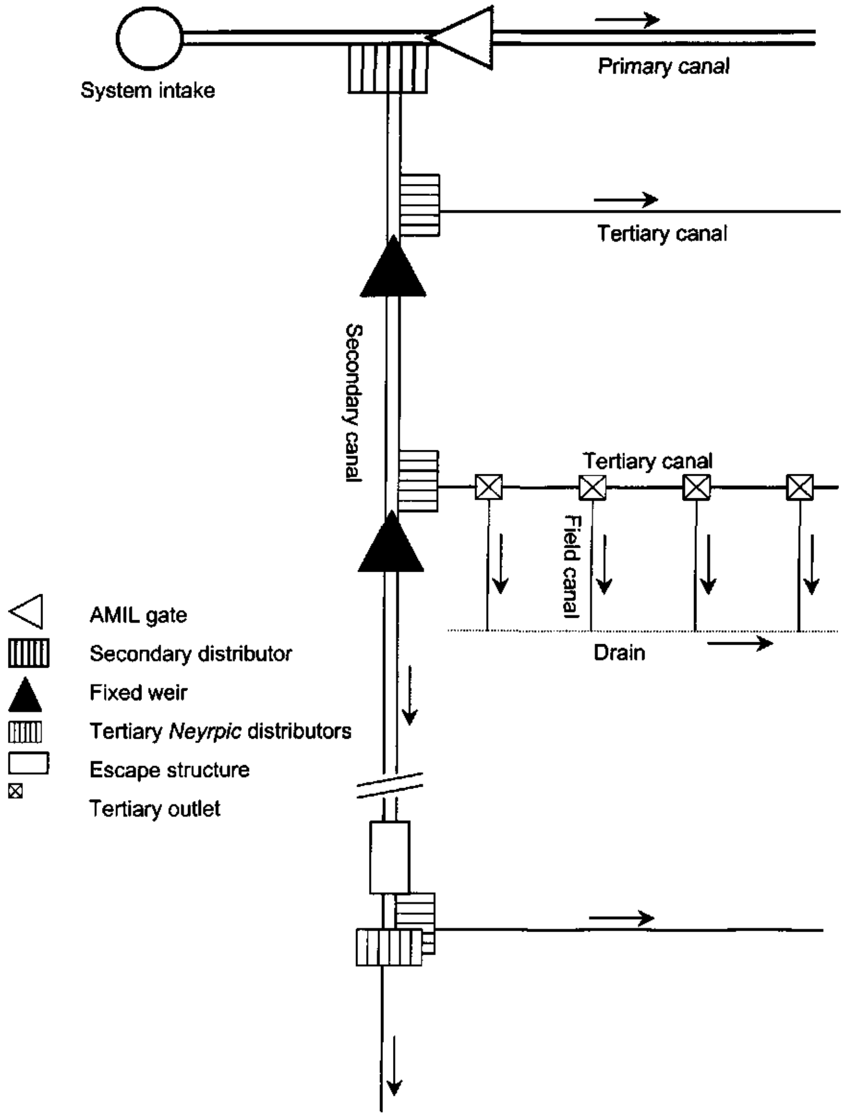

Figure 5.5. Schematic layout of the upstream control in the Tessaout Amont irrigation system.

secondary canal downstream of the tertiary canal, in order to maintain a constant water level in the secondary. The intake structure at the head of the tertiary canal consists of baffles, Neyrpic distributors with sliding metal plates for compartments of 5, 10, 15 and 30 l/s (Figure 5.6). Often the plates are equipped with padlocks to prevent tampering of the outlet by farmers. On tertiary level the flow is either divided proportionally in two equal parts or with simple on/off structures.

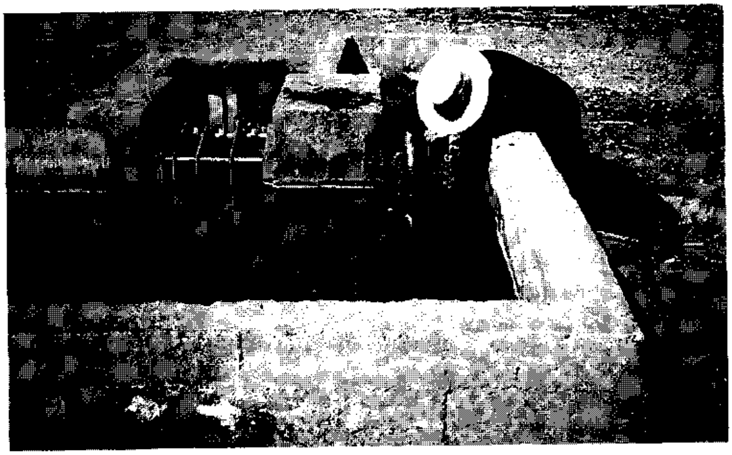

Figure 5.6. Neyrpic distributors at the head of a tertiary canal in the Tessaout Amont irrigation system. At this site two tertiary canals T1 and T2 are supplied from the upstream siphon box in the secondary canal D7. The farmer tried to meddle with the slides hoping to increase the discharge.

5.1.2. Hydraulic structures

Many different concrete hydraulic structures for water distribution and other purposes have been constructed on all canals in the Tessaout Amont irrigation system. Often the standard design of a structure has been adapted to specific local situations. Technical differences between older and more recent sectors of the irrigation system can be attributed to individual construction styles of contractors.

Figure 5.7. Sand trap at the head of the Primary Canal Ouled Gaid. With the present low water level, the silt deposits become visible.

Sand traps are only found at the head of the primary canals (Figure 5.7). The structures are constructed as wide, relatively shallow basins, designed to reduce the water flow velocity. This allows for settling of the sediment. However, the basins are too small to get rid of all suspended matter. The course particles, mainly sand, will settle first but the very fine silt particles remain suspended. Further downstream in the system, a silt layer of several mm is deposited in canals and hydraulic structures.

Angle structures between straight secondary canal strikes generally appear as shallow (0.4 m) concrete pentagons (Figure 5.8).

Figure 5.8. Angle structure at a tertiary canal, fully overgrown with weeds.

Long crested weirs, diagonally over the canal or in the form of a horse shoe, regulate the upstream water level in secondary canals (Figure 5.9). The weirs are usually designed to drain dry when the water flow is stopped.

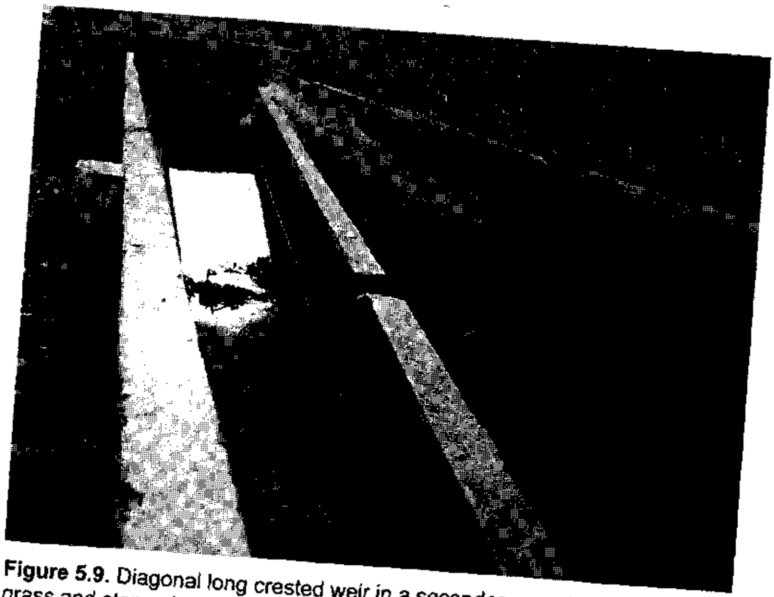

Figure 5.9. Diagonal long crested weir in a secondary canal seen from the upstream direction. The grass and stones have been put in the drainage opening of the weir by farmers who hope to increase the water flow to their intake (upper left corner of the photo). As a result, water is retained behind the weir.

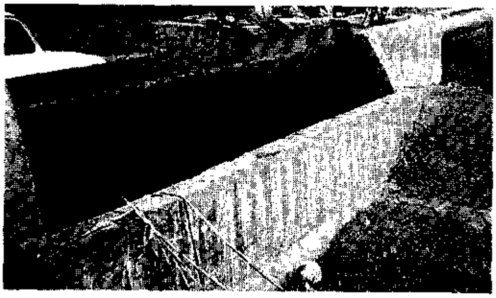

Figure 5.10. Escape structure on the secondary canal D7. The distributors along the secondary canal are not well attuned and the surplus water flows over the edges of the low section through the reception pit into the drain (bottom right).

Escape structures are constructed on secondary canals at locations where the diameter of the canal is reduced (Figure 5.10). Just after a long crested weir without drainage opening, a canal section is set below the level of the canal, forming a double-sided overflow weir. Underneath a concrete reception pit has an outlet to the nearest drain.

Drop structures on secondary or tertiary canals after an outlet to a lower order canal exist of a vertical or inclined (chute) drop and a stilling basin (Figure 5.11). With chutes, the inclined part of the structure dries out in the sun shortly after the water flow has stopped. The deeper stilling basin however, often holds water till the next turbulent flow between the stones and boulders that were put there for dissipation of energy.

Figure 5.11. Drop structure on a tertiary canal, under an olive tree.

Division boxes are often linked to other secondary or tertiary structures (e.g. to inverted siphons) and consist of square shallow basins with different outlets. Originally, the outlets could be closed with plain steel plates. After 25 years of operation, these gates are missing from most places at the tertiary canals so farmers often use mud and stones for water division (Figure 5.12).

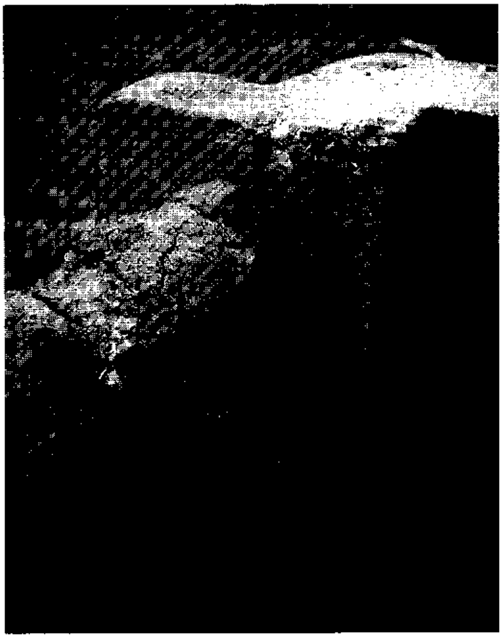

Figure 5.12. Mud wall for water division in a tertiary structure.

Inverted siphons are the most frequent type of structures, especially at tertiary level. In this thesis the inverted siphons will also be referred to simply as "siphons". In Tessaout Amont there are tens of thousands of inverted siphons. A standard siphon consists of two boxes, connected by an underground pipeline (Figure 5.13). Secondary siphons are only constructed at crossings of main tracks or roads and can be more than 2 m deep. Tertiary inverted siphons are constructed at the canal head, for crossings and for most quaternary outlets.

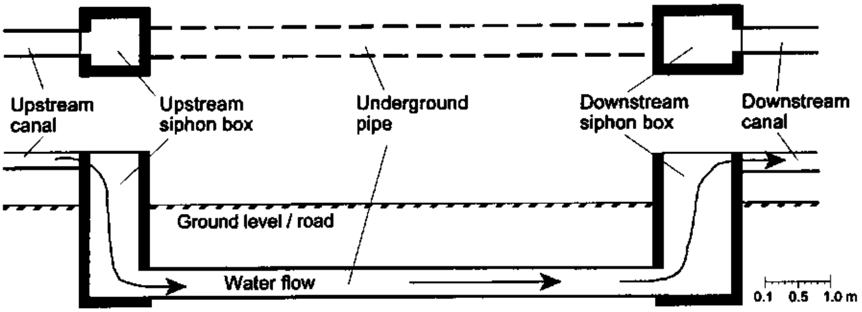

Figure 5.13. Diagram of a standard inverted siphon in a tertiary canal.

At quaternary outlets, two different types of inverted siphons are found, type A and type B. Type A is most abundant at tertiary canals that only convey 30 l/s (Figure 5.14). The upstream tertiary box is on the canal itself so every rotation flows over the box, leaving the downstream quaternary box relatively undisturbed (Figure 5.15). Type B has been constructed at tertiary canals that convey more than 30 l/s. The quaternary siphon is isolated from the canal, either beside or below the division box (Figure 5.16). Both the upstream and downstream quaternary box only convey water when the field outlet is used (Figure 5.17).

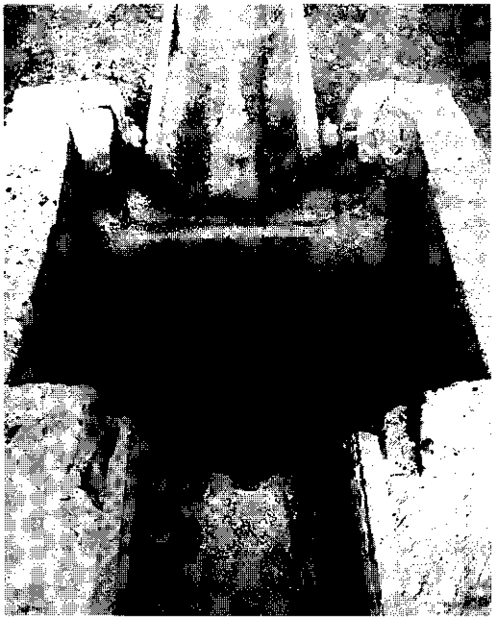

Figure 5.15. Upstream siphon box of a type A inverted siphon on a tertiary canal.

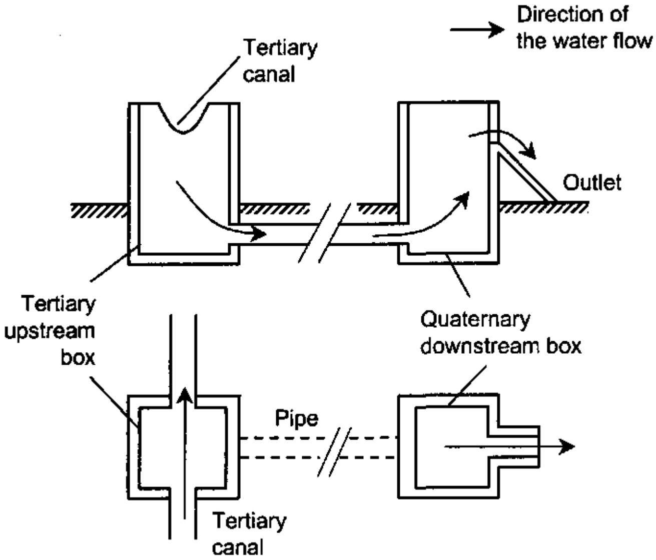

Figure 5.14. Diagram of type A inverted siphon with tertiary upstream box and quaternary downstream box.

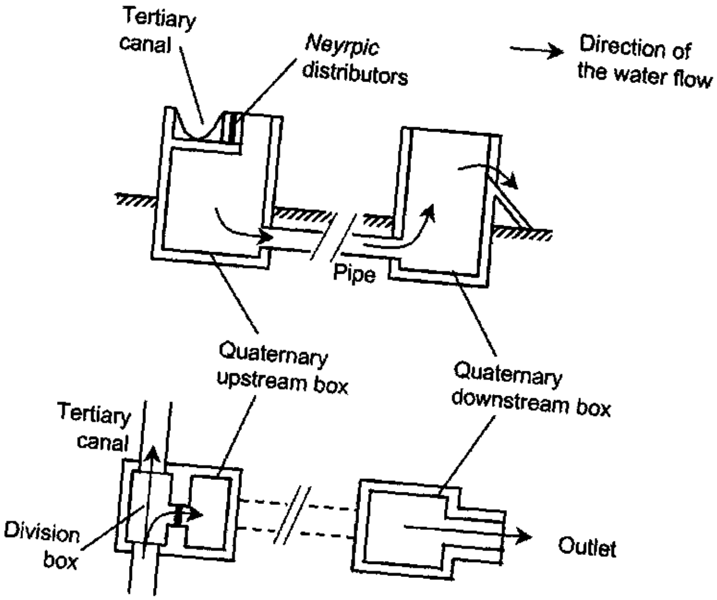

Figure 5.16. Diagram of type B inverted siphon with tertiary division box over the quaternary upstream siphon box.

Figure 5.17. Type B inverted siphon with fully overgrown division box on the tertiary canal next to the quaternary upstream siphon box. The downstream box has an outlet to the quaternary field canal.

Between rotations, siphon boxes act as sand traps for the standing water, that still bears a lot of silt, especially after heavy rains occurred in the High Atlas mountains. This period of stagnation is longer with increasing distance from the higher order canal. At the end of a tertiary canal it may add up till a full rotation period, which is sometimes more than 3 weeks. In this way a compact layer of substratum, consisting of silt and algae, can build up on the concrete walls of the structures. The floor of a siphon box may be covered with loose mud and stones that have fallen in when the farmer-made water barriers have collapsed.

5.1.3. Water management

Crops

The main crops in Tessaout Amont are barley, olive trees and fodder crops such as lucerne and maize. Other crops in the area are wheat, cotton, sugar beet, broad beans, tobacco, almonds, apricots and soy beans. Mixed cropping is also practised, usually horticulture or fodder crops under olive trees or in other orchards. Many farmers in the irrigation system depend on traditional sheep rearing. The main cropping and irrigation season is in summer. However, perennial crops such as olive trees need year round irrigation.

Water allocation

The 33 000 ha "modern" part of the Tessaout Amont irrigation system is entirely managed on the basis of actual crop water requirements. The other "traditional" 20 000 ha are provided with water from the modern system into (lined) *seguias*, following traditional water rights based on time shares or proportions. In these traditional parts, farmers are responsible for water distribution from the secondary canals that have replaced the main *seguias*. The Irrigation Board supplies these secondaries (e.g. RG2 and RG3) with flow rates that are based on the total of original water rights in the command area.

In the modern part of Tessaout Amont however, the allocation of water to irrigators is arranged fully by the Irrigation Board. In the process that leads from basic data collection to a detailed allocation programme, a large number of other parties are involved. In addition to the Irrigation Board, other services of ORMVAH, Water Users Associations and the Provincial Technical Committee can officially influence the eventual water allocation (Table 5.2). The formal decision process is presented schematically in Figure 5.18.

In dry years the amount of water in the reservoir is not sufficient to meet all agricultural water demands and hence choices have to be made concerning the water distribution. There is no feed back on the basis of actual soil moisture content. Instead standard priorities are applied (Comité Technique 1990). First

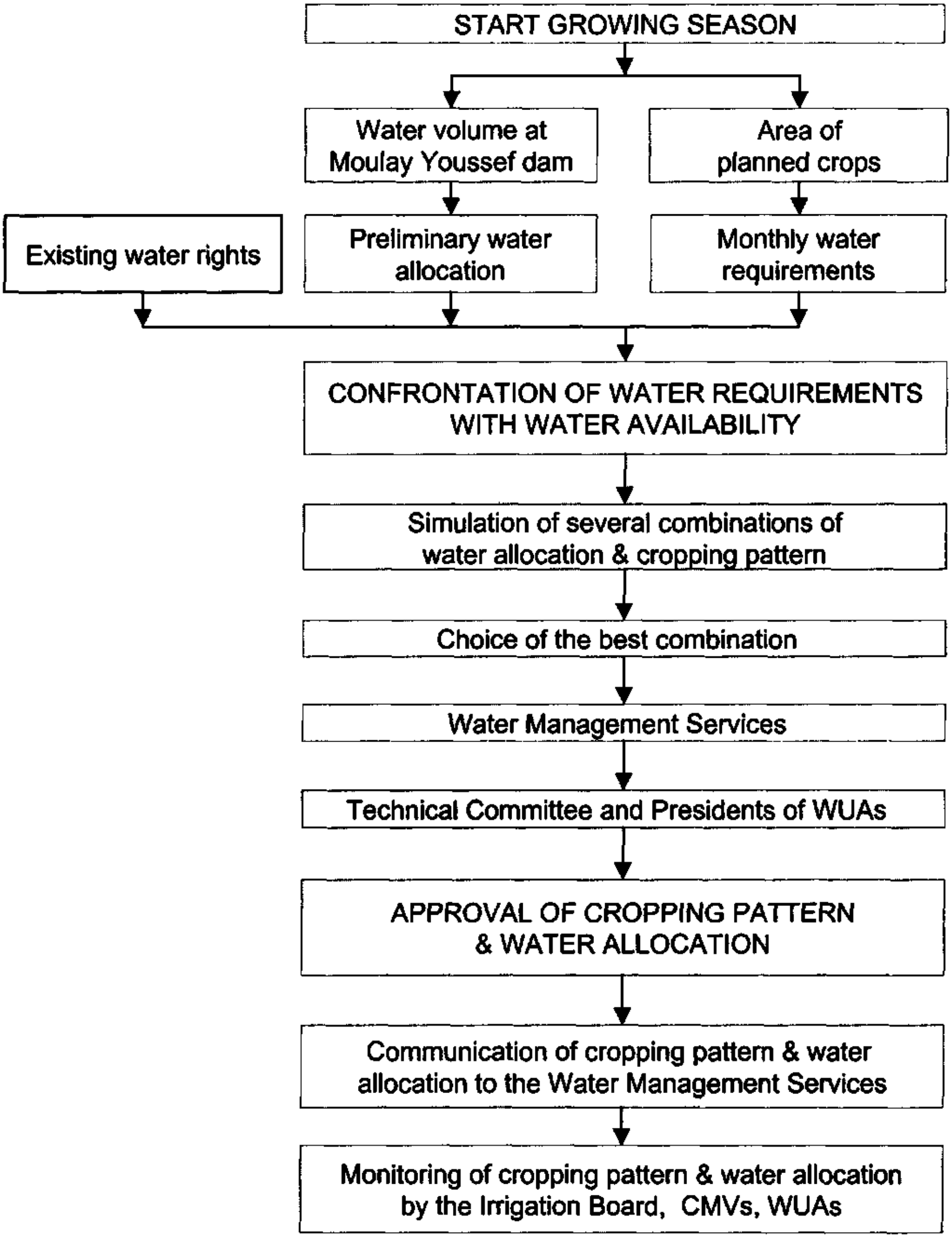

Figure 5.18. Planning of cropping pattern and water allocation in the Tessaout Amont irrigation system (after Comité Technique 1990, Lekedji 1995). CMV: agricultural exploitation centre, WUA: water users association.

Table 5.2. Actors in the decision process over water allocation in the Tessaout Amont irrigation system (Lekedji 1995).

GROUP NAME	ACTORS
Water Management Services	ORMVAH (MAMVA[1]), Regional Direction of Hydraulics (MTP[2]), Provincial Direction of Public Works (MTP), National Energy Office (MTP), National Drinking Water Office (MTP)
Technical Committee	Governor El Kelaa des Sraghna (chairman); Director ORMVAH; Chief Irrigation Board; Local Authorities; representatives of farmers, House of Agriculture, Direction of Rural Equipment (MAMVA), Direction of Crop Protection (MAMVA), National Energy Office (MTP), Regional Direction of Hydraulics (MTP), National Drinking Water Office (MTP), Provincial Direction of Public Works (MTP), professional groups (in particular Agro-industry).

[1] MAMVA: *Ministère d'Agriculture et de Mise en Valeur Agricole*, Moroccan Ministry of Agriculture.

[2] MTP: *Ministère des Travaux Publics*, Moroccan Ministry of Public Works.

summer cash crops such as cotton are cancelled, then the cultivated area is restricted. The third step is a limitation of the crop allotment, which can reach 50%. The Irrigation Board sets a minimum amount of water for each crop, prioritizing perennial and fodder crops. This process results in a peculiar relation between the actual rainfall and irrigation. In relatively wet years, there is less need for irrigation. In dry years, more irrigation water is required, but this can only be delivered if in preceding years the reservoir has been filled. If this is not the case, irrigation is seriously restricted in the dry years when it is needed most. In 1992/93 a period of drought that prevailed with the lowest rainfall in 15 years had significant implications for irrigation in the years after, as the reservoir was at only half of its capacity (Figure 5.19).

Water distribution

In the process from water allocation to distribution the first step is the verification of cropping patterns. After consultation with the cooperations and agricultural extension workers, the local centres of ORMVAH, the so-called CMVs[1], calculate the crop water requirements for each field. In summer, the crops have to be irrigated once a week, outside this season twice a month or less. Daily water allocations for each tertiary canal can then be calculated. The allocations per tertiary are summarized by the Irrigation Board for the secondary canals, that adds 10% for conveyance losses. Subsequently, total water volumes are calculated for the primary canals and eventually for the entire system, taking into account the constraints of the irrigation system and avoiding night irrigation. *The Irrigation Board strives for constant low flows in the secondary canals* to avoid large

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[1] CMV: *Centre de Mise en Valeur*, agricultural exploitation centre.

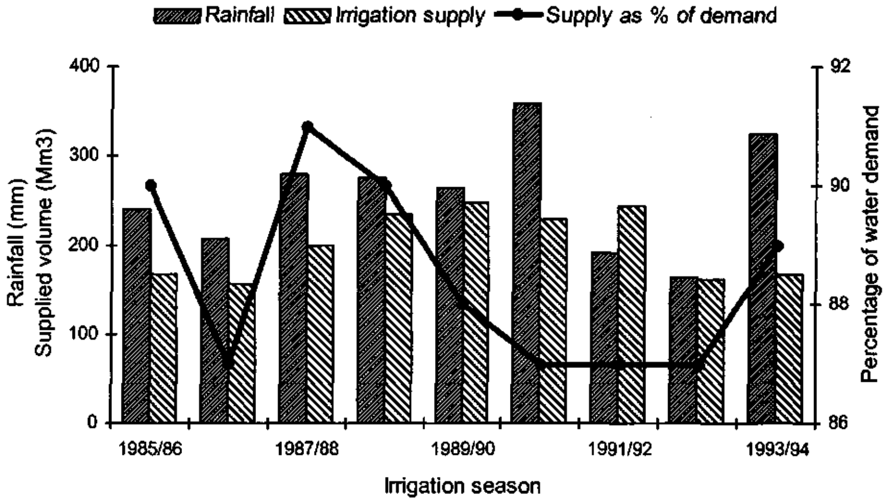


Figure 5.19. Annual rainfall and amount of water supplied for irrigation during the period 1985 - 1996 in Tessaout Amont. Also indicated is the irrigation water supply as a percentage of the (corrected) crop water requirements (Lekedji 1995).

variations in the total system water demand. From the tertiary canal to the fields, water is scheduled by the Water Users Associations. Rotation between tertiary canals generally goes from the most downstream canal to the upstream ones. In Figure 5.20 a schematic overview is given of the process of formal water distribution.

Cleaning

Primary canals and their structures, especially the sand traps, are cleaned regularly by the Irrigation Board. At lower levels, canals are maintained by farmers. Secondary canals are cleaned once every two seasons or less frequently. Inverted siphons are cleaned merely when clogged.

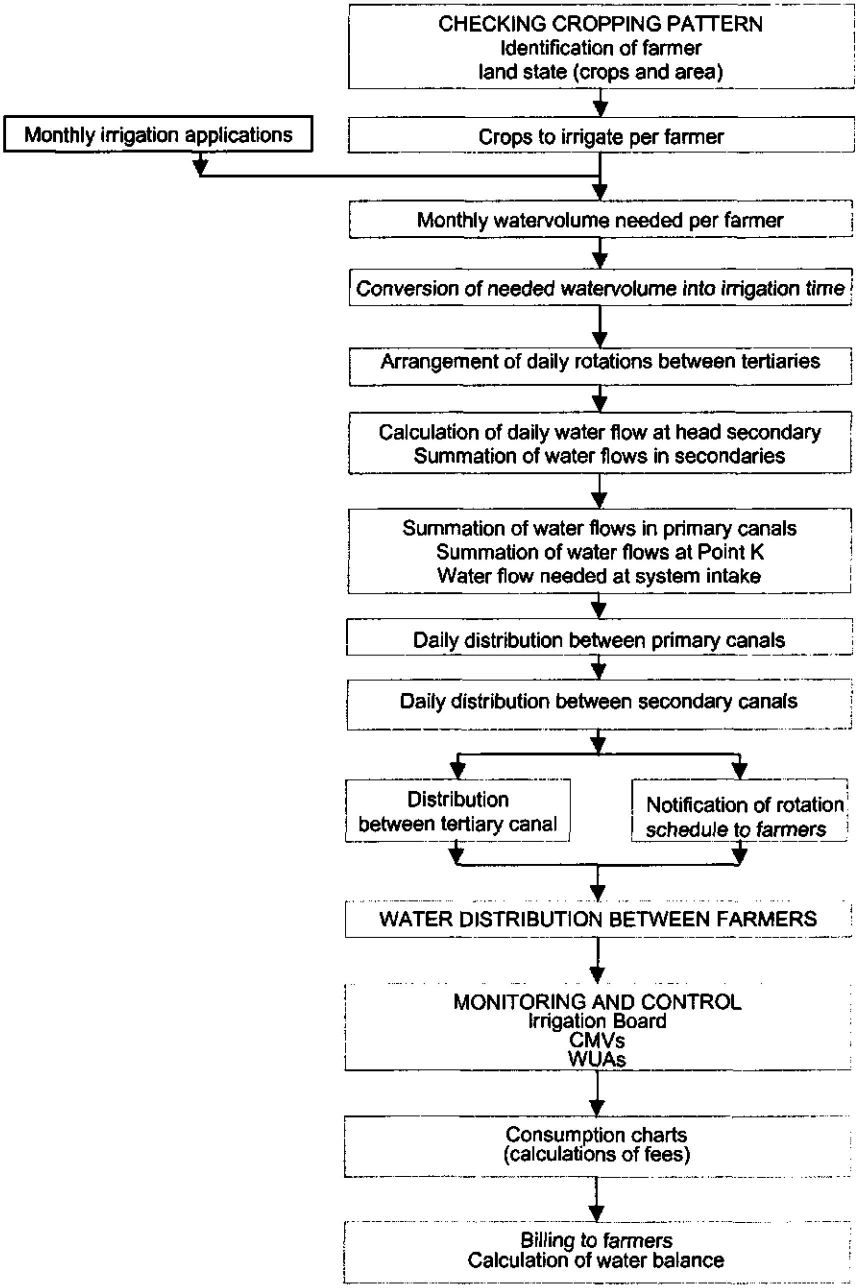
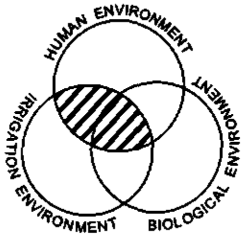


Figure 5.20. Steps in the water distribution in the Tessaout Amont irrigation system (after Comité Technique 1990, Lekedji 1995). CMV:agricultural exploitation centre, WUA: water users association.

5.2. MULTIPURPOSE USE OF WATER IN TESSAOUT AMONT

In the irrigation ecology of schistosomiasis, water contact has to be studied in the overlap of the human and irrigation environment. Though many studies have tried to evaluate the exact role of water contact in schistosomiasis transmission, *few have considered the wider environment of water use.* In this section agricultural and domestic use of water from different sources in Tessaout Amont irrigation system will be discussed.



5.2.1. Sources of water for agricultural and domestic purposes

In the Haouz plain, the traditional *seguias* have always been used as a source for drinking water and other domestic use, especially when the water was flowing near houses. In some villages, irrigation water from *seguias* was stored in so-called *metfias*, (partly) *underground tanks*. Water for these tanks was provided according to special water rights, ensuring a continuous store of water for domestic purposes to the communities. These domestic purposes include laundry, the washing of household utensils and the use of water for other household-related activities.

Nowadays, the rural population in the Tessaout Amont irrigation system has mainly two sources of water for domestic purposes: ground water and surface water. The ground water depth in the Haouz plain varies from 15 m to over 100 m. In areas with relatively shallow (roughly between 15 and 40 m) ground water depth, numerous wells equipped with windlass or motor pump provide water for all kinds of purposes. Since a severe drought in the 1980s, several new wells have been excavated and equipped with diesel pumps to provide supplementary irrigation water in addition to water for domestic use.

In the areas with deep ground water, special provisions are necessary, because few people have the means to drill wells over 100 m depth. The construction of the modern open canal irrigation system in the 1970s, went along with land reform. Fragmented holdings were consolidated and villages were newly planned and equipped with a deep well, diesel pump, water tower and public taps. Most families however, did not want to move to a new village and preferred to either stay in their old village, or if that was too far, to construct a house right at their fields. The few fields. The few new villages that did become inhabited, lacked the social coherence necessary to bear the responsibility for the operation and maintenance of new drinking water supply systems. Hence at first the systems functioned well, but later it proved practically impossible for the community leaders to organize the required support and financial contributions (Boelee et al 1999). Consequently they often address the Irrigation Board with requests for repairs. The Board however, only provides technical assistance.

Water storage in metfias

In absence of separate drinking water supply systems, some of the old *metfias* were renovated and connected to the new concrete irrigation canals. In the dry 1980s, a large number of new *metfias* has been constructed. A preliminary survey in 1996 in two sectors of the Tessaout Amont irrigation system where the ground water is deep, identified 101 functioning *metfias* (Figure 5.21).

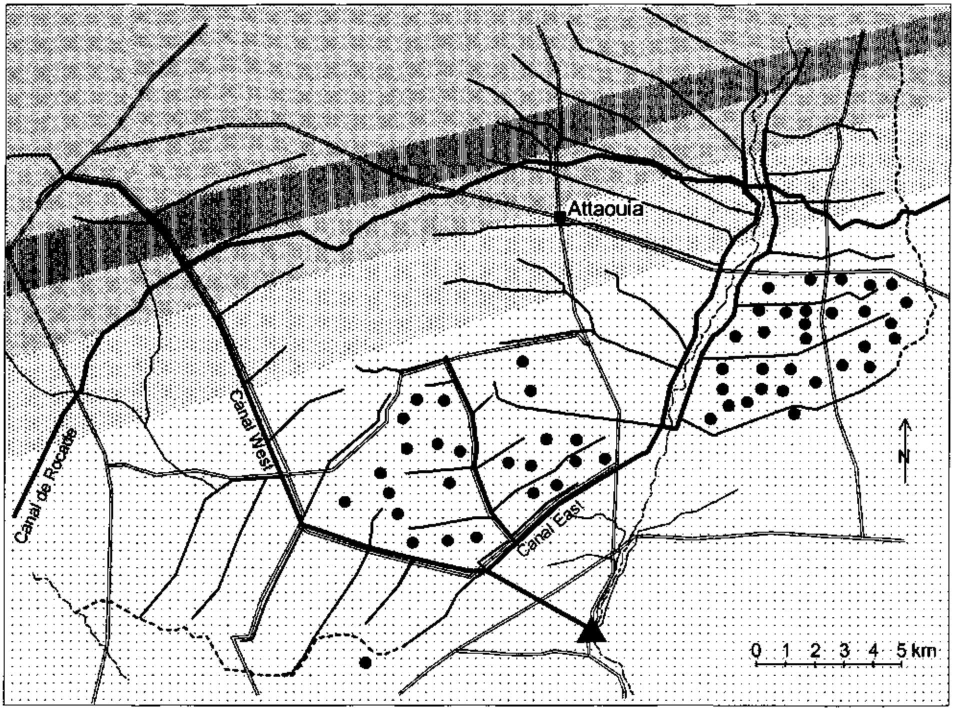


Figure 5.21. Approximate range of ground water depths and *metfias* in the Tessaout Amont irrigation system (after Laamrani et al 1999).

The tanks have different sizes and shapes, varying from 17 to 500 m^3 (Table 5.3). Contrary to similar structures such as the open *diggis* in Punjab Pakistan, all *metfias* in Tessaout Amont are covered. The communal *metfias* are generally quite large, originally built of mud and stones (Figure 5.22). Rehabilitation of old *metfias* with cement or construction of new tanks has been carried out with support from the Irrigation Board. Most of the small ones are privately owned and built in the court yard of individual houses (Figure 5.23). Only a fifth of the private *metfias* is used exclusively by the owners (Table 5.4), as according to custom, nobody can be refused water for drinking. The individual owners use water from their personal irrigation water rights to fill their *metfias*. Communal reservoirs have always been entitled to special water gifts and the Irrigation Board still respects these water rights in rotation with their irrigation water schedules.

Table 5.3. Capacity of *metfias* in the southern Tessaout Amont irrigation system (Laamrani et al 1999a).

SIZE	< 50 m^3	50 - 100 m^3	> 100 m^3
Number of *metfias*	43	40	18

Table 5.4. Ownership and type of use of 101 *metfias* in the southern Tessaout Amont irrigation system (Laamrani et al 1999a).

	USE	
OWNERSHIP	Personal	Collective
Personal	16	59
Collective	-	26

The users feel that the *metfias* are no longer adequate in fulfilling their needs for domestic water, because of the lengthy interval between water gifts. Another problem is that most of the connections to the concrete irrigation infrastructure are provisional so the water flows into the *metfias* through earthen feeder canals and is liable to become soiled. Facilities for cleaning or flushing the *metfias* are limited and water treatment is restricted to irregular application of chlorine tablets from the health centre, the use of ordinary household liquid chlorine (0.5-1 l for a full *metfia*) or treatment at home before consumption (Laamrani et al 1999a).

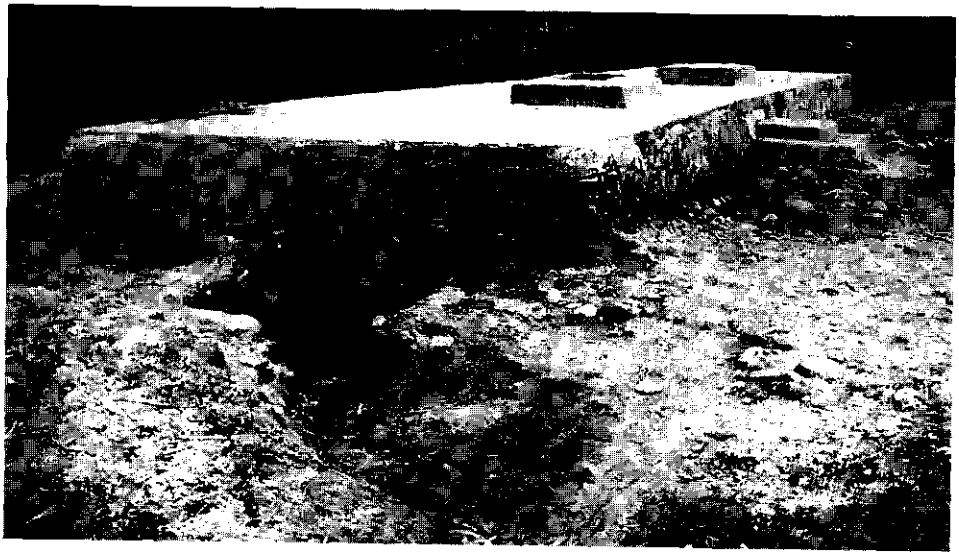


Figure 5.22. Communal *metfia* built with mud and stones and renovated with cement. The feeder canal that connects the secondary canal RG2 to the *metfia* has not been lined and is prone to pollution.

Figure 5.23. Privately owned *metfia* with a grid protecting the opening. The farmer constructed a partly lined canal to convey the water from the tertiary canal into his court yard. To fill such a *metfia*, the farmer uses his own irrigation water rights.

The irrigation system as a source of water

For people without access to wells or metfias, the irrigation infrastructure as such is often the only source of domestic water available. The construction of the dam and the new Tessaout Amont irrigation system increased overall water availability in the region and the high density network of lined canals brought the water closer to people's homes. Combined with the present water management, resulting in a regular flow of water in the secondary canals and intermittent flow in tertiary canals, the irrigation system has turned into an almost permanent and readily available source of water. To the rural population this is a distinct improvement compared to the old earthen canal system with limited water availability. *During the period between irrigation turns, the tens of thousands of inverted siphons on tertiary canals are the only water source at hand for people living at some distance from a secondary canal. The quality of the standing surface water in the boxes will considerably deteriorate over the rotation period.*

In periods of drought, the Irrigation Board not only has to safeguard perennial and fodder crops, it is also responsible for the provision of sufficient fresh drinking water for livestock. In the standard priorities for dry years' water allocation in Tessaout Amont irrigation system, this is referred to as "domestic water supply to the population (supply to animals etc)" (Comité Technique 1990). This implies that the Irrigation Board is well aware that the special water gifts provided for watering the animals will be used for domestic purposes as well, though the Board has no means to guarantee drinking water quality. The water flow for this "animal water supply" at the same time refreshes and supplements the standing water in the inverted siphons.

5.2.2. Water contact and water use

The relatively high incidence and prevalence of urinary schistosomiasis among children and youngsters can be explained from their high rates of water contact. In Tessaout Amont, the collection of water from a non-household source for storage on the premises is mostly done by children. They may be kept from school specially for this task and make several journeys a day (Houtstra 1995). The most common form of water transport is by donkey, with two rubber containers slung over its back. These are made of old car tires and have a capacity of approximately thirty litres each (Figure 5.24). Wealthier families may have a donkey- or mule-drawn cart carrying plastic containers, a converted oil drum or a small tank with a capacity between one and two hundred litres. Occasionally, plastic hoses are used to lift the water from a primary or secondary canal into a container. Whereas the fetching of water with a bucket or donkey is done by young girls and boys alike, the carts are only used by older boys or men. For youngsters who do not go to school, nor have a job, some points at secondary canals that are suitable for lifting water, have become favourite meeting places.

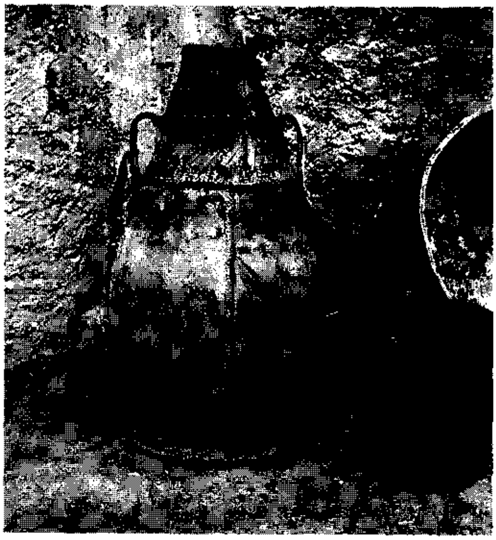


Figure 5.24. Rubber container for water transport (± 30 l), made of old car tires.

Apart from the collection of water, other water contacts can be observed in and around irrigation infrastructure in Tessaout Amont (Table 5.5). Most of these activities can be observed anywhere in irrigated areas throughout the world, but in an area where schistosomiasis occurs, water contact is a necessary link in the transmission cycle and deserves special attention. The very focal and specific water use pattern in Tessaout Amont can partly be explained from the nature of the irrigation system itself. The typical elevated concrete canals seem to make out an essential part of "rural furniture". In the otherwise flat plain, the canals and their structures offer support to sit on, lean against, give shade, use as a table and, of course, provide water for all purposes. Canals seem to be as important as roads and tracks in concentrating human activities and have a similar dense net.

Water quality

Many adults in Tessaout Amont realize that the water supplied to their *metfias*, as well as water taken directly from siphons and canals, is of poor quality. However, they have no choice but to use it, since no other water source is easily available. Despite this dependence, there seems to be no control over the upstream pollution of the water. For example, a butcher regularly washes his utensils and the intestines of slaughtered animals in the secondary canal next to his shop. People living in a village downstream are aware of this threat to health but seem unable to take any action against the polluter.

Table 5.5. Different types of water use and water contact at irrigation infrastructure, observed in Tessaout Amont.

TYPE OF ACTIVITY	DESCRIPTION	MAIN USER
Irrigation	Operating gates and structures, manipulating field canal banks.	Male adults
Laundry	Clothes with soap and scrubbing preferably in separate basins, rinsing in streaming canals, large items on structures.	Females
Bathing	Elaborate bathing with soap, ritual washing before prayers, anal cleansing, splashing water for refreshment.	Males[1]
Playing	Splashing, running through canals, swimming through inverted siphons[2].	Children
Washing	Straw and other animal fodder, grains for bread.	Female adults, children
Cleaning	Household utensils, farmer's tools, cars, milk cans, pesticide application equipment.	All
Drinking	Directly drinking from the canal, watering animals.	Males
Other	Making bricks etc.	Male adults

[1] *Females generally bathe inside the house only.*

[2] Especially some of the large secondary siphons provide a challenge to children. In a daring game boys attempt to swim through the pipe under the road, which even has resulted in a number of casualties.

Another common cause of pollution is the washing of animal fodder. In this sheep-rearing region, straw from barley and wheat is commonly cut up finely and stored in mud-coated stacks (Figure 5.25). The straw has to be washed to remove the dust, make it digestible and in some cases mix it with highly nutritional but expensive bran. Some of the children tie up the straw in woven bags and then shake them up and down in a siphon box, thus making the water unfit for human consumption.

Figure 5.25. Half used stack of finely cut straw covered with mud.

In the absence of means to influence water quality, people have developed temporal and spatial strategies for the selection of certain sources of water for particular purposes. While quality is an important criterium for all water uses, different qualities are required for each purpose. Selection criteria are based on the required quantity and quality and on convenient availability. Water pumped from deep wells supplied through taps is generally considered the best quality for drinking, followed by shallow wells. But as it is quite laborious to lift a bucket of water from a depth of 40 m, generally the water from wells is used for drinking and kitchen use only. Where no wells are present, streaming water in canals is preferably taken in the morning, when chances of upstream pollution are lowest, arguing that "even after boiling a soap taste remains a soap taste" (Houtstra 1995). *If no other alternatives are available, people will use the standing water from inverted siphons for consumption.*

For the washing of clothes and especially coverlets or rugs, that take a large amount of water, a different practical strategy is applied: this activity takes place outside the house, along the irrigation canals. Women and girls find it time consuming to take the water back to the house and perform the task there, in the absence of sewerage (Boelee et al 1999). Even in areas where wells are present, the canals, inverted siphons, other hydraulic structures and bridges serve as a convenient support for scrubbing and for drying clothes (Figure 5.26). At the same time, laundry often provides the only opportunity for teen and adolescent girls to leave the house and meet other women.

Figure 5.26. A tertiary irrigation canal in the Tessaout Amont irrigation system is used for the drying of laundry.

5.2.3. Sources of water determining water use

To illustrate the local differences in water use in the Tessaout Amont irrigation system, three case studies[1] are discussed (Figure 5.27).

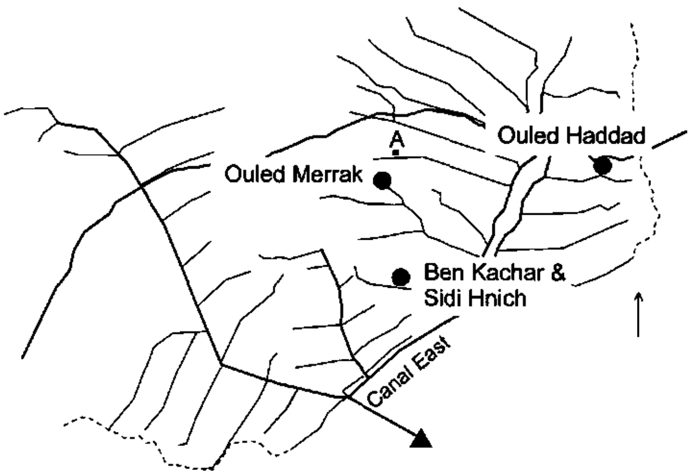


Figure 5.27. Position of 3 case studies for water use in the Tessaout Amont irrigation system ("A" is the town of Attaouia).

The case of Ouled Merrak

The village of Ouled Merrak is situated in the "traditional" part of the irrigation system (Figure 5.28). The old *Seguia Lambarkia* has been replaced by the lined canal RG2. This secondary canal has no tertiary canals but serves old minor *seguias*. Three of these *seguias* feed a total of 7 private *metfias*. In addition, there is one motorized deep well in the village and another one 1.5 km away. For high quality drinking water people select well water but also streaming water in RG2 early in the morning. Occasionally, water is purchased in the town of Attaouia, some 3.5 km away. If large quantities of water are required, the siphon boxes at RG2 and the 7 *metfias* are preferred; the first because they always hold water, that is regularly refreshed and the latter because it is nearby. At the canal, other activities than water collection are laundry and the washing of grain, but together only in 9% of 255 observed activities in five days.

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[1] Based on data collected by Wageningen Agricultural University student Menno Houtstra in 1994. He made his observations of water use in 3 villages that had a history of schistosomiasis and were less than 10 km away from Attaouia. Water users were observed during four or five days in each village. The findings were supplemented with interviews and participatory observations.

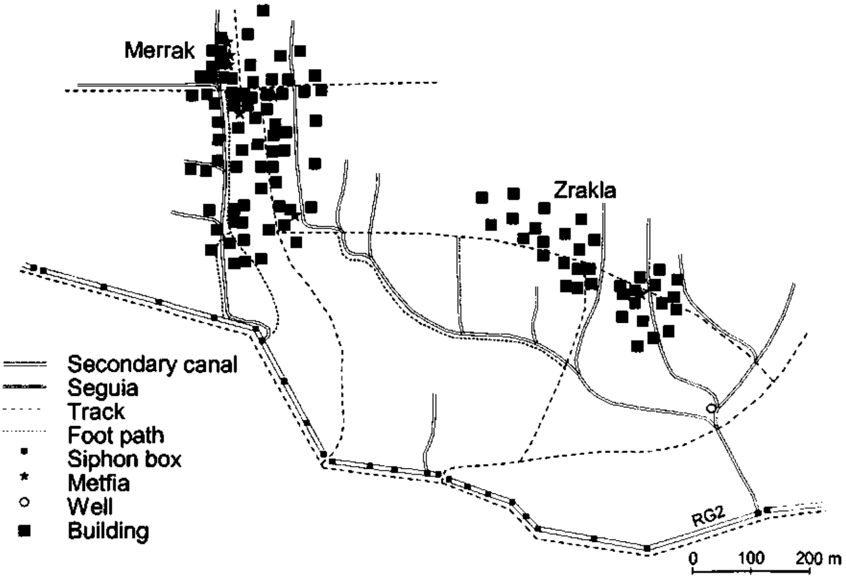


Figure 5.28. The case of Ouled Merrak with the villages of Merrak and Zrakla as well as their sources of water (after Houtstra 1995).

The case of Ben Kachar and Sidi Hnich

The village of Ben Kachar and the cooperative of Sidi Hnich are situated at the border of the "traditional" and the "modern" part of Tessaout Amont, on either sides of the seventh tertiary canal of the secondary RG1 (Figure 5.29). Most people have built a house next to their fields and the cooperative is hardly functioning as a community. The only available water for the population in these settlements comes from the irrigation system: the secondary canal RG1 and its siphons, the tertiary canal RG1T7 and its siphons and some minor *seguias* in Ben Kachar, fed from RG1T6. Only one house had a private *metfia*. In addition, people sometimes fetch water at the inverted siphons of two tertiary canals in the nearby sector of OGD2, that can only be reached by donkey. Water is taken from the canals, siphons and *seguias* only when it is streaming in the morning. The water in the tertiary inverted siphons of OGD2 is preferred over the more convenient supply in RG1T7, because of the perception of less upstream pollution and a better, less salty taste. The distance from the system intake to OGD2 is slightly shorter than to RG1, but no measurable differences in electric conductivity or other parameters were found that could explain the bad taste of the water in RG1. In the villages of Ben Kachar and Sidi Hnich, many activities take place along the tertiary canal next to their houses. Throughout the day, women often walk to the canal or siphon to get just one bucket of water for immediate use. Sometimes drainage water is used for laundry. At the tertiary canal and its siphons the washing of straw, watering of animals, washing of grain and laundry together account for 24% of the observed 189 activities in five days.

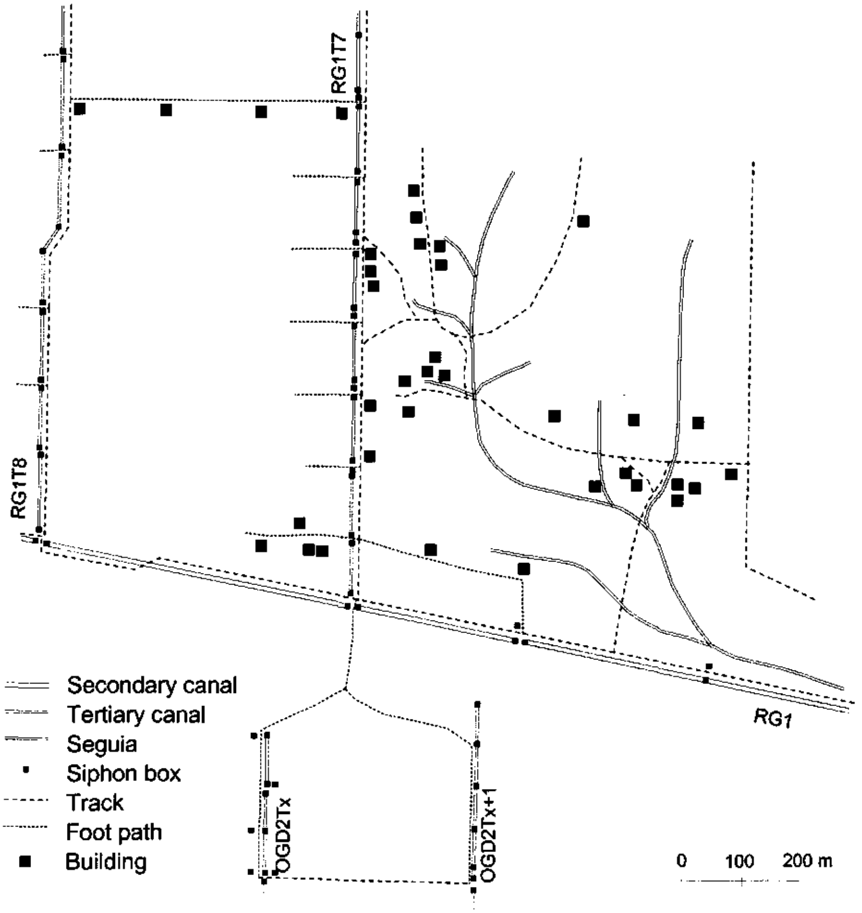


Figure 5.29. The dispersed houses of Ben Kachar and Sidi Hnich with their sources of water (after Houtstra 1995).

The case of Ouled Haddad

Ouled Haddad is an old village in the "modern" part of the irrigation system (Figure 5.30). Water allocation is based entirely upon crop water requirements. In practice this is not always sufficient because the land is used more intensively than planned and often olive trees have high water demanding fodder crops planted underneath. Irrigation water is delivered through the secondary canal RD4 and two of its tertiaries, RD4T7 and RD4T8. The five wells in the village are used for drinking water only. For all other purposes, water is taken from both tertiary canals and their siphons. In addition, especially outside the irrigation season, water is fetched at the "Canal de Rocade". This is a large principal canal, conveying water across the Tessaout Amont area to the Nfis irrigation system and for urban water supply in Marrakech. The slopes of this trapezoidal canal are steep and slippery, making it very difficult to lift water (Figure 5.31). Often people fall into the canal and children may be swept with the strong current and drown. Still, with an almost constant flow, the large canal is a popular source of water. Only 6% of the observed 461 water use activities in four days at the "Canal de Rocade" are other than water collection: watering animals, laundry and washing grain.

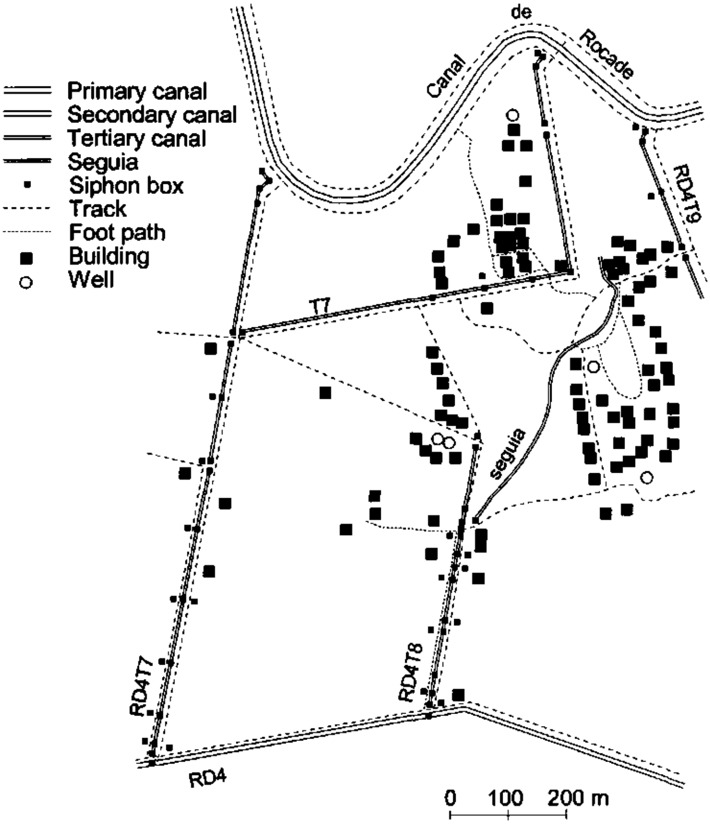


Figure 5.30. The village of Ouled Haddad with its sources of water (after Houtstra 1995).

Figure 5.31. Water collection by children at the "Canal de Rocade" close to Ouled Haddad.

Comparison of the three cases

Similar ideas about water quality seem to exist at the three sites, but under local circumstances they are applied in various ways. When looking at water collection only, which is the most frequently observed activity in the three villages (91, 76 and 94% of all observations), the specific situation in each village determines who is mostly involved in this activity (Table 5.6). The three different situations in the same region lead to distinct patterns in the participation of sex/age groups in water collection. In the case of Ouled Merrak, where the best water is rather far away, children fetch the water (85% of the times), while most water use activities take place at home. In the case of Ben Kachar and Sidi Hnich, this is much less as the canal next to the houses provides a convenient place for instant water supply. Boys are generally responsible for the collection of better quality water further away. In the case of Ouled Haddad, though drawing water from the "Canal de Rocade" can be a hazardous activity, women and girls still account for 70% of the transport of water. As a consequence, *in each case the separate population groups are exposed to a different degree to water that is possibly infected with schistosomiasis.*

Table 5.6. Participation (%) of separate sex/age groups in water collection.

RELATIVE CONTRIBUTION	OULED MERRAK (secondary canal RG2)	BEN KACHAR/SIDI HNICH (tertiary canal RG1T7)	OULED HADDAD ("Canal de Rocade")
Observation site	74	100	91
Water collection	91	76	94
Male adult	9	1	15
Male child	45	26	16
Female adult	7	56	35
Female child	40	18	35
N = 100 %	233	136	430

5.3. CONCLUSIONS

In the large modern Tessaout Amont irrigation system general design principles of upstream flow control determined the typical lay out of open canals and different types of hydraulic structures. Water allocation following crop water requirements and water availability resulted in a rotational water distribution.

Water contact and water use in Tessaout Amont have been shown to be regulated by the availability of water sources in the irrigation environment: individual or communal water supply systems, wells and surface water from the irrigation system. Local variations in the availability of water are limiting factors to water contact. The sources of water differ locally in quality, quantity and accessibility, which determine the participation of each sex-age group in the collection of water and other water contact activities. Thus exposure to possibly infective water and consequently micro-epidemiology of schistosomiasis may contrast significantly from one village to the other. *The availability of water from different sources thus is a key factor in the irrigation ecology of schistosomiasis transmission.*

In Tessaout Amont, water is scarce both for irrigation and for domestic purposes. Ground water is not sufficient or unavailable in parts of the region whereas limited availability of water in the storage lake has often induced under-irrigation, especially in dry years. With increasing competition for other needs of water, a comprehensive strategy is needed, mobilizing additional water resources and ameliorating application efficiencies. If domestic water supply is identified as the most critical need for water, the surface water flowing through the modern irrigation system could be utilized in an integrated way. As the quantities of water needed for domestic purposes are very small compared to agricultural needs, such an approach might result in a more efficient use of water.

An over-exploitation of groundwater in the Haouz plain is expected for the year 2020 (Benazzou 1994) so it might be wiser to use the already mobilized surface water for domestic water supply. Rather than constructing deep wells with taps, rural drinking water supply can be improved in Tessaout Amont by upgrading the traditional *metfias* (Boelee et al 1997). The *metfias* could be connected to the irrigation canals with additional elevated concrete conduits to replace the present earthen feeder canals. Quality of the stored water could then be improved by treatment. The surface water in the Tessaout Amont irrigation system could be classified as slightly polluted with medium to at times very high turbidity (rough estimation). Slow sand filters that can be built from local materials and using local skills, might be sufficient to provide clear and safe water to the local population. If necessary a rapid sand filter or a (horizontal) roughing filter could be added to avoid rapid clogging of the slow filter. However, any filter would require substantial alterations in the construction of the *metfias* and provisions for flushing the filters might be difficult to install. The water quality could be further improved by chlorination of the stored filtered water. Measures for upgrading *metfias*, for managing the water flow, and for better operation and maintenance, would need to be developed in collaboration with local users and the Irrigation Board. New community *metfias* could still be incorporated into the irrigation infrastructure.

To rationally mobilize water from all resources, define local priorities and subsequently allocate the water to the fulfilment of different needs, an overall view is needed. An integrated approach to water resources development would bring a number of benefits to rural development, while ensuring a better mobilization and distribution of water. Regional bodies or units with representatives of different sectors such as agriculture, water, health, local authorities and the communities themselves can play a crucial role in the coordination of a basin wide master plan. Such a plan has to consider existing local practices of water use. Water rights should be attributed not only to crops and fields, but to all domestic, agricultural, and other uses. Subsequently, the quantity of high quality water required for drinking would be reduced so totally different solutions could be sought for, ranging from in-house treatment of irrigation water to make it suitable for human consumption (boiling, filters, disinfection) to separate low demand piped systems in the long term.

The data in Section 6.1 and Appendix III are also discussed in the paper in preparation by Laamrani H, Boelee E, Khallaayoune K, Laghroubi MM, Madsen H, Gryseels B (1999) Distribution of freshwater molluscs with emphasis on *Bulinus truncatus*, intermediate host of *Schistosoma haematobium* in Tessaout Amont irrigation system, Morocco.

The data in Section 6.2 and Appendix IV are also discussed in the paper in preparation by Boelee E, Laamrani H, Laghroubi M, Khallaayoune K, Gryseels B, Madsen H (1999) Distribution of freshwater molluscs in secondary and tertiary irrigation canals in Tessaout Amont in central Morocco.

6

DYNAMICS OF *BULINUS TRUNCATUS* IN THE TESSAOUT AMONT IRRIGATION SYSTEM

Snail breeding takes place in the overlap of the biological and irrigation environment in the modern open canal irrigation systems in Morocco. The suitability of certain hydraulic structures for the intermediate host of schistosomiasis, *Bulinus truncatus*, may be determined by several inter-related characteristics. While the relevance of studies on snail ecology for the control of schistosomiasis transmission has been stressed by several authors (Madsen 1992a, Madsen & Christensen 1992, Sturrock 1993b), *few studies have tried to link the characteristics of favourite breeding sites to irrigation design and water management.* The aim of this chapter is to identify those elements of the irrigation system that are crucial for the development of *B.truncatus* and can be modified to environmentally control schistosomiasis.

6.1. DISTRIBUTION OF *BULINUS TRUNCATUS* AND SOME OTHER FRESHWATER SNAILS OVER THE IRRIGATION SYSTEM: CROSS-SECTIONAL SNAIL SURVEY

A cross-sectional snail survey was carried out in summer 1994 and spring 1995 in the Tessaout Amont irrigation system. The survey was aimed at providing information on the distribution of *B.truncatus* in relation to site characteristics. In addition, other freshwater snails were investigated to find out if these were associated with *B.truncatus.*

6.1.1. Methodology of the cross-sectional snail survey

Snails were systematically searched for in all potential breeding sites throughout the area of Tessaout Amont irrigation system i.e. canals, hydraulic structures, drains and River Tessaout. Descriptions and illustrations of the different canals and hydraulic structures were given in Sub-section 5.1.2. Canals were selected so as to cover the entire region and the widest possible range of water bodies. At each designated secondary canal, three to four tertiary canals were picked at random to be sampled. Nearby drains were always inspected for the presence of water and if so, a sample was taken. Selection of the sampling points was based on the relative importance of the type of site in the irrigation system. Hence tertiary inverted siphons were sampled most.

In order to examine standing water only, the survey activities were always coordinated with the irrigation service. Flowing water may make snail sampling impossible or give a great bias in density estimates. Furthermore, some snail species may detach during irrigation and sink to the bottom.

At each selected site, a number of characteristics was recorded:
- Type of site.
- Distance (m) from the canal head.
- Water depth (m).
- Thickness (mm) of silt layer. This characteristic was defined differently according to the type of site. In concrete canals and hydraulic structures it refers to the inter-woven layer of fine silt and algae attached to the walls of these sites. The thickness was measured directly on parts dislodged by the drag scoop at the scraped area. In rivers, drains and *seguias*, the silt layer refers to debris, silt or clay deposits at the sampling point and its thickness was measured by plunging the drag handle into the deposits.
- Vegetation: degree of cover (%) by submerged, floating and emergent aquatic plants, both macrophytes (large plants) and algae, estimated visually.
- Presence of aquatic vertebrates.
- Distance (m) to houses.
- Importance of the site as a water contact point, observed from water use activities at the moment of sampling or signs of water use such as puddles where there was no leakage.

Chemical characteristics have not been measured as water chemistry parameters were not found to be determining the distribution of *B.truncatus* in an earlier survey in Tessaout Amont (Khallaayoune et al 1998a on a survey carried out in 1991/92).

A standardised semi-quantitative snail sampling technique was applied in concrete sites, using a drag scoop (Appendix II). At other sites, three quadrates of 0.1 * 0.1 m were searched for all snails present. Snail densities are presented as number of individuals/m^2. Percentages in the tables are rounded, so totals are not always exactly 100%.

The samples were transported to the field laboratory in Attaouia Health Centre where snails were identified according to Kristensen (1985) and Brown (1994). All collected snails were placed with a maximum of five individuals in small troughs containing canal water and exposed to artificial light for at least 4 hours to induce cercarial emergence. Emerged cercaria were prepared and identified according to Combes (1980), Frandsen & Christensen (1984), Nasir (1984) and Schell (1985).

For the purpose of analyses, the Tessaout Amont irrigation system has been divided into three parts. The western, middle and north-eastern part each serve 14 secondary canals and have been compared to determine the spatial distribution of site characteristics.

One way Anova (Zar 1984) was used to analyze the relationship between snail density and type of site or other parameters. For this analysis, snail counts were logarithmically transformed to obtain a normal distribution and eliminate a few extreme outliers (Krebs 1989, Tabachnik & Fidell 1996). Associations between occurrence of a snail species and site characteristics were evaluated using the logistic regression analysis of Hosmer & Lemeshow (1989), adjusting for the effect of other characteristics. Spatial distribution of parameters and associations between snail species were tested using Pearson's correlation coefficient. For all statistical analyses, a significant relation is defined as a 95% confidence interval with probability factor $p<0.05$.

6.1.2. Sampled sites in the 1994/95 cross-sectional snail survey

A total of 223 sites being well distributed over the Tessaout Amont irrigation system (Figure 6.1) and representing eight categories were sampled (Table 6.1). During the summer of 1994, about 89% of these sites were sampled and the remaining sites during the spring of 1995.

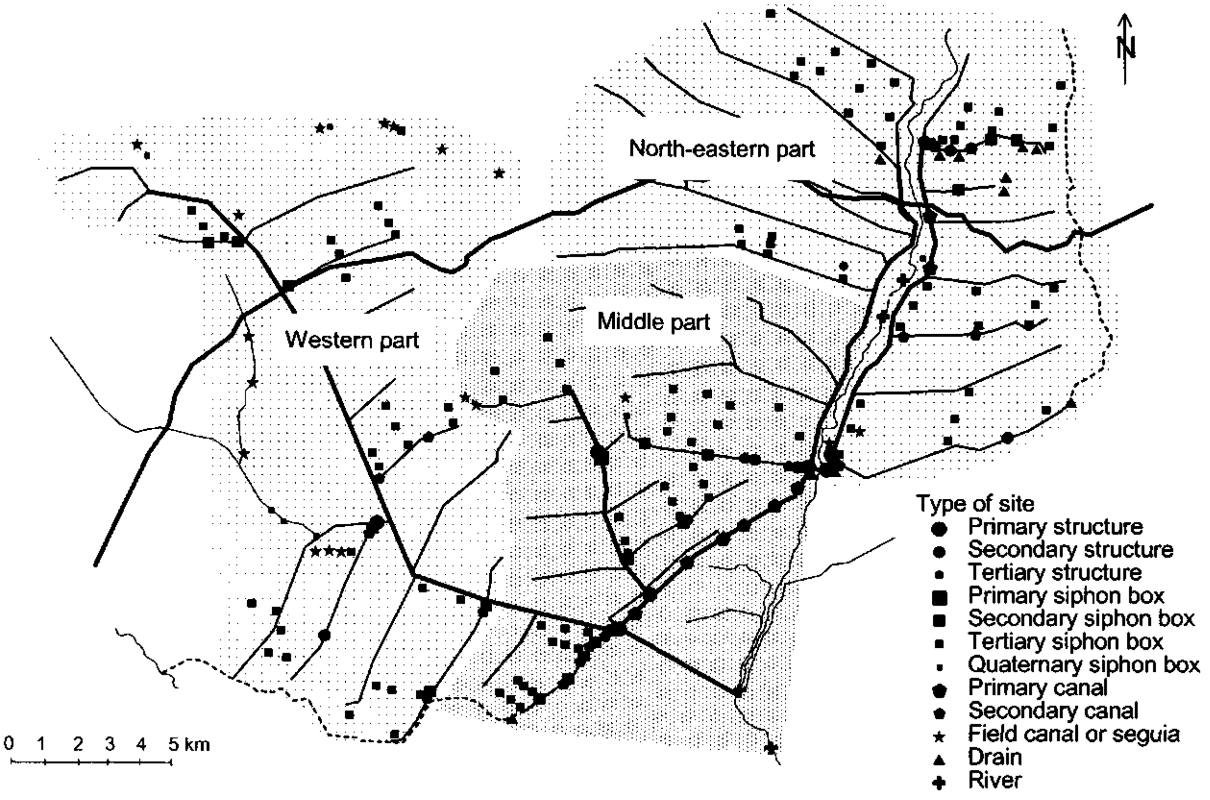


Figure 6.1. Distribution of sampled sites in the cross-sectional snail survey in 1994/95 over the western, middle and north-eastern part of the Tessaout Amont irrigation system.

Table 6.1. Sampled sites in the cross-sectional snail survey in Tessaout Amont.

SAMPLED SITES	NUMBER OF SITES	PERCENTAGE OF TOTAL
Primary canals (& structures)	13	6
Secondary canals (& structures)	24	11
Secondary siphons	23	10
Tertiary siphons	113	51
Quaternary siphons	11	5
Drains	23	10
Seguias (& field canals)	22	10
River Tessaout	5	2
Total	223	100

6.1.3. Snail populations in sampled sites in Tessaout Amont

Nine fresh water snail species have been identified in the Tessaout Amont irrigation system, belonging to seven families. These species with some characteristics and frequency of occurrence are presented in Table 6.2. Of these nine species, three are of medical or veterinary importance. *Bulinus truncatus* is the intermediate host of urinary schistosomiasis. *Planorbarius metidjensis* is suspected of transmitting this disease as well. It has been shown to be experimentally susceptible to the local strain of *Schistosoma haematobium* (Khallaayoune & Laamrani 1995) but has never been found carrying natural infections in Morocco. *Lymnaea truncatula* can serve as an intermediate host of *Fasciola hepatica*, sheep liver fluke.

Planorbid snails were the most frequent ones because of the wide distribution of *B.truncatus* in almost half of the sampled sites. The distribution of the nine snail species over the irrigation system is related: twenty significant associations between snail species were found (Table 6.3). *B.truncatus* appeared to be positively correlated with *P.acuta*, *L.peregra* and *A.fluviatilis*, which probably reflects similarity in their ecological requirements. Therefore these species were included in further analyses, as well as *P.metidjensis* that might be an intermediate host of schistosomiasis too.

Table 6.2. Fresh water snail species with their relative frequency of occurrence (percentage of 223 sampled sites) in the cross-sectional survey 1994/95 in Tessaout Amont.

ORDER	NAME	SHAPE	AVERAGE SIZE (mm)	FREQUENCY (%)
GASTROPODA				
Pulmonata	Planorbidae			
(fresh water snails)	*Bulinus truncatus*	Conical	8	49
	Planorbarius metidjensis	Discoid	7	6
	Lymnaeidae			
	Lymnaea peregra	Conical	9	42
	Lymnaea truncatula	Conical	4	5
	Physidae			
	Physa acuta	Conical	7	39
	Ancylidae			
	Ancylus fluviatilis	Cap-like	3	14
Prosobranchia	Melanopsidae			
(amphibian snails)	*Melanopsis praemorsa*	Narrow conical	20	25
	Hydrobiidae			
	Mercuria confusa	Conical	7	10
LAMELLIBRANCHIA	Sphaeridae			
(fresh water snail)	*Pisidium casertanum*	Bivalve	3	9

Table 6.3. Pearson's correlation coefficient between densities (^{10}Log[snails/m^2+1]) of different snail species in the cross-sectional snail survey in Tessaout Amont (significant correlations in *italics*).

SNAIL SPECIES	*Bulinus truncatus*	*Planorbarius metidjensis*	*Lymnaea peregra*	*Lymnaea truncatula*	*Physa acuta*	*Ancylus fluviatilis*	*Melanopsis praemorsa*	*Mercuria confusa*
B.truncatus	1							
P.metidjensis	0.170	1						
L.peregra	*0.175*	0.091	1					
L.truncatula	-0.058	-0.014	*0.191*	1				
P.acuta	*0.307*	0.037	*0.609*	*0.227*	1			
A.fluviatilis	*0.139*	*0.184*	*0.396*	0.109	*0.336*	1		
M.praemorsa	-0.055	0.017	*0.289*	*0.207*	*0.162*	*0.310*	1	
M.confusa	0.004	-0.045	*0.221*	*0.291*	*0.321*	*0.251*	*0.292*	1
P.casertanum	0.067	-0.026	0.091	0.037	*0.264*	*0.142*	-0.035	0.052

The snails were well distributed over the three parts of the irrigation system. In Table 6.4 the frequency of occurrence is specified for the five snail species in each site, while subsequent densities are elaborated in Table 6.5 (details for all snail species in Appendix III). The high standard deviations show that the variability in the snail densities is enormous and values for each species should be interpreted with caution. The total snail density varied spatially. Low densities, up to 10 snails/m^2 were mainly found in the north-eastern part, middle densities from

10-150 snails/m^2 in the middle part and highest snail densities in the western part of Tessaout Amont (Pearson's χ^2=18.9, p<0.05).

Table 6.4. Frequencies of occurrence (%) of 5 snail species in 223 sampled sites in the cross-sectional snail survey 1994/1995 in Tessaout Amont.

SAMPLED SITES	N	*Bulinus truncatus*	*Planorbarius metidjensis*	*Lymnaea peregra*	*Physa acuta*	*Ancylus fluviatilis*
Primary canals	13			23	8	15
Secondary canals	24	41		54	50	21
Secondary siphons	23	26		35	22	13
Tertiary siphons	113	66	11	46	46	16
Quaternary siphons	11	27		45	45	9
Drains	12	50		17	33	8
Seguias	22	45	5	41	36	
River Tessaout	5			40	20	40

Table 6.5. Mean snail density (individuals/m^2 in bold and standard deviation in small) of 5 snail species in 223 sampled sites in the cross-sectional survey 1994/1995 in Tessaout Amont.

SAMPLED SITES	*Bulinus truncatus*	*Planorbarius metidjensis*	*Lymnaea peregra*	*Physa acuta*	*Ancylus fluviatilis*
Primary canals			**8** 24.7	**0.5** 1.8	**0.5** 1.3
Secondary canals	**3** 5.7		**66** 149.3	**31** 85.7	**5** 16
Secondary siphons	**19** 75.2		**9** 22.1	**1** 1.9	**0.3** 0.8
Tertiary siphons	**36** 96.8	**4** 20.1	**19** 43.2	**14** 31.4	**2** 4.4
Quaternary siphons	**11** 32.9		**10** 20.9	**76** 226.7	**0.2** 0.5
Drains	**61** 137.2		**1** 3.4	**13** 36.6	**0.4** 1.4
Seguias	**14** 33.4	**0.3** 1.5	**3** 4.3	**24** 56	
River Tessaout			**14** 28.6	**2** 3.7	**8** 11.3

Bulinus truncatus was common in most sites all over the Tessaout Amont irrigation system (Figure 6.2). However, the intermediate host of schistosomiasis was not recorded in the river or in primary canals. *The density of* B.truncatus *varied significantly across the sites* (p<0.01)*, with the highest frequencies and densities in the abundant tertiary siphon boxes* and in the few drains that were found holding

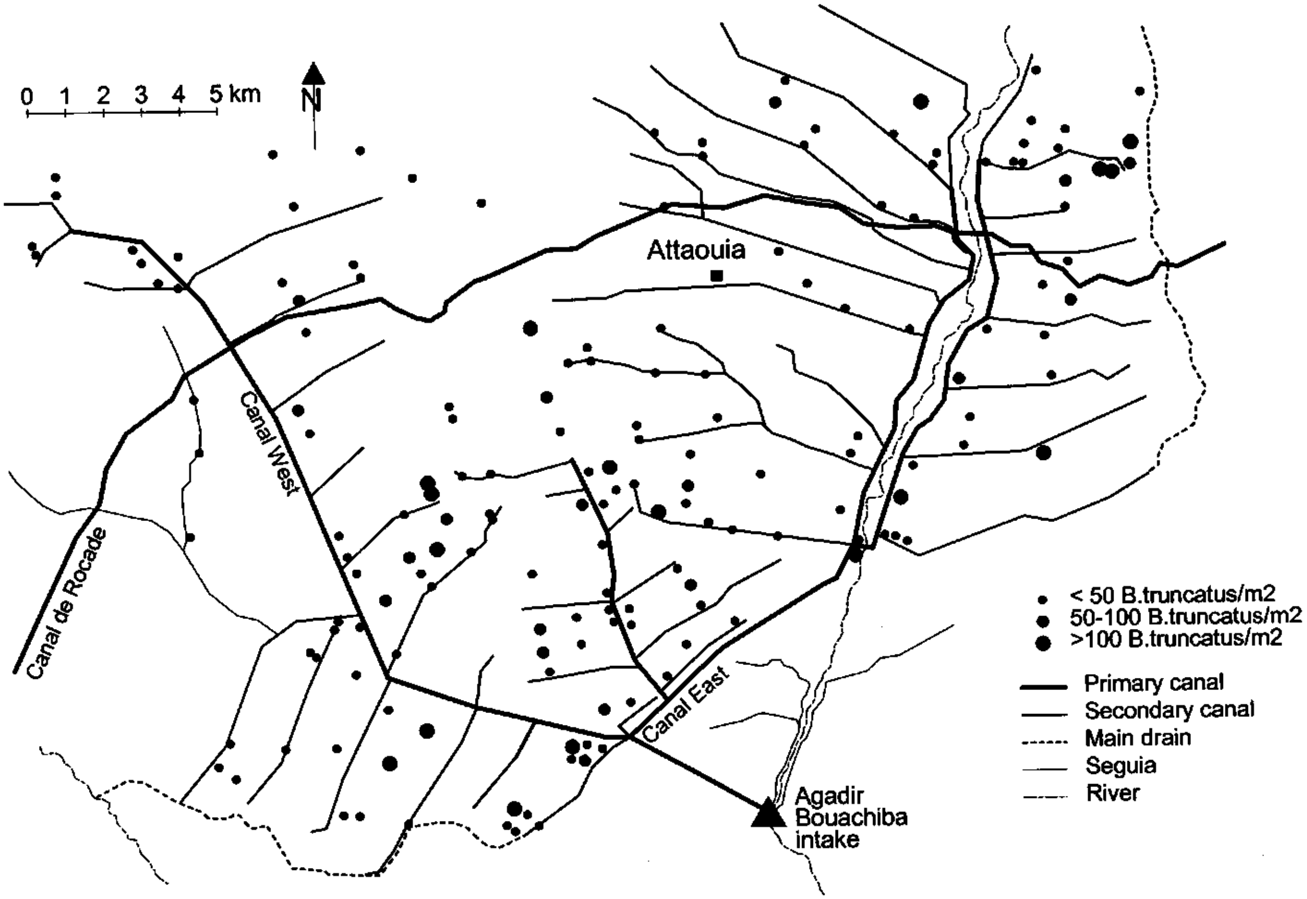


Figure 6.2. Density of *Bulinus truncatus* in different habitats throughout the Tessaout Amont irrigation system during the cross-sectional snail survey 1994/95, supplemented with data from the survey in 1991/92.

water. In the secondary canals, *B.truncatus* was frequently observed, but only in low densities. However, it was present in only a quarter of the sampled secondary siphon boxes with relatively high density.

The few drains where *B.truncatus* was found in high densities do not play an important role in schistosomiasis transmission. Drains in Tessaout Amont hardly ever convey water in the irrigation season, that is also the main transmission season. In the rare cases where distribution structures have been manipulated or where water is deliberately led into drains to lower lying areas, the drains convey water only for short periods. Afterwards the drains rapidly dry out and water contact is unlikely.

Planorbarius metidjensis occurred sporadically in the system but was mainly found in tertiary siphon boxes and at the head of *seguias*.

Lymnaea peregra and *Physa acuta* were widely distributed and showed distribution patterns similar to that of *B.truncatus*. *L.peregra* and *P.acuta* were recorded in all types of sites. Density of both species was relatively low in primary canals, where the snails were mainly found in hydraulic structures. At the secondary level, densities were high in canals and low in siphon boxes, contrasting to *B.truncatus*. Both *P.acuta* and *L.peregra* occurred at moderate densities in tertiary siphon boxes. *P.acuta* was found at very high densities in some quaternary siphon boxes. *P.acuta* was more abundant than *L.peregra* in drains and *seguias*, while the opposite was true for River Tessaout. Density of *L.peregra* showed a significant difference between sites ($p<0.01$).

Ancylus fluviatilis was recorded from all sites except *seguias*. The cap-like species was generally found firmly attached to the sides of siphons, to stones in canals and structures, and on gravel and rocks in the upstream part of River Tessaout between Timinoutine and Agadir Bouachiba dams.

Comparison of 1991/92 with 1994/95 surveys

Density and frequency of *Bulinus truncatus* in the 1991/92 survey (Khallaayoune et al 1998a) and the present 1994/95 survey revealed different patterns. In the second cross-sectional snail survey, after two years of low irrigation water supply (Figure 5.19) there seems to be an increase in frequency and a decrease in density of *B.truncatus* (Table 6.6). However, this was not statistically significant.

Table 6.6. Frequency of occurrence and mean density of *Bulinus truncatus* in cross-sectional snail surveys conducted in 1991/92 respectively 1994/95 in Tessaout Amont.

	SURVEY 1991/92			SURVEY 1994/95		
SAMPLED SITE	N	Frequency (%)	Density (snails/m^2)	N	Frequency (%)	Density (snails/m^2)
Primary canal	6	0	0	13	0	0
Secondary canal	47	26	6	24	41	3
Secondary siphon box	38	17	26	23	26	19
Tertiary siphon box[1]	110	47	54	113	66	36
Seguia	36	17	23	22	45	14

[1] *Tertiary and quaternary siphon boxes together.*

Snail infection by trematode parasites

Three of the 5 snail species under study were found being infected with larval digenetic trematodes that belonged to 4 families (Table 6.7). No mixed infection occurred and the prevalence of infection was too low to be determinant in the distribution and abundance of snails. Nine individuals of *Bulinus truncatus* infested with *Schistosoma haematobium* were found (Figure 6.3).

Table 6.7. Cercariae shed by 3 snail species in the 1994/95 cross-sectional snail survey in Tessaout Amont (families marked with * have been mentioned in previous studies in Morocco).

SNAIL SPECIES	TYPE OF CERCARIA	FAMILY	PREVALENCE (%)
B.truncatus	Longifurcate pharyngeate distome	Strigeidae*	0.10
	Brevifurcate apharyngeate distome	Schistosomatidae*	0.06
	Amphistome	Paramphistomidae	0.07
L.peregra	Echinostome	Echinostomatidae	0.58
A.fluviatilis	Longifurcate pharyngeate distome	Strigeidae*	1.03

More than one third (36%) of the sampled sites harboured aquatic vertebrates that may be final hosts for these trematode parasites. The observed vertebrates can be divided into four categories: Batrachia, (i.e. tadpoles and adult frogs (*Rana Rana, Rana esculenta*) and toads (*Bufo bufo, Bufo mauretanicus*)), fish, snakes (*Natrix sp.*) and turtles. Batrachia were the most frequent vertebrates, especially in the river (in 4 out of 5 sites), and in drains (in 8 out of 12 sites). In concrete canals and structures the frogs and toads inhabited less than one third (29%) of the sampled sites, except for primary canals (only in 1 out of 8 sites). The other vertebrates were only found sporadically.

Figure 6.3. Sites in Tessaout Amont where *Bulinus truncatus* snails infested with *Schistosoma haematobium* were found in the 1994/95 cross-sectional snail survey.

6.1.4. Snail populations related to site characteristics in Tessaout Amont

The occurrence and densities of the five snail species are linked to the type of site with its specific characteristics, that are often inter-related.

Water depth

The sampled sites ranged from shallow puddles in drains, not exceeding a depth of 3 cm, to siphon boxes of over 2.3 m depth. To determine the height of the sample, the actual water depth at the time of sampling was measured (Figure 6.4). This depth was used to calculate snail densities (Appendix II). The water depth at the time of sampling is only a rough indication of the real depth of the site, especially in the case of hydraulic structures. Sometimes, right after a water flow, the structures were completely full, while water collection and evaporation later reduced the amount of water to a tenth or less of its original volume, resulting in a low measured water depth.

On primary canals, structures with the highest water depth such as sand traps, drops and escape structures, were the main snail habitats. High densities of *Bulinus truncatus* were found in shallow sites such as drains and *seguias*. This can be explained by the fact that the earthen sites are subject to drying, concentrating all snails in the remaining puddles of water. Most high densities however, were registered in the relatively deep sites of the siphon boxes. *The occurrence of* B.truncatus *was positively associated with water depth* ($p<0.01$).

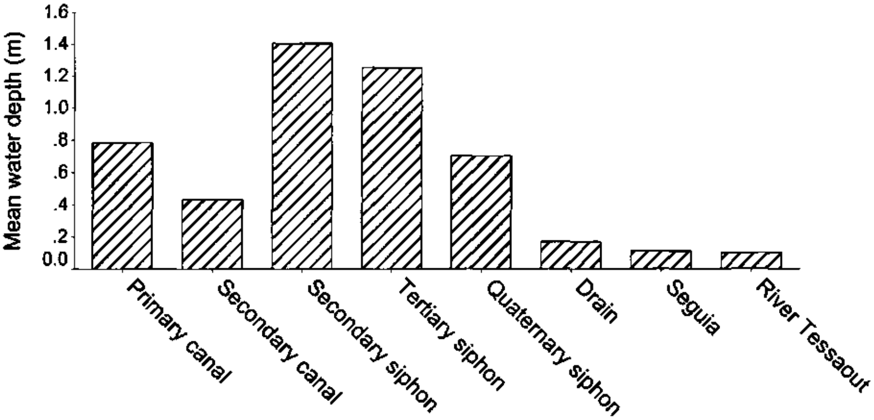


Figure 6.4. Mean water depth in the sampled sites in the cross-sectional snail survey 1994/95 in the Tessaout Amont irrigation system.

Silt layer

The layer of silt was variable in thickness, structure and texture within as well as between sites. In concrete canals and on the walls of siphon boxes and other hydraulic structures, a particular kind of firmly attached and coherent silt layer was found, consisting of silt particles bound together with fine filamentous green algae. This layer was slightly thicker in the primary and secondary canals than in siphon boxes (Figure 6.5). A more loose mixture of silt, debris and vegetation was found at the bottom of shallow structures, drains and *seguias*. The thickest layers, maximally 31 cm, were found in drains and in sand traps on primary canals. Sand and silt were predominant in canals and at the bottom of the hydraulic structures, including inverted siphons. In River Tessaout and in *seguias* with a rocky surface, different types of layers were found on the stones.

A positive association ($p<0.05$) was found between *Bulinus truncatus* and the thickness of the silt layer. This could be due to the thick layer of mud and sand in the drains where densities were high. Therefore *the association between snail species and thickness of the silt layer should be interpreted with caution.* The compact silt layer in concrete canals and structures is not really comparable to the substratum of earthen sites.

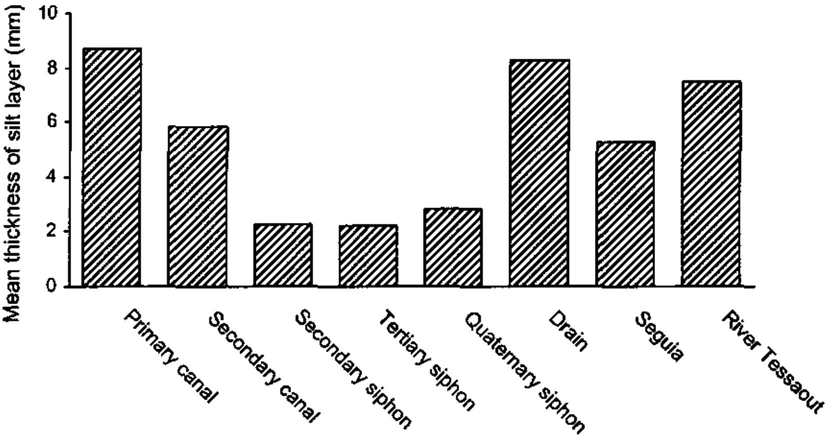


Figure 6.5. Mean thickness of the silt layer in sampled sites in the Tessaout Amont irrigation system.

Vegetation

A diverse aquatic flora of algae and macrophytes was observed. Representatives of *Characeae*, *Diatomiaceae*, *Chlorophyceae*, *Cyanophyceae*, *Herbaceae* and *Graminae* were described in previous studies (Khallaayoune et al 1998a). Both algae and macrophytes were not evenly distributed over the different concrete sites in the western, middle and north-eastern parts of the irrigation system. A higher percentage of cover with algae was found in the north-eastern part of Tessaout Amont (Pearson's $\chi^2 = 16.4$, $p<0.005$), while macrophytes were more frequent in the western part with a higher degree of cover in the middle part (Pearson's $\chi^2 = 9.9$, $p<0.05$).

In shallow structures, rooted aquatic and terrestrial macrophytes were found as well as filamentous macroscopic algae. The frequencies of vegetation over the sampled sites are presented in Table 6.8 (details in Appendix III). In concrete canals and structures, algae and macrophytes were less frequent than in other sites (river, drains and *seguias*). Algae were present in almost all sites, but mostly with a cover of less than 5%. A higher degree of cover with algae were found in 40 and 39% of the sampled sites in the River Tessaout and in secondary canals, respectively. For macrophytes there was a remarkable difference between concrete sites and earthen ones. In about half of the sampled sites macrophytes were present, mostly in a low degree of cover. Primary canals were an exception to this, with very little macrophytes. Higher vegetation in earthen sites varied. Siphon boxes sometimes contained terrestrial plant parts that had fallen in, mainly reed leaves (*Fragmites communis*) or food remains.

Table 6.8. Frequency of occurrence (%) of algae and macrophytes in the cross-sectional snail survey in Tessaout Amont.

SAMPLED SITES	ALGAE	MACROPHYTES
Primary canals	100	15
Secondary canals	75	46
Secondary siphons	78	43
Tertiary siphons	90	59
Quaternary siphons	91	45
Drains	83	67
Seguias	73	91
River Tessaout	100	40

The importance of macrophytes in snail distribution has been stressed by several authors (Klumpp & Chu 1980, Thomas & Tait 1984, Madsen et al 1988, Ndifon & Ukoli 1989, Meyer-Lassen 1992). Floating organic material including decaying plants might play a role as a direct or indirect food resource for snails and as a means of dispersing over the irrigation system. Rooted plants in hydraulic structures with intermittent flowing and turbulent water might also provide shelter for snails.

While the degree of cover by algae or macrophytes was not the same in the three parts of the irrigation system, the distribution of *Bulinus truncatus* was similar in the western, middle and north-eastern part of Tessaout Amont. No significant correlations could be indentified for any of the 5 snail species and vegetation. The high snail densities in tertiary siphon boxes with low frequency and density of macrophytes reflects that large plants are not used directly as a food resource (Lodge 1986, Madsen 1992b). The preference of *B.truncatus* for tertiary siphon boxes could be explained by the availability of food resources in the form of microscopic algae. With long periods between irrigation turns, eutrophication and subsequently algal growth would be higher at tertiary and quaternary siphon boxes.

Distance to housing and water contact sites

Many hydraulic structures and irrigation canals are used as a source of water for all agricultural and domestic purposes in the Tessaout Amont irrigation system. In the 1994/95 cross-sectional snail survey, 21% of the sampled sites could be identified as water contact sites. In water contact sites less than 100 m from houses, many perturbations due to human activities (organic pollution, use of detergents, quick changes in water level) were noticed, mainly in siphon boxes. Evaporation and water collection may intensify the process of eutrophication and make inverted siphons suitable habitats for *Bulinus truncatus* which prefers slightly polluted water (Watson 1958).

6.2. DISTRIBUTION OF *BULINUS TRUNCATUS* IN CONCRETE CANALS AND STRUCTURES IN SECTOR DZOUZ: LENGTH PROFILE STUDY

Cross-sectional snail surveys in Tessaout Amont have shown that *Bulinus truncatus* was widely distributed throughout the irrigation system. *B.truncatus* is abundant in the various hydraulic structures, particularly in tertiary siphon boxes. However, no sufficient insight has been gained into the relation between snail distribution and design and water management of the irrigation system. No data could be collected in the cross-sectional snail survey on water flow, while this might be a key factor in snail ecology. Water flow may hinder the snail directly and indirectly. Moderate water flow hinders the snail directly in its movements and reproduction by exerting friction on the shells. Indirectly regular flow influences the availability of detritus (Appleton 1978). High water flows may directly dislodge the snail host and bring it to downstream parts of the irrigation system. Snails that are washed out can either end up in structures more downstream in the irrigation system or in the field. Since no submerged crops such as rice are cultivated in the Tessaout Amont irrigation system and field canals dry out completely within days, *B.truncatus* will desiccate in the field and die.

In an irrigation system with rotational flow, such as Tessaout Amont, the location of a sampling site relative to the head of the canal determines its exposure to certain frequencies and velocities of water flows. The upstream parts of canals convey water more often and with larger flows than the downstream parts. In addition, snails may drift with the stream and strand in structures downstream in the irrigation system. Hence an ecological length profile was made of one secondary canal and some of its tertiaries in the north-eastern part of Tessaout Amont irrigation system in spring 1995. The aim of this length profile study was to *provide more information on location-specific characteristics* of breeding sites for *B.truncatus* in one ecological unit while minimizing the variability of other factors.

6.2.1. Methodology of the length profile study

Snail samples were taken from all hydraulic structures on the secondary canal RG7 and on four of its tertiaries. The same standardized quantitative snail sampling technique as in the cross-sectional snail survey has been used (Appendix II) and the same site characteristics were recorded. The canals did not convey water at the time of sampling. Collected snails were classified on the spot and returned to their site to diminish the effect of sampling on the ecological unit.

To compare results from different types of site, snail densities were calculated as *the number of snails per sampled surface.*

For the siphon boxes, an additional analysis has been made, based on an estimation of the total number of snails per siphon box. The quantity of water in the boxes may be reduced between two irrigations by evaporation and people collecting water from siphons. With a lower water level, the height of the sample is lower and the subsequently calculated snail densities will give an overestimation of the real snail population in the siphon box.

In addition to the statistical methods that were used in the cross-sectional snail survey, the data in this length profile study have been analyzed in some other ways. Comparison of the frequency of different snail species between structures in the secondary and tertiary canals was done on the basis of χ^2-values from cross tabulations (Zar 1984). To avoid low cell counts, hydraulic structures were grouped into three categories based on their similarity in lay out or function: upstream siphon boxes, downstream siphon boxes and other hydraulic structures. For multiple comparisons the Scheffé post hoc test was used. Spearman rank correlation was used to determine associations between snail density and aquatic vegetation scores as well as between snail species both at secondary and tertiary canals (Zar 1984). For all statistical analyses, only those sites were included where good quantitative samples were obtained, at each table indicated as N.

6.2.2. Sampled sites in the length profile study

The canal selected for the present study, RG7, is a long secondary canal situated on the left bank of the river Tessaout, in the north-eastern modern part of Tessaout Amont irrigation system (Figure 6.6). It has a length of 8900 m, with a maximum flow capacity of 0.42 m^3/s and 23 tertiary branches. The canal replaced the original *Seguia Dzouzia* and now encompasses the sector or secondary unit *Dzouz* of 1135 ha. The available 0.37 l/s/ha from the canal is not sufficient for irrigated agriculture. The relatively shallow water table (20-25 m deep) enabled the farmers in the area to excavate numerous wells equipped with diesel pumps for supplementary irrigation. The village wells for drinking water and other domestic needs are generally operated manually.

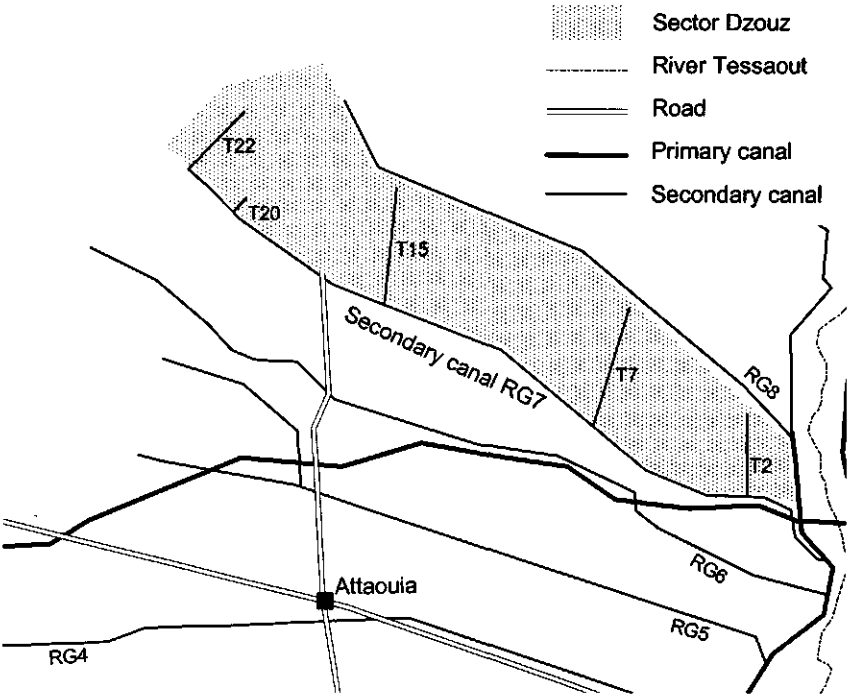


Figure 6.6. Sector Dzouz in the Tessaout Amont irrigation system. On the secondary canal RG7 five tertiaries have been indicated: T2, T7, T15, T20 (first part only) and T22.

On the secondary as well as on the tertiary canals several hydraulic structures have been constructed (Sub-section 5.1.2). All accessible concrete structures have been sampled on the secondary canal RG7 and on four of its 23 branches: RG7T2, RG7T7, RG7T15, RG7T22 (Table 6.9). Two secondary siphon boxes could not be sampled because they are very high above the ground, which made access too dangerous.

The selected tertiaries are well spread over the secondary canal and have different lengths. After sampling four siphon boxes at T20, this tertiary had to be left aside because all other siphons were empty. The data from the four boxes at T20 were included in some of the analysis however. Instead, the tertiary canal T22 was sampled; unfortunately right after an irrigation turn, so the findings of this canal may provide an underestimation of the true snail populations (Laamrani 1999). No samples have been taken in the canal beds.

Table 6.9. Characteristics and number of structures of the sampled canals in Sector Dzouz.

	SECONDARY	TERTIARY CANALS				
CANAL CHARACTERISTICS	RG7	T2	T7	T15	T20[1]	T22
Length (m)	8909	836	1621	1556	132	982
Average slope (%)	0.3	0.8	0.7	0.7	0.4	0.4
Number of branches	23	9	15	17	1	11
Number of siphon boxes						
Upstream	18	8	16	15	2	9
Downstream	20	8	14	17	2	9
Number of other structures						
Angle structure	9					
Long crested weir	19					
Division box	12	1	12	1		
Drop structure	6	4	1	5	1	1
Outlet		2	12	12		6
Total number of structures	84	23	55	50	5	25

[1] Tertiary canal RG7T20 is considered till the fourth siphon only.

The two sampled canals at the head of the secondary, T2 and T7, have quaternary field canals on their right sides. T15 and T22 have quaternaries to both sides, so on these tertiaries extra quaternary boxes were constructed at some of the inverted siphons. Most of the field canals receive water directly from the downstream siphon box. At 33 of the total of 52 quaternary canals at T2, T7, T15 and T22, the outlet is made of concrete and can be considered as a separate structure. Almost half of the outlets (15) and 4 other tertiary structures were found dry and could not be sampled, or only qualitatively. As this is typical for these structures, it can be considered being representative for the irrigation ecology of a tertiary canal at the moment of study. Therefore the total number of outlets (N = 32) is used in the first series of calculations of snail frequencies.

On the *secondary canal RG7*, 84 sites were described, of which 77 were sampled quantitatively and included in the statistical analyses. A total of 153 *tertiary structures* were described, 132 of these were sampled quantitatively and 122 were considered in the analysis. Siphon boxes were the most frequent structures. They represent 69% (137/199) of the sites considered in the analysis. In this study a distinction was made between upstream and downstream siphon boxes (Figure 6.7).

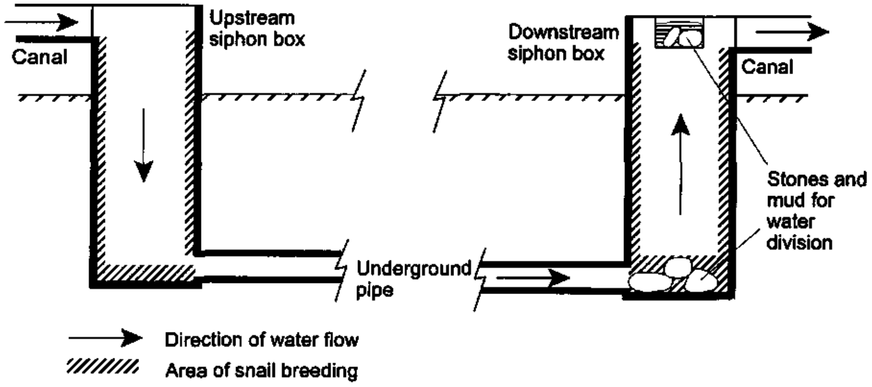


Figure 6.7. Diagram of a standard tertiary inverted siphon with an indication of the preferred area of snail breeding (not to scale).

6.2.3. *Bulinus truncatus* populations in sampled sites in Sector Dzouz

All snail species found during the previous cross-sectional snail surveys were present in the sampled secondary canal RG7 or its tertiaries except *Planorbarius metidjensis*. Both frequencies and densities of the 8 present snail species were different from the average values for the whole system. In this Section only the determinants of *Bulinus truncatus* will be discussed. Where this is illustrative, data for *B.truncatus* are compared to those of the total snail population. Separate information on the other snail species is summarized in Appendix IV.

Bulinus truncatus was *rare in the secondary canal RG7*. At the *tertiary canals*, the occurrence of *B.truncatus* showed a significant relationship with the type of hydraulic structure. Its highest frequencies and densities were found in tertiary siphon boxes (Table 6.10). A significant difference was observed between upstream and downstream tertiary siphon boxes, with the highest densities being observed in the downstream boxes. The additional analysis for the *estimated snail population* in siphon boxes, correct for reduced water depth, shows an even more evident difference between upstream and downstream siphon boxes. The preference of *B.truncatus* for downstream siphon boxes could be explained by differences in turbulence. All other characteristics such as depth, vegetation and silt layer seem to be similar to those in the upstream box. Frequency of water flow as well as water velocity are the same, but in the upstream box the change in water velocity from the small canal to the wide box causes an hydraulic jump that results in turbulence.

Table 6.10. Distribution of *Bulinus truncatus* in hydraulic structures on secondary canal RG7 and 4 tertiary canals together in Sector Dzouz.

	FREQUENCY		DENSITY		POPULATION	
SAMPLED SITES	N[1]	(%)	N	snails/m^2	N	number
Secondary canal RG7						
Upstream siphon box	17	12	17	5.7	16	33
Downstream siphon box	19	11	19	3.7	19	22
Long crested weir	21		14			
Division box	19	14	18	43.5		
Drop structure	6		6			
Tertiary canals						
Upstream siphon box	48	71	48	43.2	48	110
Downstream siphon box	48	81	48	69.2	42	261
Division box	14	29	11	25.0		
Drop structure	11	46	11	8.2		
Outlet	32	16	14	3.5		

[1] Number of sampled sites included in the calculations.

The number of *Bulinus truncatus* per siphon box may give an indication of the transmission potential. With an estimated infection rate of 0.06% for *Schistosoma haematobium* (Table 6.7), a population of 1667 *B.truncatus* snails would harbour on average one infected snail. This threshold was only passed in two quaternary downstream boxes at canal T15 (Table 6.11). As a comparison, the total snail population is indicated as well.

Table 6.11. Average estimated number of *Bulinus truncatus* and total snail population in siphon boxes *on 5 tertiary canals* T2, T7, T15, T20 and T22 in Sector Dzouz.

SIPHON BOXES	T2	T7	T15	T20	T22
Bulinus truncatus					
Tertiary upstream box	137	40	193	16	103
Tertiary downstream box	306	254	323	96	111
Quaternary upstream box			1958		
Quaternary downstream box			1290		212
Total snail population					
Tertiary upstream box	181	68	282	52	532
Tertiary downstream box	473	384	487	168	1094
Quaternary upstream box			2142		
Quaternary downstream box			1512		537
N	16	30	32	4	18

6.2.4. ***Bulinus truncatus*** population related to site characteristics in Sector Dzouz

Distance to canal head

In the *secondary* canal, *Bulinus truncatus* was collected in structures located at the terminal part of the canal only (Figure 6.8). This was typical for the intermediate host of schistosomiasis as other snails were found in all but three structures at different distances from the canal off-take (Figure 6.9). The characteristics of the tail end of the secondary canal RG7 in terms of dimensions and with respect to frequency and velocity of water flows are similar to those of a tertiary canal: the frequency of the water flow is low and between irrigations shallow structures may dry out completely.

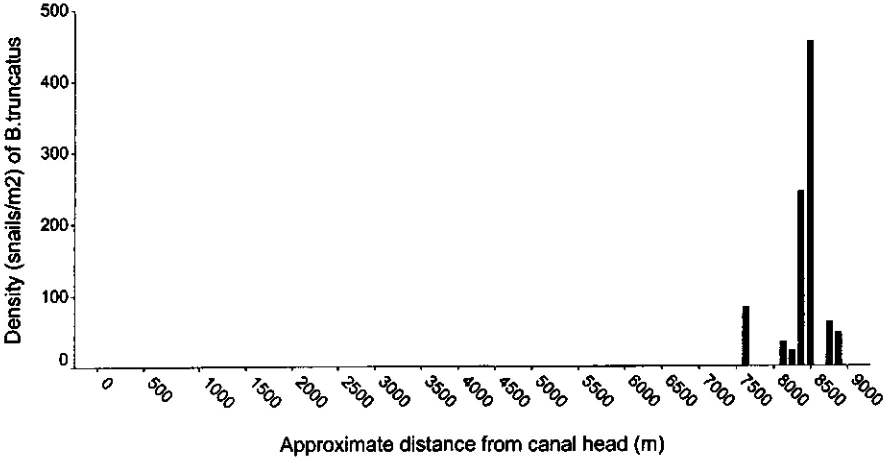


Figure 6.8. Distribution of *Bulinus truncatus* in hydraulic structures on the *secondary canal RG7* in Sector Dzouz.

The density of *Bulinus truncatus* in the *tertiary* canals increased from the head end towards the tail end of the canal, while the total of all snails did not (Figure 6.10). The relations between density of *B.truncatus* and distance from the tertiary canal head was significant for $p<0.001$. The overall pattern could mask a difference between canals. Indeed the highest density of *B.truncatus* was noticed at the *mid section* of the tertiary canal T15 that is situated at about two-thirds from the head of the secondary canal RG7.

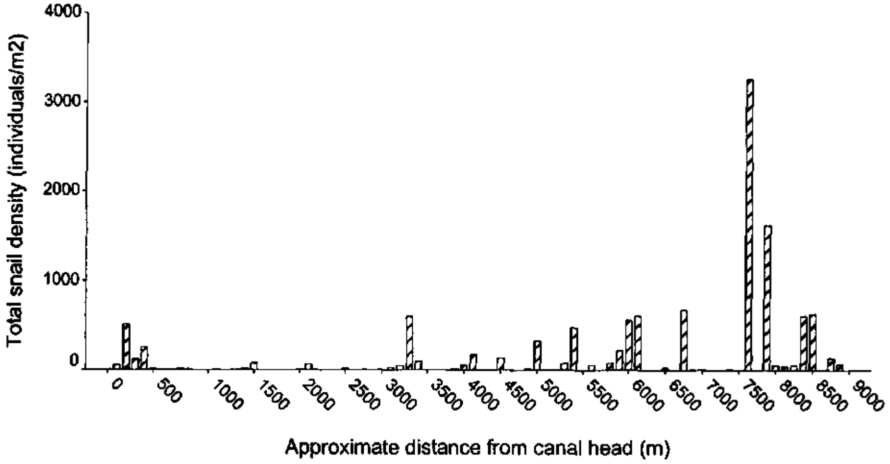


Figure 6.9. Distribution of *all snails together* in hydraulic structures on the *secondary canal RG7* in Sector Dzouz. Note that the scale on the y-axis differs from the scale in Figure 6.8.

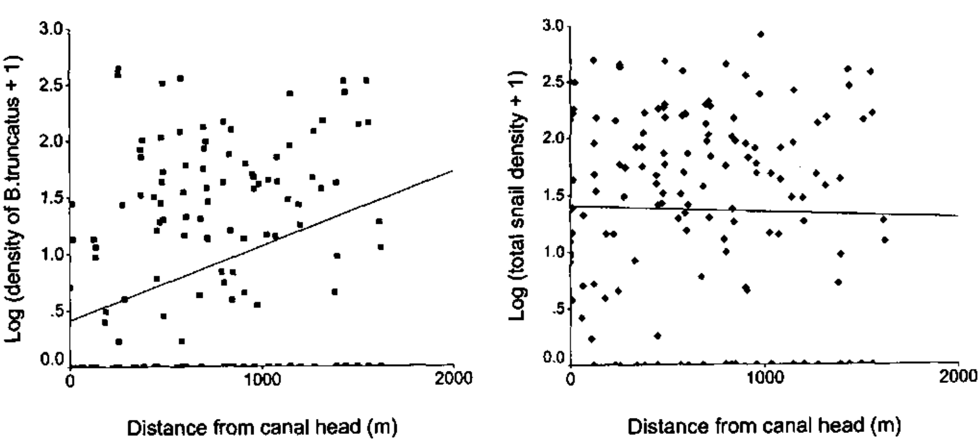


Figure 6.10. Density of *Bulinus truncatus* (left graph, ^{10}log[snails/m^2+1]) plotted against the *distance from the canal head (four tertiary canals combined) in Sector Dzouz. A linear regression* line has been generated that best fits the data points on the scatter plot. As a comparison, total snail density (^{10}log[snails/m^2+1]) has been added (right graph).

When adding populations of two boxes and thus considering the *total number of snails in each inverted siphon*, the spatial distribution of *Bulinus truncatus* (Figure 6.11) over the secondary and tertiary canals in Sector Dzouz appears even moreclear. The total number of snails in tertiary siphons is higher than in secondary ones, but the distribution pattern of *B.truncatus* clearly differs from that of all snails. In the tertiary canals T2 and T7, near the head of the secondary, the

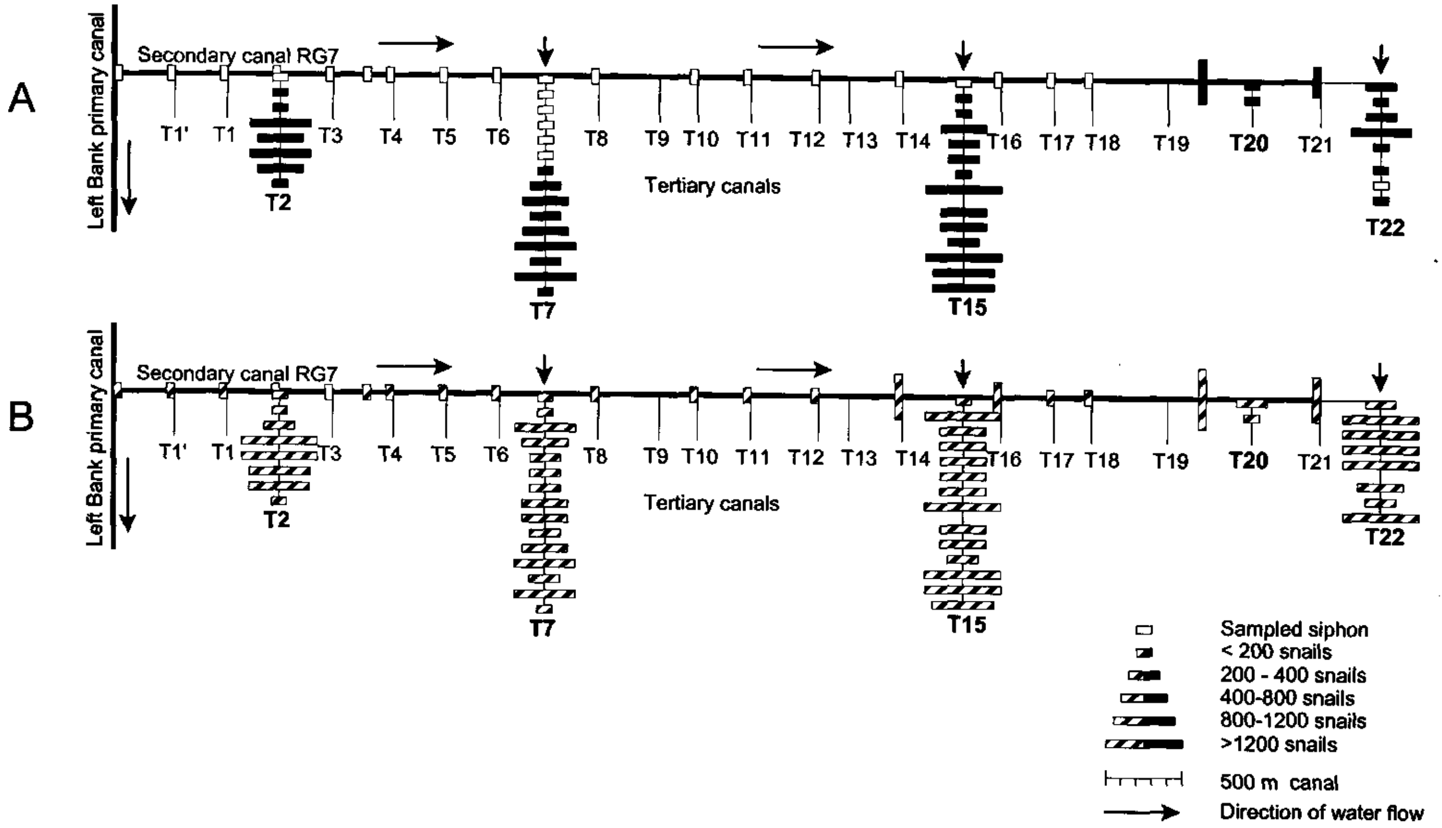


Figure 6.11. Estimated populations of *Bulinus truncatus* (upper graph A) and total snail populations (lower graph B) *in siphons* (both boxes taken together) on the secondary canal RG7 and the 5 tertiaries T2, T7, T15, T20 (partly) and T22 in Sector Dzouz.

high populations of *B.truncatus* increased with distance from the canal head. In the tertiaries T15 and T22, further down the secondary canal, *B.truncatus* was already present in high numbers in the first part of the canals. *Populations of* B.truncatus *are larger in tertiary than in secondary siphons and increase with distance from the canal head.*

Water depth

This is determined by the type of structure, evaporation and water collection. Therefore it has not been included as a separate characteristic in the analyses of the length profile study. The mean water depths of the structures can be found in Appendix IV.

Silt layer

In Sector Dzouz the silt layer was on average thinner than in the entire Tessaout Amont irrigation system. The mean thickness of the silt layer in hydraulic structures *on the secondary canal RG7* ranged from 1.9 mm to 2.7 mm (absolute range 0.5 - 10 mm). The thickest silt layers were noticed in structures on the second half of the canal (Figure 6.12). *In tertiary structures,* the thickness of the silt layer varied from 0.5 to 3 mm (Table 6.12). A significant difference in thickness of the silt layer (logarithmically transformed) was found between tertiary canals ($p<0.001$). Scheffé's post hoc test showed that silt thickness was significantly lower in canal T15 than in T7 and T22 ($p<0.01$).

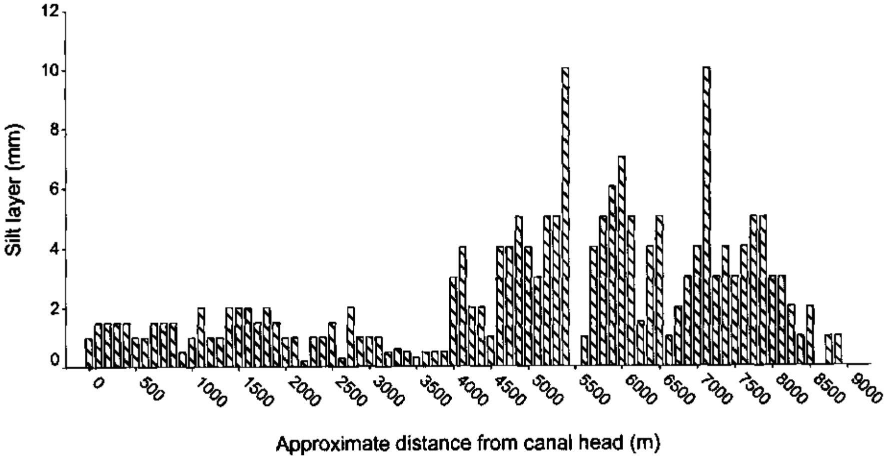


Figure 6.12. Thickness of silt layer (mm) in hydraulic structures on the secondary canal RG7 in Sector Dzouz.

Table 6.12. Mean thickness of the silt layer (mm) in sampled structures in Sector Dzouz.

SAMPLED SITES	N	RG7	T2	T7	T15	T20	T22
Upstream siphon box	66	2.2	1.4	1.5	0.7	0.8	1.7
Downstream siphon box	71	2.3	1.0	1.4	0.9	0.8	1.3
Long crested weir	15	2.2					
Division box	28	2.7	1.5	1.0	0.8		
Drop structure	14	1.9	1.3	1.0	1.3	1.5	1.0
Outlet	5		0.8	1.0	0.5		1.5

A significant *negative* correlation was found between the occurrence of *Bulinus truncatus* (p<0.001) and thickness of the silt layer in tertiary structures. The intermediate host rarely occurred in sites with the thickest silt layers. This seems contrary to the results obtained in the cross-sectional snail survey, where a more diverse variety of sites had been sampled, including unlined canals. In reality the relation between *B.truncatus* and thickness may be more complex, as suggested by the increase of both the silt layer and *B.truncatus* density with distance in secondary structures (Figures 6.8 and 6.12 respectively).

Vegetation

Vegetation collected in the length profile study consisted of algae and macrophytes as in the cross-sectional snail survey. Only few sites had a vegetation cover of more than 25% both in secondary and tertiary canals and the cover of algae was never more than 50% (Table 6.13, details in Appendix IV). Both algal and macrophytic cover increased in secondary structures with distance from the canal head. In the tertiary inverted siphons *Bulinus truncatus* was positively associated with the degree of cover by macrophytes, a relation that could not be indentified in the cross-sectional snail survey.

6.3. CONCLUSIONS

A cross-sectional snail survey was carried out in the Tessaout Amont irrigation system to determine the relationship between snail distribution and characteristics of the sampled sites. A total of 223 sites has been sampled in 1994/95. About one third of these were siphon boxes, as inverted siphons are the most frequent hydraulic structures in Tessaout Amont. The nine present fresh water snails were well distributed over the area, though the total snail density varied spatially. There was no significant difference between this survey and one that was done three years earlier.

Table 6.13. Frequency of occurrence (%) of algae and macrophytes in hydraulic structures in Sector Dzouz.

SAMPLED SITES	N	ALGAE	MACROPHYTES
Secondary canal RG7			
Upstream siphon box	17	94	29
Downstream siphon box	20	100	20
Long crested weir	15	93	20
Division box	19	89	37
Drop structure	5		33
Tertiary canals			
Upstream siphon box	49	98	53
Downstream siphon box	51	94	43
Division box	9	100	56
Drop structure	8	100	37
Outlet	5	80	40

Bulinus truncatus, the intermediate host of schistosomiasis, was common in most sites, but most frequent in high densities in the abundant tertiary siphon boxes. Nine individuals of *B.truncatus* infested with *S.haematobium* were found. The occurrence of *B.truncatus* in Tessaout Amont was positively associated with water depth and with the thickness of the silt layer. However, the latter could be due to the thick layer of mud and sand in the drains where densities were high, so the association between snail species and thickness of the silt layer should be interpreted with caution.

Planorbarius metidjensis, a potential intermediate host, occurred sporadically in the system but was mainly found in tertiary siphon boxes and at the head of *seguias*. *B.truncatus* was associated with three other snail species, *Lymnaea peregra*, *Physa acuta* and *Ancylus fluviatilis*. *L.peregra* and *P.acuta* showed distribution patterns similar to that of *B.truncatus*, while *A.fluviatilis* was recorded from all sites except *seguias*. The presence of *L.peregra* and *P.acuta* in the siphon boxes was not significantly related to any of the analyzed site characteristics. Contrary to the literature (Wright 1968, El Hassan 1974), neither of the associated snail species are therefore expected to be competitors of *B.truncatus*.

The degree of cover by algae or macrophytes was not related to frequencies or densities of any of the 5 studied snail species. However, the preference of *Bulinus truncatus* for tertiary siphon boxes could be explained by the availability of food resources in the form of microscopic algae. Long periods of stagnation between irrigation turns, evaporation and water use activities may all stimulate eutrophication. Subsequent algal growth would be higher at tertiary and quaternary siphon boxes than at other sampled sites. The frequent presence of high densities of *B.truncatus* combined with regular water contact makes the tertiary siphon boxes to the main transmission sites of urinary schistosomiasis in the Tessaout Amont irrigation system.

The different characteristics that make siphon boxes ideal breeding sites for *Bulinus truncatus* are inter-related. The characteristics of the sampled sites appear to depend on irrigation design (type of site and its location on the system), water management (rotational flow) and water use (organic pollution). The relative location of hydraulic structures downstream of the canal head determines the exposure of each site to water flow. Both the frequency and the velocity of the water flow are higher in upstream parts of canals than in the downstream parts. Hence an ecological length profile study was carried out of one secondary canal and four of its tertiaries in Sector Dzouz of the Tessaout Amont irrigation system. A total of 77 secondary and 132 tertiary structures have been sampled in Spring 1995. All species except *Planorbarius metidjensis* were found in Sector Dzouz. The analysis has been focused on *B.truncatus*.

In the secondary canal, *Bulinus truncatus* was collected in structures located at the terminal part of the canal only. The highest frequencies and densities of the intermediate host of schistosomiasis were found in tertiary siphon boxes. Densities in the downstream siphon boxes were significantly higher than in upstream boxes, probably because of differences in turbulence. The density of *B.truncatus* in the tertiary canals increased from the head end towards the tail end of the canal. After correcting for water depth, a separate analysis of the number of snails per siphon box showed the same pattern: populations of *B.truncatus* in tertiary inverted siphons are larger than those in secondary siphons. Both at the secondary and the tertiary canals the numbers of *B.truncatus* snails per siphon box increase with distance from the canal head.

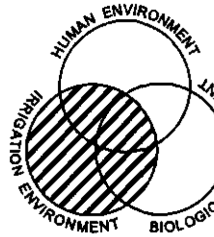
At the secondary canal thickness of the silt layer, cover by algae and cover by macrophytes increase with distance from the canal head. However, none of these characteristics is significantly correlated with *Bulinus truncatus* that was confined to the last part of the canal. At the tertiary level, the occurrence of the intermediate host of schistosomiasis was negatively correlated with the thickness of the silt layer. Algae were present in almost all sampled sites (80 - 100%). A positive association has been identified only between *B.truncatus* and the degree of cover by macrophytes.

The results of the ecological length profile confirmed that the location of each site upstream or downstream in the irrigation system is important. Canals and structures upstream in the irrigation system are less suitable for *Bulinus truncatus*. Siphon boxes, especially towards the tail end of secondary and tertiary canals have been shown to be ideal for *B.truncatus*. The tertiary inverted siphons are equally appropriate for the *Schistosoma haematobium* parasite, that may find a final host through frequent human water use activities at the siphon boxes.

Results of the different interventions discussed in Section 7.2. are also analyzed and discussed in the paper in preparation by Laamrani H, Khallaayoune K, Boelee E, Laghroubi MM, Madsen H, Gryseels B (1999) Evaluation of sustainable environmental methods to control snails in an irrigation system in Central Morocco.

7

ENVIRONMENTAL CONTROL OF SCHISTOSOMIASIS AT INVERTED SIPHONS IN THE TESSAOUT AMONT IRRIGATION SYSTEM



The study of water use activities in Chapter 5 and the inventories of the fresh water snail population in Chapter 6 have *identified tertiary siphon boxes as the main transmission sites of urinary schistosomiasis in Morocco.* The *inverted siphon therefore provides a good starting point for focalized schistosomiasis control against the snail host as well as to reduce water contact and water contamination.* Several schistosomiasis control measures in irrigation systems have been directed at the inverted siphons (unpublished data SIAAP and Khallaayoune & Laamrani) but these were typically mono-sectoral initiatives and had limited practical applicability.

The Ministry of Public Health suggested and performed chemical snail control in the inverted siphons. The applied molluscicide, Niclosamide®, is not toxic for vertebrates, but it is unknown what happens after long exposure to sunlight and high temperatures in the open siphon boxes. However, when looking at the overlap between the human environment and the irrigation environment, the restrictions of chemical snail control are obvious. In places where alternative water supplies are not available, it is impossible to prevent the local population from using the standing water in the siphons for domestic purposes. Molluscicides are not supposed to be consumed, so in fact this schistosomiasis control measure may turn out to be harmful to human and animal health.

The biological environment generates its own focal solutions: biological snail control with natural enemies such as fish or competitive snail species. This option is of limited value too in an irrigation environment. In the case of fish, small species have to be selected, as large fish cannot survive in the small siphon boxes. Small fish however, may be washed away to the fields with the irrigation water flow. Likewise, competitor or predator snail species might be successful in controlling *Bulinus truncatus* for a short time but are impractical in the abundant siphon boxes.

The inverted siphons form an integral part of the irrigation system and control measures thus have to be considered in this wider irrigation environment.

7.1. ENVIRONMENTAL CONTROL OPTIONS ON INVERTED SIPHONS

Tertiary siphon boxes in the Tessaout Amont irrigation system are ideal schistosomiasis transmission sites. In this section, technical options to change the characteristics of the inverted siphon will be explored in order to make this structure less suitable for *Bulinus truncatus* and for water contact.

The current design of the inverted siphons combined with a rotational water delivery makes the tertiary siphon boxes very attractive environments for *B.truncatus* snails. The prolonged periods of stagnant silt loaded water, exposed to the sun, stimulate the development of a coherent silt and algae layer on the walls of the siphon boxes that in turn provides a preferred food source for the snail. Slight organic pollution, following human water use activities, may contribute to this ideal environment, while the relatively long periods between irrigation turns allows large populations of *B.truncatus* to build up (Laamrani 1999).

The location of the structures in the irrigation system cannot be changed, but design and water management might be modified. Irrigation engineering approaches to environmental schistosomiasis control in siphon boxes could be aimed at the human environment by measures that reduce water contact and water contamination. Other approaches are directed at the biological environment by hindering snail development, directly or indirectly through a reduction of snail food resources. Preferably measures in the irrigation environment affect both environments simultaneously. *Three different schistosomiasis control approaches directed at the siphon will now be explored: removing the silt layer, creating a dark environment and increasing the water flow velocity.*

7.1.1. Removing the silt layer

In the Tessaout Amont irrigation system *Bulinus truncatus* is associated with a thin silt layer in hydraulic structures. This silt layer consists of a firm layer of fine silt deposits, bound together by green algae. This compact silt layer serves as a substratum for other, filamental algae. In the primary and secondary canals, this substratum is frequently removed with routine cleaning activities. In the tertiary canals however, the silt layer is not very firm because of frequent drying and cracking in the sun, after which it is washed away by the next water flow (Figure 7.1). The inverted siphons are cleaned once every 2 or 3 years, but only when the pipe is blocked by collapsed man-made water division barriers of stones and mud. The chances of this material falling into a siphon box can be prevented by re-installing the original metal slide flow dividers.

Figure 7.1. Tertiary canal with silt layer that is dried and cracked in the sun. The deposits may be washed away with subsequent irrigation flows.

Between subsequent cleanings, both the loosened material from tertiary canals and the dissolved silt from the catchment area settle in inverted siphons downstream in the system, which thus function as silt traps. For the hydraulic functioning of the siphon the little silt layer is hardly a problem, as it only mildly affects the roughness of the surface and thus causes no additional friction to the water flow. To *Bulinus truncatus* however, it provides just the ideal "pasture" and breeding ground. Additionally, fruit remains and other organic material thrown in by people living and working in the area serve as an indirect food source for *B.truncatus* as well. It would require intensive education campaigns to change this behaviour.

Canals are now cleaned every other year, inverted siphons only when being clogged. More frequent cleaning might have a reductive effect on snail populations too, while such activities simultaneously increase conveyance efficiencies of the irrigation water. The silt layer in the siphons could be removed by various methods of cleaning. Field experiments using frequent cleaning will be discussed in Sub-section 7.2.1.

7.1.2. Creating a dark environment

Laboratory experiments have shown that in a dark environment, both snail development and algal growth are hindered. However, the experiments with snails from Tessaout Amont showed that darkness as such is not the factor that affects the growth, mortality and fecundity of *Bulinus truncatus* (Laghroubi et al 1997). The effect of darkness on snail development is probably indirect: through a reduction of photo synthesis less food resources will be available to the intermediate host. This indirect effect of darkness on *B.truncatus* under laboratory conditions has been mentioned before (El Emam & Madsen 1982). Stagnant water with less photosynthetic activity also contains less dissolved oxygen and would be favourable to the proliferation of anaerobic micro-organisms. Perhaps some of the bacteria could have a controlling effect on fresh water snails.

To create a dark environment in the field, inverted siphons could be darkened by covering the boxes. Field experiments using steel covers on siphon boxes will be discussed in Sub-section 7.2.2.

Alternatively, the present model of siphon with square boxes could be replaced by sloping pipes, with a reduced surface that is exposed to sunlight. These inverted siphons are also less accessible for playing children and will thus reduce water contact and water contamination. An sloping pipe type of siphon could be constructed in new irrigation systems, while maintaining the same basic lay out with elevated canals. The idea of an inverted siphon consisting of sloping pipes is not new. In some of the older open canal irrigation systems in Morocco, the siphon was entirely constructed with wide sloping and horizontal pipes (Figure 7.2). The diameter of the pipe was similar to the diameter of the canal, 0.4 to 0.6 m. Because of the difficult access for maintenance and the vulnerability of the 50 mm concrete layer, this type of siphon was later replaced by the two box type. Square boxes are cheap in construction, very durable and easily accessible for maintenance. Unfortunately, *easy access is exactly what makes the square box type of siphon so attractive for playing children.*

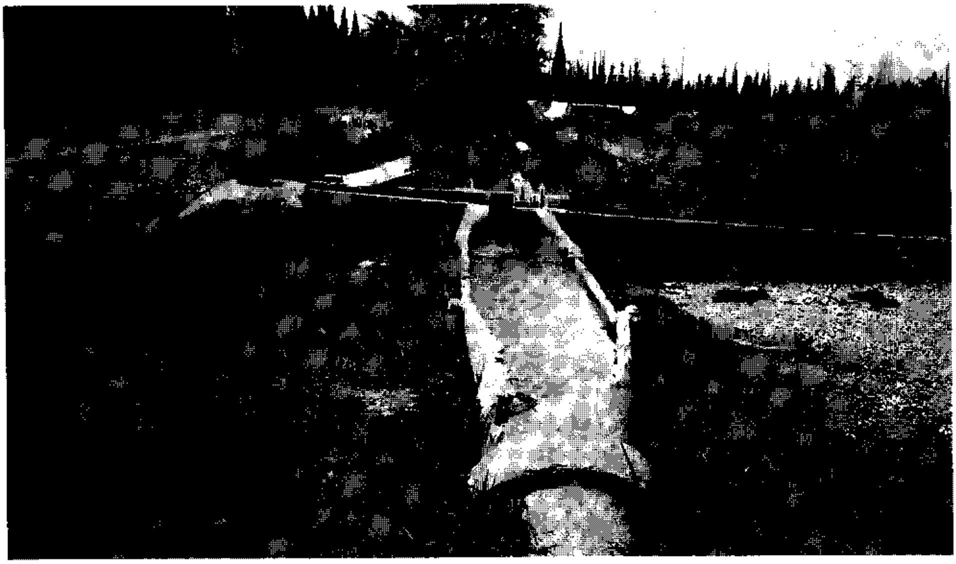


Figure 7.2. Detail of the old model of inverted siphon.

A third option would be to replace the entire canal-siphon system by underground low pressure pipes (Van Bentum & Smout 1994). That would provide an absolute dark environment and prevent both water contamination and water contact. However, pipe systems would silt up very rapidly in areas such as Tessaout Amont in Morocco.

7.1.3. Increasing the water flow velocity

In Chapter 6 it was shown that *Bulinus truncatus* in the Tessaout Amont irrigation system is mainly restricted to siphon boxes that are situated near the tail end of secondary and tertiary canals. In these favourite breeding sites long periods of water stagnation occur and the occasional water flow in the wide siphon boxes results in low velocities. The fact that downstream siphon boxes are preferred over upstream boxes, indicates a *particular sensitivity of* B.truncatus *for turbulent flow.* Indeed in the canals many snails were observed to align their shells to produce the least resistance to the flow. In the siphon boxes with three-dimensional turbulence this behaviour is not possible (Jones 1994).

Jones (1993) performed elaborate field research in the Tessaout Amont irrigation system on the snail controlling effect of water flow. He tried to analyze separately the effect of flow velocity and turbulence on the one hand and the period of stagnant water between irrigations on the other hand. In all studies in Tessaout Amont, the water flow velocity v (m/s) has been calculated as the flow rate Q (m^3/s) divided by the wetted area A (m^2): $v = Q / A$.

There appeared to be no unique critical v nor frequency of flow that controlled the snails. Jones (1993) did however find that snail numbers depend on velocity, frequency and duration of this flow. Based on data from 23 sampling points at secondary canals, Jones found a strong correlation between *Bulinus truncatus* populations and the mean *annual* velocity $\overline{v_a}$, which has been calculated as the weighed average velocity Σvf, with f being the flow frequency (fraction). Consequently, all days of the year, whether there is water flow or not, were included in the calculation of $\overline{v_a}$. For a total of 130 upstream and downstream siphon boxes, one single relation was derived, with a *critical mean annual velocity* $\overline{v_c}$ *= 0.042 m/s above which the development of* B.truncatus *snails is prevented* (Jones 1994).

A $\overline{v_c}$ = 0.042 m/s *could theoretically be obtained under different flow regimes.* It could be achieved for example with a high v = 0.42 m/s during 10% of the time, or with a medium $v = 0.21$ m/s for half the time. But also a continuous $v = 0.042$ m/s would result in the same $\overline{v_a} = \overline{v_c}$. *The various flow regimes however, will each have a different impact on the snail populations.* The effect of a permanent low v would mainly be indirect by continuously refreshing the water and removing the main food resource of *B.truncatus*. A medium v would directly hinder snail movement.

A high v would scour out silt deposits and flush away all snails into the fields. To remove *Bulinus* from a concrete surface in a laboratory, the required flushing velocity $v_f = 0.44$ m/s to remove 80% of the snails (Meyrick 1986 in Jones 1993). Under field conditions, $v_f = 0.3$ m/s (Appleton 1975 in Jones 1993). Both flushing velocities were measured at snail height, less than 0.01 m from the surface. Considering that the turbulence in the siphon boxes is three dimensional, a v_f below 0.3 m/s at snail height will already be effective against the snail host. *A vertical or sloping $Q / A = v_f = 0.42$ m/s is expected to generate sufficient friction at snail height to have a flushing effect on* B.truncatus *in inverted siphons in the Tessaout Amont irrigation system.*

The present water flow velocity for a standard tertiary inverted siphon with boxes having as $A = 0.8 * 0.8$ m $= 0.64$ m^2 and $Q = 0.03$ m^3/s can be calculated as $v = 0.047$ m/s. Assuming that a tertiary canal in the Tessaout Amont irrigation system conveys water for 6 days a month (i.e. 20% of the time), then a tertiary siphon halfway an average canal is flowing for 0.5 * 20% = 10% of the time, leading to a $\overline{v_a} = 0.0047$ m/s only. Hence *radical measures are needed to arrive at a $\overline{v_c} = 0.042$ m/s.* Different flow regimes leading to this $\overline{v_c}$ could be achieved theoretically by an increase either of the flow rate Q by means of changing the water management, or by changing the design of the siphon to reduce the wetted area A.

Increase the flow rate

In the Tessaout Amont irrigation system with high crop water requirements and limited water availability, the water gifts to the crops cannot be changed. An increase of the water flow rate Q would thus imply a decrease of the duration of the water flow or an increase of the interval between irrigation turns. Both result in longer periods of stagnation and $\overline{v_a}$ remains 0.0047 m/s, which, according to Jones (1993), is too low for snail control.

However, an increased Q might wash the snails out of the siphon into the fields. To obtain a $v_f = 0.42$ m/s in a siphon box with a wetted area $A = 0.64$ m^2, a flow rate $Q = 0.269$ m^3/s would be required, i.e. practically 9 times the normal *main* *d'eau* of 0.03 m^3/s. Most of the canals on which the inverted siphons are situated in the Tessaout Amont irrigation system are too small to convey such a high flow rate. The existing tertiary canals, designed with a maximum capacity of $Q = 0.03$ to 0.06 m^3/s, would have to be replaced with larger ones. This is very expensive and only feasible for new irrigation systems or elaborate rehabilitation projects. Another possibility to increase the canal capacity is to lay the existing conduits under a higher slope. As a consequence, all canals have to be laid at a higher level above the ground to be able to irrigate all land by gravity. A third option is to use pumps, but that would change the design concept of the entire irrigation system.

Reducing the diameter of the inverted siphon

With the same *main d'eau*, $\overline{v_c} = 0.042$ m/s can be obtained by *reducing the wetted area A of the siphon. This could be achieved through a reduction of the dimensions of existing siphon boxes or by replacing the siphon with a different design. Both options would have consequences for the hydraulic functioning of the siphon. Before proposing alternatives, first the hydraulics of the present inverted siphons will be discussed.*

Present standard tertiary inverted siphon - In gravity-fed irrigation systems such as Tessaout Amont, all canals, drains and hydraulic structures are sloping. Contrary to the semi-circular open canals, siphons provide resistance to flow all around the water. This resistance is expressed as energy head loss ΔH (m) and is compiled of wall friction or sheer stress in both boxes and the connecting pipe, but also of bending, converging and diverging streamlines in the water (Figure V.1 in Appendix V). In a standard inverted siphon, theoretically the following phenomena cause successive energy head loss:

1. Water flowing from the upstream canal A into the upstream siphon box A (diverging streamlines);
2. Water flowing downwards (bending streamlines);
3. Wall friction (sheer stress) in box A;
4. Water flowing from box A into the pipe (bending and converging streamlines);
5. Wall friction in the pipe;
6. Water flowing from the pipe into the downstream box B (bending and diverging streamlines);
7. Wall friction in box B;
8. Water flowing from box B into the downstream canal B (bending and converging streamlines).

To estimate ΔH under different conditions considerate research has been performed (Idel'cik 1969). Dimensions of the structure and water flow velocities are important, but also the construction material and even the water temperature. Idel'ciks equations have been applied to a standard Tessaout Amont tertiary inverted siphon with an upstream box of $A = 0.8 * 0.8 = 0.64$ m^2, a downstream box of $A = 0.8 * 1.1 = 0.88$ m^2 and a flow rate $Q = 0.03$ m^3/s (Figure 7.3). In this siphon $\Delta H = 0.055$ m, which is the required difference in water level between the upstream and downstream box (detailed calculations in Appendix V.1). If the siphon is constructed with less fall, it will result in overtopping of the upstream canal. Consequently, in an average tertiary canal with 12 siphons, the water level at the head of the canal needs to be 0.65 m higher than the level required to irrigate the fields at the end of the canal.

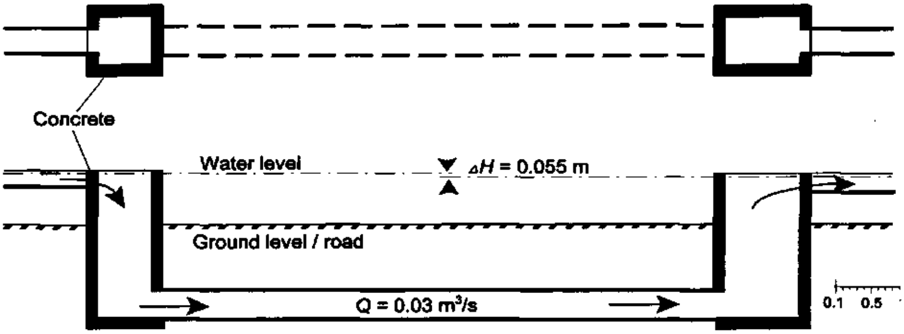


Figure 7.3. *Present standard* tertiary inverted siphon in the Tessaout Amont irrigation system to convey a $Q = 0.03$ m^3/s with a $v = 0.034 - 0.047$ m/s. The inner dimensions of the upstream box are 0.8 m * 0.8 m and of the downstream box 1.1 m * 0.8 m.

Reducing the dimensions of the siphon boxes - If only the dimensions of the siphon boxes would be reduced, the size and the frequency of the flow would be maintained at $Q = 0.03$ m^3/s for 10% of the time. To arrive at $\overline{v_c} = 0.042$ m/s, the water flow velocity should be $v = 0.42$ m/s $= v_f$, which can be obtained by reducing the inner dimensions of the siphon boxes to $A = 0.07$ m^2 = 0.2 m * 0.35 m (Figure 7.4). In addition to increasing the v, this will interfere with water use activities. Such dimensions of the siphon boxes result in a $\Delta H = 0.067$ m, which means that the water level in the downstream box will be 0.067 m lower than in the upstream box (Appendix V.2). For an average tertiary canal with 12 inverted siphons this would mean that the water level h at the canal head should now be $\Delta H_{tot} = 12 * 0.067 = 0.80$ m higher than is required at the tail, which is 0.15 m higher than with standard siphons. This small difference can probably be overcome rather easily in the field. With only minor adaptations to the canal, existing tertiary siphon boxes could thus be reduced to obtain $\overline{v_c}$ = 0.042 m/s, the critical water flow velocity below which no *B.truncatus* snails were found (Jones 1994).

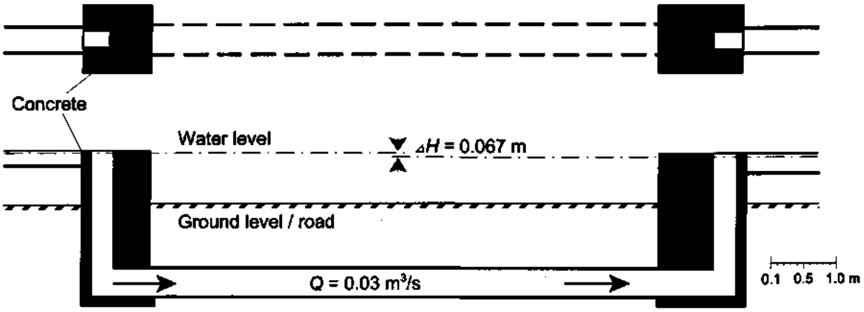


Figure 7.4. Theoretical standard tertiary inverted siphon with *reduced dimensions* to convey a Q = 0.03 m^3/s with a v = 0.43 m/s. The inner dimensions of both siphon boxes are 0.2 m * 0.35 m.

Changing the shape of the siphon boxes - With smaller siphon boxes, access for cleaning is no longer possible, while the pipe gets blocked more easily. In a totally different type of inverted siphon, based on the old model with sloping pipes, but with a smaller diameter of 0.3 m, silt would be flushed away with a $v = v_f$ = 0.42 m/s. The need for cleaning under normal conditions is prevented and $\overline{v_c}$= 0.042 m/s will be achieved.

Theoretically speaking, two alternative models could be conceived to replace the present inverted siphon with two boxes and horizontal underground pipe: an alternative U-shaped siphon, being still close to the early model (Figure 7.5) and a simpler V-shaped one (Figure 7.6). The V-shaped siphon is however a very impractical type of siphon that has to be dug 3 m deep to leave sufficient space for a road. Besides, it would get clogged very rapidly as larger floating objects such as twigs easily get stuck in the bend and accumulate other debris and silt. The V-shaped model has been elaborated anyhow as an exercise because in the calculations of energy head loss in a standard siphon, be it with or without reduced dimensions, the bending streamlines account for most of the energy losses and a V-shaped siphon would only have one curve.

In these theoretical alternative siphons the energy head loss ΔH is low. In the U-shaped alternative siphon ΔH = 0.030 m and bending streamlines account for most of the energy head loss (Appendix V.3). For an average tertiary canal with 12 siphons ΔH_{tot} = 12 * 0.03 = 0.36 m, less even than what the present standard siphons require (ΔH_{tot} = 0.65 m). The V-shaped alternative siphon would cause a

ΔH = 0.036 m, surprisingly with bending streamlines still accounting for most of the energy loss (Appendix V.4). For an average tertiary canal, the water level at the canal head should thus be ΔH_{tot} = 12 * 0.036 = 0.43 m higher.

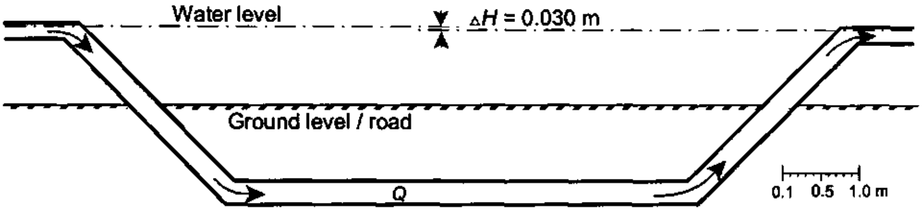


Figure 7.5. Theoretical alternative *U-shaped tertiary siphon* to convey a $Q = 0.03\ m^3/s$ with a $v = 0.42$ m/s. The diameter of the pipe is 0.3 m.

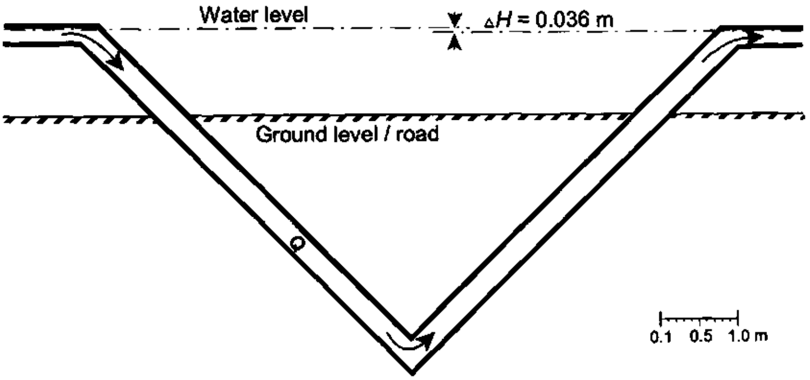


Figure 7.6. Theoretical alternative *V-shaped tertiary siphon* to convey a $Q = 0.03\ m^3/s$ with a $v = 0.42$ m/s. The diameter of the pipe is 0.3 m.

The theoretical alternative U-shaped siphon with 0.3 m pipes has a hydraulic advantage over the existing standard square box type of siphon. The compact size would make this U-shape less vulnerable than the old model with 0.4 - 0.6 m diameter pipes (Figure 7.2). The accumulated silt will be scoured out from the U-shaped siphon with v_f = 0.42 m/s, which reduces the need for maintenance. The $\overline{v_c}$ = 0.042 m/s should control *Bulinus truncatus* snails, while additionally, the sloping pipes provide a dark environment and make water contact almost impossible. *In new irrigation systems, a U-shaped siphon, consisting of two sloping pipes, connected by an underground pipe of the same 0.3 m diameter, could thus be a good alternative to the existing standard siphon.*

7.2. FIELD EXPERIMENTS ON INVERTED SIPHONS

Some of the suggested environmental control strategies that are suitable for existing inverted siphons, have been applied and evaluated at different sites in the Tessaout Amont irrigation system (Figure 7.7). The *selected environmental interventions have been aimed at reducing the snail populations and obstructing water contact*. These interventions on inverted siphons consisted of *cleaning, covering and reducing the box dimensions*.

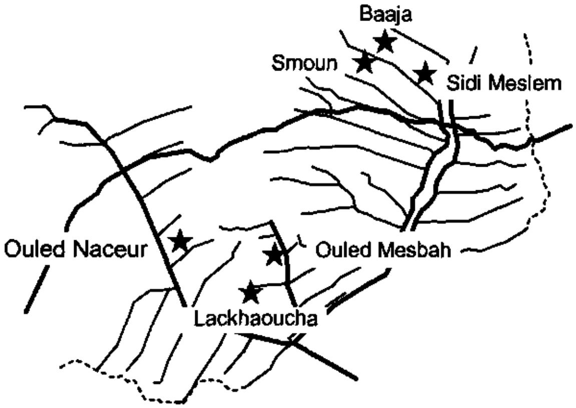


Figure 7.7. Intervention and control sites for environmental control of schistosomiasis on inverted siphons in the Tessaout Amont irrigation system.

The low incidence of urinary schistosomiasis in Tessaout Amont made it unrealistic to base an evaluation of the interventions on changes in the number of detected cases. Still, the entire population in the study villages was screened and tested for schistosomiasis, a few weeks before implementation of the intervention. The impact of the interventions has been measured in terms of adult snail population and egg masses, while changes in water use and water contact behaviour were considered qualitatively.

To evaluate the impact on *Bulinus truncatus*, siphon boxes were sampled monthly for snails in a number of villages. Sampling started one year before implementation of the intervention and continued one year after the intervention. The selected siphon boxes were characterized by high densities of the snail host and regular water use. The drag scoop method as described in Appendix II was used in a total of 18 siphon boxes around 5 villages. Collected snails and egg masses were sorted to species, measured, screened for schistosome infection and within 24 hours returned to their sites.

Snail data were compared over the period before and after the control measures and between intervention and control sites. The reason for this both spatial and temporal comparison is the seasonal pattern in the distribution of *B.truncatus*. Typically, in accordance with the high temperatures, snail densities are highest in summer. From summer time onwards, both the adult snail population and reproduction decrease until November and then remain low until March/April (Khallaayoune & Laamrani 1992).

Four villages were selected for detailed social studies to monitor possible changes in water use patterns: Baaja, Smoun, Chamchita and Ouled Mesbah. Throughout the period before and after the intervention, water use patterns have been studied to determine who used which water sources for what purposes, when, how and in what quantities. The users were described in terms of age, gender and social status. Many water use activities around the different sources of water showed a scattered pattern, with a small number of people involved (Watts et al 1998).

7.2.1. Drying and cleaning to remove the silt layer

In 1992 in an experimental setting in Tessaout Amont the silt layer with all snails on it was brushed away from the walls of some siphon boxes several times during the irrigation season. This was done while the water was flowing, so the dislocated snails were transported to the field, where they died. It turned out to be an effective control measure against *Bulinus truncatus* snails in tertiary inverted siphons (Khallaayoune et al 1998b).

In 1996 a different experiment was carried out near the village of Ouled Mesbah in the middle part of Tessaout Amont. Here, cases of urinary schistosomiasis were detected in 1990 to 1994, one of the reasons the village was included in the socio-economical studies (Hanne & Alioua 1995). Ouled Mesbah was selected for the emptying and cleaning intervention, because the siphons contained large populations of *B.truncatus* snails and alternative water supply was available. A water tower with public taps insured good quality drinking water while Primary Canal Ouled Gaid, less then 10 meters away from the intervention boxes, provided high quantities of streaming water most of the time for other domestic purposes. The work could easily be organized as farmers were united in the local water users association.

The tertiary siphon boxes on canal OGG2T1, close to the village of Ouled Mesbah, were cleaned three times in 1996: at the beginning (July), halfway (September) and at the end (December) of the irrigation season. The works were executed in collaboration with the local Water Users Association *Al Hamra* and the Irrigation Board. Cleaning consisted of emptying the siphons and removing the mud and stones from the bottom of the box as well as from the first 0.20 m of the pipe. All inverted siphons on OGG2T1 were cleaned, 2 of which were sampled and monitored. The mean number of *B.truncatus* snails in the two boxes were then compared to the mean number of snails in five untreated control siphon boxes in Smoun and Sidi Meslem.

The first emptying and cleaning in July 1996 resulted in a pronounced reduction of snail densities (Figure 7.8). A similar reduction occurred only in September 1995 in the same sites without intervention. The second cleaning in September 1996 had hardly any additional effect. On the contrary, an increase in snail density was observed in October, probably building up from snails hiding in the underground pipe. With the third cleaning in December densities dropped again, but that is common in this time of year and can thus not be attributed to the intervention. The control sites show a high snail density in 1996 peaking in September, while the sites in Ouled Mesbah showed only low numbers of *B.truncatus*. In May and June 1997 the population of *B.truncatus* in Ouled Mesbah consisted for more than 50% of juvenile snails.

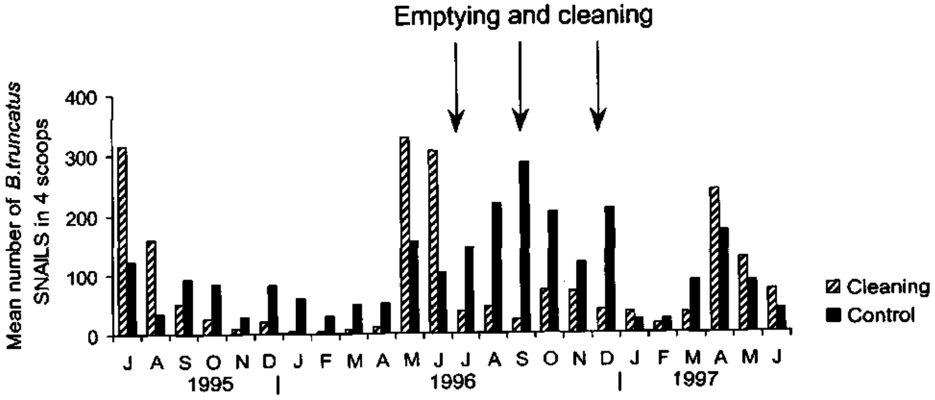


Figure 7.8. SNAILS of *Bulinus truncatus* in tertiary intervention siphon boxes near Ouled Mesbah and control sites. In July, September and December 1996 the boxes in Ouled Mesbah were emptied and cleaned to control snail populations. This intervention seems to have moved up the seasonal decrease in snail density with three months from September (as in 1995) to July in 1996. The high number of *B.truncatus* in the control sites in 1996 suggest that this year was a good year for the intermediate host of schistosomiasis, with much higher snail densities than in Ouled Mesbah. In spring 1997, snail numbers started to increase again in all siphon boxes.

The first emptying and cleaning removed the adult *Bulinus truncatus* snails while the egg masses remained stuck to the walls of the siphon box (Figure 7.9). With the sun burning in the empty siphon however, the eggs rapidly dried out and very few egg masses were found in Ouled Mesbah in July and August 1996. This result is in line with laboratory experiments on *B.truncatus* snails from Tessaout Amont, that revealed a pronounced effect of desiccation on the viability of egg masses. At a relative humidity of 62% after 9 hours of exposure, no eggs hatched, while with a relative humidity of 25% only 7 hours were needed to kill all eggs (Mehdaoui 1996).

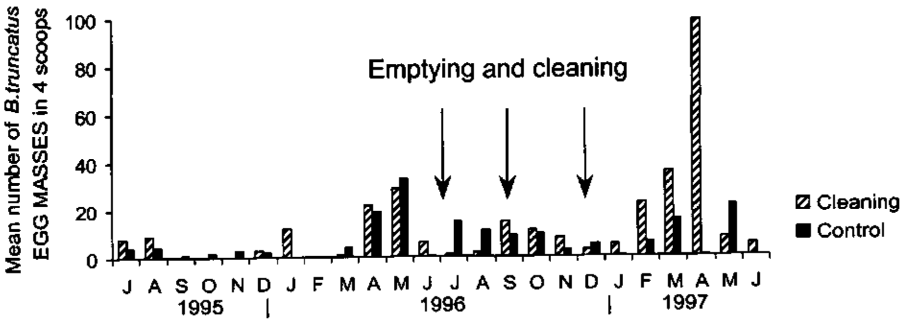


Figure 7.9. EGG MASSES of *Bulinus truncatus* in tertiary intervention siphon boxes near Ouled Mesbah and control sites. Before the intervention in 1995, few egg masses were found in both sites. In July, September and December 1996 the siphon boxes in Ouled Mesbah were emptied and cleaned to control *B.truncatus* populations. The first intervention in July 1996 exposed the egg masses of *B.truncatus* to drying and very few eggs were found in July and August. In autumn reproduction increased again to be higher than in the control sites. In the following spring a high number of egg masses was found in the intervention sites, with an absolute peak of 99 egg masses in April 1997, resulting in a high ratio of small juvenile snails in May and June 1997 (Figure 7.8).

The emptying and cleaning activities proved to be difficult to implement, as the incentive for the water users association was not enough to justify the effort. Although this kind of cleaning prevents obstruction of the underground pipe, in the long run it has no direct effect on irrigation performance and brings no additional water to individual irrigators. The effect of this intervention on both adults and egg masses of *B.truncatus* was limited on the short term and nil on the long term. Hence *the emptying and cleaning of tertiary inverted siphons to remove the silt layer and desiccate the snails is not an effective measure* to control *Bulinus truncatus*, the intermediate host of schistosomiasis.

7.2.2. Covering by iron plates to create a dark environment

In 1992, a field study in Lackhaoucha evaluated the impact of concrete covers on *Bulinus truncatus* snail populations in siphon boxes. This experiment was successful in snail control but not sustainable as the covers were repeatedly destroyed (Khallaayoune et al 1998b). Apparently people need all the water in the boxes for domestic purposes and are prepared to use force to get there. When the villagers found out that after removing the covers, these were replaced, the covers were demolished again till only the steel used for reinforcement was left. To prevent a repetition of this failure, in 1995 a new intervention in another village, Baaja, was preceded by social studies.

Preparation of the intervention in Baaja

The village of Baaja in the command area of secondary canal RG8 in the northern part of Tessaout Amont was considered very convenient for an intervention covering siphon boxes. New cases of schistosomiasis had been detected in 1994/95 and the densities of *B.truncatus* in the tertiary inverted siphons around the villages were high. Drinking water supply in this village is ensured by a few shallow wells. Most other water use and water contact activities were concentrated around two parallel canals west of the village, where 7 siphon boxes (2 inverted siphons with 3 additional quaternary boxes) constitute a favourite washing place. The lower canal, a branch of the independent *seguia* Ghabia, is preferred to the higher elevated tertiary canal RG8T16, as the *seguia* is easier accessible and conveys a small and convenient water flow most of the time.

The social studies in Baaja revealed contradictory expectations of the male and female population towards the intervention. The women were quite positive about having iron covers on the siphons, but the men feared that these would disappear very soon for the same reasons as in Lackhaoucha. The men pointed out that drawing water from the wells demands a considerable physical effort, so the easily accessible water in the siphon would have to remain available to the women for laundry.

The Irrigation Board agreed to have modifications on the inverted siphons on the condition that the covers would not hamper operation of the irrigation system and were approved by the local population. Additionally, all metal division slides in the structures around Baaja had to be reinstalled. With these slides the structures could be shut off from the canals and a simple iron cover was sufficient to keep all the light out of the siphon box. A skilled local mechanic fitted the covers on the siphon boxes at the tertiary canal RG8T16 and at the branch of the *seguia* Ghabia end May 1996. The covers consisted of flat plates of locally available iron, embedded in the top of the concrete siphon with cement (Figure 7.10).

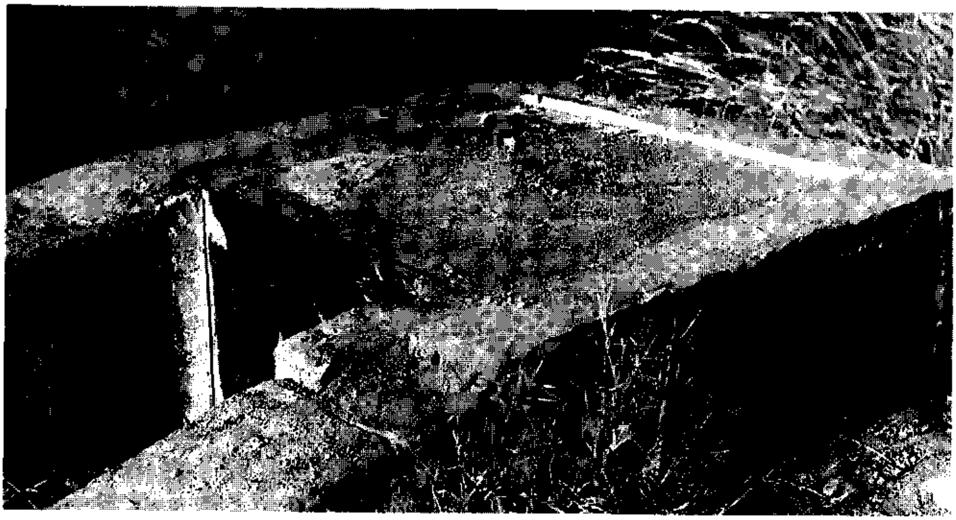


Figure 7.10. Detail of a *simple iron plate cover* on a concrete siphon box, fixed with cement.

The water in every covered inverted siphon was made accessible to the population by equipping at least one box on each siphon with an iron cover that had a moveable lid (Figure 7.11). The lids were large enough to allow the passage of a bucket. The covers with moveable lids were fabricated beforehand in a workshop and adapted to size on each siphon separately. If necessary, this type of cover could easily be removed after one year without any permanent damage to the structure.

All 57 inverted siphons on the entire two canals were covered to eliminate upstream breeding pockets and avoid in-flush of snails. As the moveable lid would allow light into the box occasionally, this type of cover would be placed at the upstream box whenever possible. Then total darkness would be created in the downstream box, where densities of *Bulinus truncatus* are much higher. At sites where water use was very intensive, the social scientists helped to identify the additional siphon boxes that required iron covers with moveable lids. Three siphon boxes were sampled monthly during two years. The mean number of *B.truncatus* snails in the three boxes were compared to the mean number of snails in five untreated control siphon boxes in Smoun and Sidi Meslem.

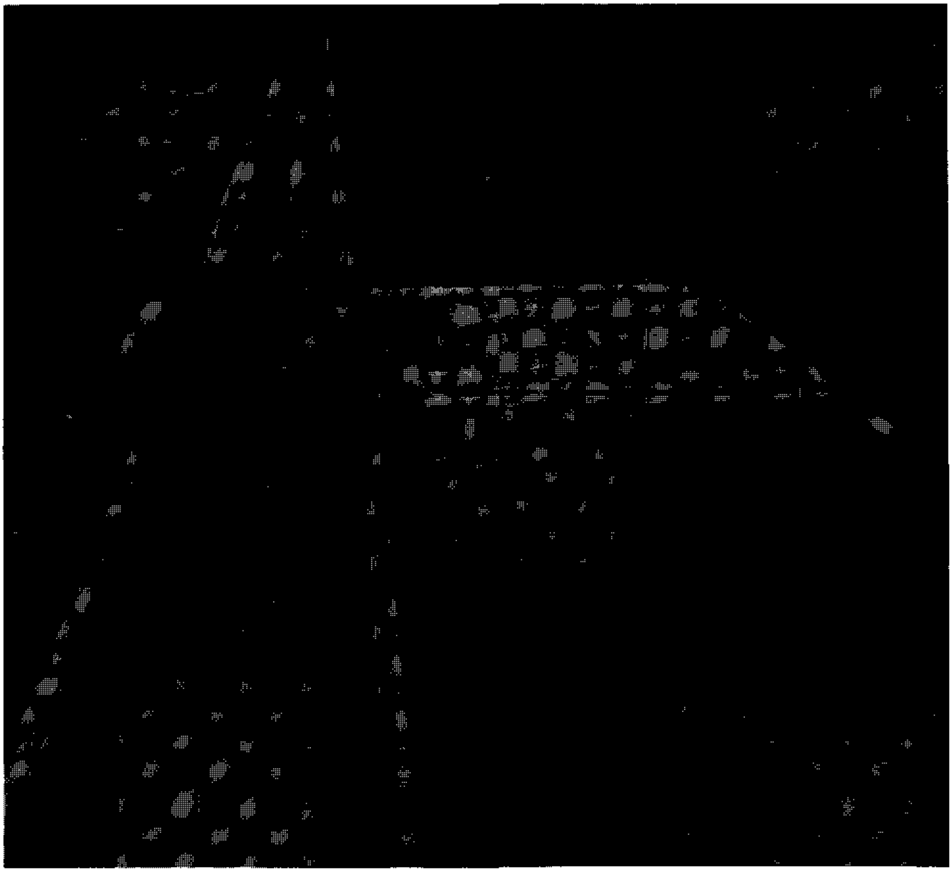


Figure 7.11. Detail of an *iron plate cover with a moveable lid* on a concrete siphon box to allow for the withdrawal of water.

The population of Baaja was involved in the intervention through village meetings and through bilateral discussions with village leaders and key persons. The purpose of the covers was explained and the community was made aware of its own responsibility. Otherwise, the covers might easily be manipulated or even molested, as happened in the earlier intervention in Lackhaoucha. In Baaja notably the moveable lids were vulnerable as people could e.g. use a stick to keep the lid open and leave it like that after they had finished their task of fetching water, thus exposing the inside of the siphon to sunshine and invalidating the experiment. The Village Committee agreed to look after the covers and ensure the proper closing of the lids during the post-intervention year.

Results of the covering

In 1995 and the first half of 1996, before the intervention, the snail densities in Baaja were somewhat higher then in the control sites. After the construction of the covers in June 1996, the density of *Bulinus truncatus* decreased rapidly in Baaja, while in the control sites the normal summer peak was observed (Figure 7.12). In the covered siphon boxes densities of *B.truncatus* remained low during the entire post-intervention period, significantly lower than before intervention ($p<0.001$). Covering also had a rapid and lasting effect on the reproduction of *B.truncatus*, as much less egg masses and juvenile snails were found in the siphons around Baaja than in the control sites (Figure 7.13).

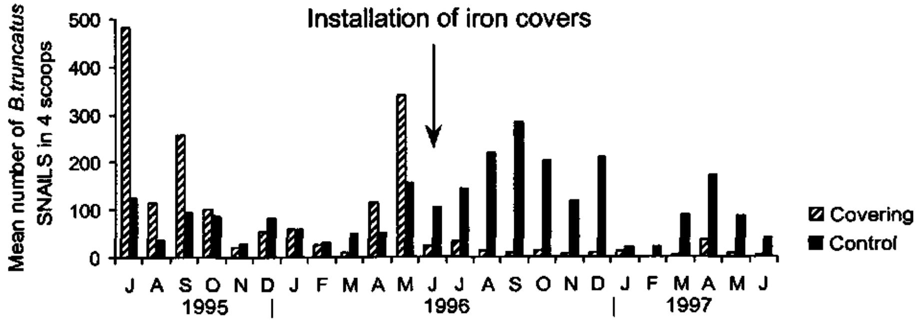


Figure 7.12. SNAILS of *Bulinus truncatus* in tertiary siphon boxes around Baaja. The snail densities before the intervention were generally (much) higher than those in the control sites. The installation of iron plate covers on the siphon boxes in June 1996 resulted in a pronounced and lasting decrease of the snail population of *B.truncatus*. The slight peak in snail numbers in April 1997 was mainly due to small juvenile snails that are believed to be washed in from upstream structures, as no egg masses were found in that month.

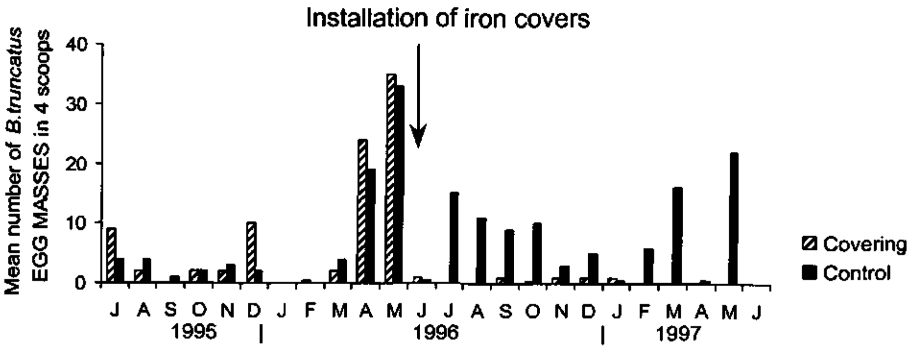


Figure 7.13. EGG MASSES of *Bulinus truncatus* in tertiary siphon boxes around Baaja. The numbers of egg masses before the intervention were similar to those in the control sites. The installation of iron plate covers on the siphon boxes in June 1996 resulted in a pronounced and lasting decrease of the reproduction of *B.truncatus*.

The results of the intervention in Baaja confirm the indirect effect of darkness on *Bulinus truncatus*. On the inner walls of the covered siphon boxes algal growth was low, while the chlorophyll content of the water was also significantly lower than in non-covered boxes nearby. Hence food availability for *B.truncatus* was reduced.

Women in Baaja involved in daily water use activities around the siphons, generally appreciated the covers. The water was still accessible through the moveable lids, that were kept closed as much as possible. The quality of the water zwas perceived as better, now that no leaves or dust could fall in. Also the water smelled better. The women valued the covers in preventing small children to play in the often deep boxes. According to the villagers, an extra benefit appeared to be a substantial reduction in the density of mosquitoes. Consequently, the siphon boxes stayed covered after the post-intervention monitoring year. Till late 1998, only five covers were broken and removed; the remainder was still in place two and a half year after construction.

The covering of tertiary inverted siphons with iron plate covers to obtain a dark environment and restrict water contact is a highly effective measure to control *Bulinus truncatus*, the intermediate host of schistosomiasis. The iron plate covers with moveable lids leave the water accessible for domestic purposes while water contact is reduced.

7.2.3. Reduction of the physical dimensions to increase the water flow velocity

The calculations in Sub-section 7.1.3 showed that it is possible to reduce the physical dimensions of the siphon boxes. However, some hydraulic consequences because of increasing energy head losses have to be taken into account. Near the village of Ouled Naceur, 3 inverted siphons were selected in which the mean annual water flow velocity $\overline{v_a}$ approached $\overline{v_c}$ = 0.042 m/s, but stayed below it. *B.truncatus* was present in these siphons in low densities. The siphons were over-dimensioned, constructed with a higher ΔH than required to compensate the energy head loss. As a result, water flowed with turbulent velocities out of the siphons and a reduction of the dimensions would not cause overtopping in the upstream canal. People in the area did not use these siphons very often to draw water for domestic or other purposes. Therefore the location was considered suitable for an experiment reducing the dimensions of the siphon boxes.

In May 1996 the inner dimensions of the boxes of two secondary siphons at canal D5 and one tertiary siphon were reduced by 30% by means of concrete blocks covered with cement (Figure 7.14). The $\overline{v_e}$ in each of the siphon boxes was thereby increased above the $\overline{v_c}$ = 0.042 m/s. All six modified boxes were sampled monthly during 14 months after the construction. A nearby tertiary siphon where the $\overline{v_e}$ remained largely below 0.042 m/s was selected as a control site. In this control siphon the densities of *Bulinus truncatus* were high, while in the siphons that were to be modified, the densities were low. *If B.truncatus would not recolonize the modified siphon boxes, then the control velocity* $\overline{v_c}$ *= 0.042 m/s would be confirmed* (Jones et al 1996).

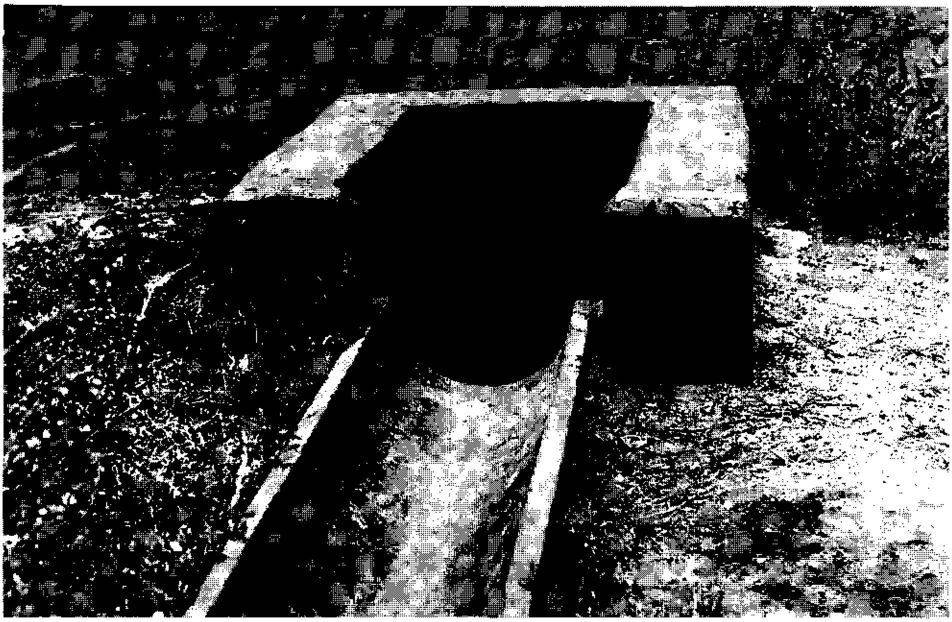


Figure 7.14. The physical dimensions of 4 secondary and 2 tertiary siphon boxes at the secondary canal D4 were reduced by 30% by means of concrete blocks and cement. The "shade" on the border of the outgoing canal shows the occurrence of the "wave" in the water flow, as an indication of the turbulent flow before the intervention.

During the construction works in May 1996, all aquatic snails and their egg masses were eliminated from the siphon boxes near Ouled Naceur. However, the most upstream modified siphon was rapidly re-colonized: *B.truncatus* snails and egg masses were present already within a month time. In the reduced tertiary siphon boxes it took 4 months for the snail population to re-establish itself again. Though the densities of the snail host were relatively low, *B.truncatus* remained present in all modified siphons throughout the year after the intervention (Figure

7.15 and 7.16). Apparently the critical mean annual flow velocity $\overline{v_c}$= *not* 0.042 m/s and *the reduction of the physical dimensions of inverted siphons to obtain a* $\overline{v_c}$*= 0.042 m/s is not an effective measure* to control *Bulinus truncatus*, the intermediate host of schistosomiasis.

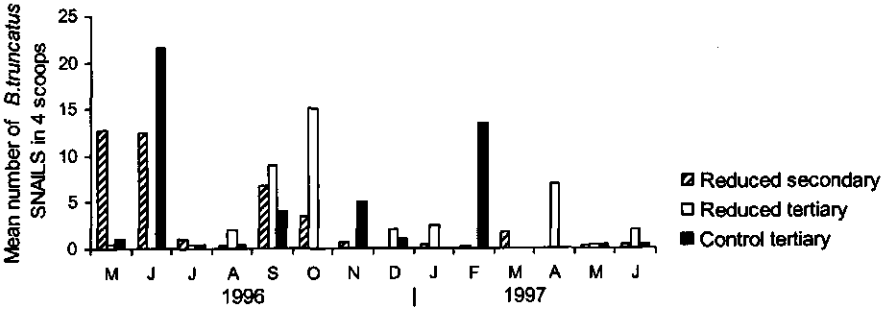


Figure 7.15. SNAILS of *Bulinus truncatus* in secondary and tertiary siphon boxes near Ouled Naceur *after a reduction of the physical dimensions in May 1996. The snail densities in the* secondary and tertiary intervention sites as well as in the control site are low and erratic. No clear seasonal patterns can be detected, nor any differences between the intervention and control sites.

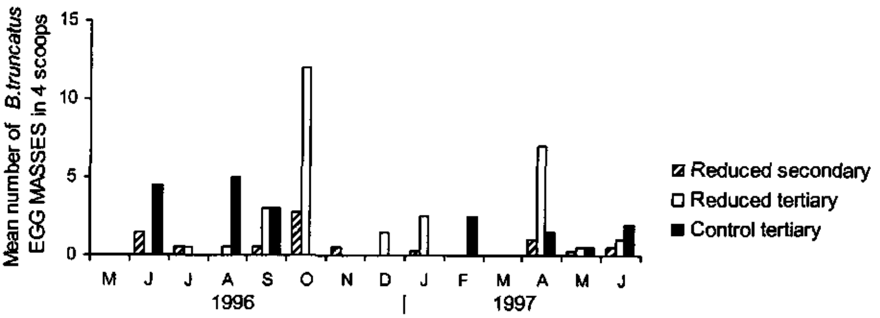


Figure 7.16. EGG MASSES of *Bulinus truncatus* in the secondary and tertiary siphon boxes near Ouled Naceur after a reduction of the physical dimensions in May 1996. The egg densities in the secondary and tertiary intervention sites as well as in the control site are low and erratic. No clear *seasonal patterns can be detected, nor any differences between the intervention and control sites.* In the tertiary modified siphon more eggs were found than in the control site.

7.2.4. Changing the lay out of the irrigation system

From the intervention studies in Sub-section 7.2.3 to reduce the dimensions of siphons in the Tessaout Amont irrigation system, it has become clear that *a* $\overline{v_a}$ *= 0.042 m/s is not the critical mean annual velocity that can be used in practice to control* Bulinus truncatus *in inverted siphons*. Perhaps the *value* of 0.042 m/s is too low. If this value as proposed by Jones (1993) would be doubled, then $\overline{v_c}$= 0.084 m/s. With the same flow regime (Q = 0.03 m^3/s for 10% of the time), the required $v = 0.84$ m/s. Even if the flow regime would change and the frequency and duration of the irrigation water flow would be reduced, while Q remains 0.03 m^3/s, a $v = 0.84$ m/s should be largely sufficient to flush out all silt and snails even during a short period. In order to obtain this $v_f = 0.84$ m/s, the siphon boxes would have to be reduced to an $A = 0.035$ $m^2 = 0.175$ m * 0.2 m (Figure 7.17). Then $\Delta H = 0.174$ m (Appendix V.5) and for an average tertiary canal with 12 siphons $\Delta H_{tot} = 12 * 0.174 = 2.09$ m. This implies that *the existing siphons cannot be modified, or else the area beyond the fourth siphon, i.e. 67% of the fields, can no longer be irrigated,* unless pumps are used.

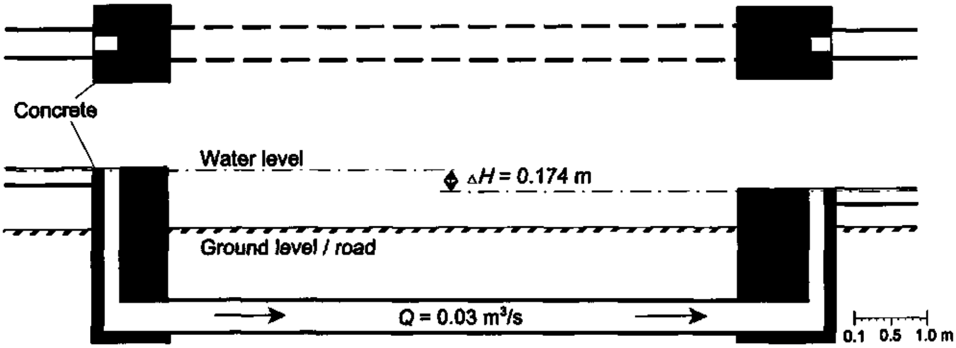


Figure 7.17. *Theoretical standard tertiary inverted siphon with much reduced dimensions* to convey a $Q = 0.03$ m^3/s with a $v = 0.86$ m/s. The inner dimensions of both siphon boxes are 0.175 m * 0.2 m.

For the promising theoretical alternative U-shaped siphon, a higher $\overline{v_c} = 0.084$ m/s causes a similar hydraulic disadvantage. *With a pipe diameter of 0.2 m (Figure 7.18), $\Delta H = 0.131$ m (Appendix V.6) and the water level at the canal head should be $\Delta H_{tot} = 12 * 0.131 = 1.57$ m higher than is required at the tail.* Though this is less disadvantageous than the siphon with reduced dimensions, in most of the Moroccan topography, still U-shaped siphons with a 0.2 m pipe are unrealistic.

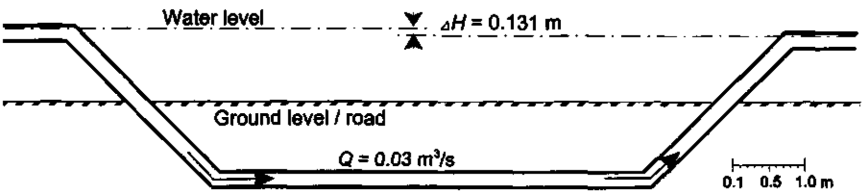


Figure 7.18. *Theoretical narrow alternative U-shaped siphon* to convey a $Q = 0.03$ m^3/s with a $v = 0.96$ m/s. The diameter of the pipe is 0.2 m.

Unless the true value of $\overline{v_c}$ is carefully established from experimentation with different inner dimensions of the siphons under field conditions, present recommendations for schistosomiasis control can only provide a kind of estimated value of $\overline{v_c}$. As flow regimes are influenced by many factors other than disease control, it may be wise to apply a safety factor and assume a low frequency *f* of a low flow rate Q. However, a double value of $\overline{v_c}$ already results in very high energy head losses ΔH. The alternative reduced and U-shaped siphons that have been proposed on the basis of $\overline{v_c}$= 0.084 m/s have decisive hydraulic disadvantages over the presently used siphons with two square boxes. *These rather extreme types of inverted siphon however, will make snail development, water contamination as well as water contact practically impossible.*

Siphons that have a high energy head loss of $\Delta H > 0.10$ m, can still be applied in Moroccan open canal gravity irrigation systems, but only if their number is reduced. This requires a totally different layout that could be implemented in new irrigation systems or if drastic rehabilitations are planned only.

In the present irrigation systems in Morocco, access to the fields is provided from both the canal and the drain sides (Figure 7.19). *It is the access from the canal side that requires many tertiary inverted siphons. If the main access roads were restricted to the drain side, the number of siphons could be reduced drastically* (Figure 7.20). Access from the drain side can be facilitated by building bridges, that are cheaper than the construction of siphons (El Yadouni 1995). Even if access roads by the secondary canals are maintained and only the roads along the tertiary canals are relocated, 70 percent less siphons would be required (Jones 1993). *This would allow the inclusion of alternative siphons that are prevent snail development as well as water contact. An alternative lay out of modern open canal irrigation systems in Morocco would provide more opportunities for envrionmental disease control than the present systems.*

7.3. CONCLUSIONS

For the tertiary siphon boxes that are the main transmission sites for urinary schistosomiasis in modern Moroccan open canal irrigation systems, several control options have been analyzed, theoretically as well as experimentally in the Tessaout Amont irrigation system.

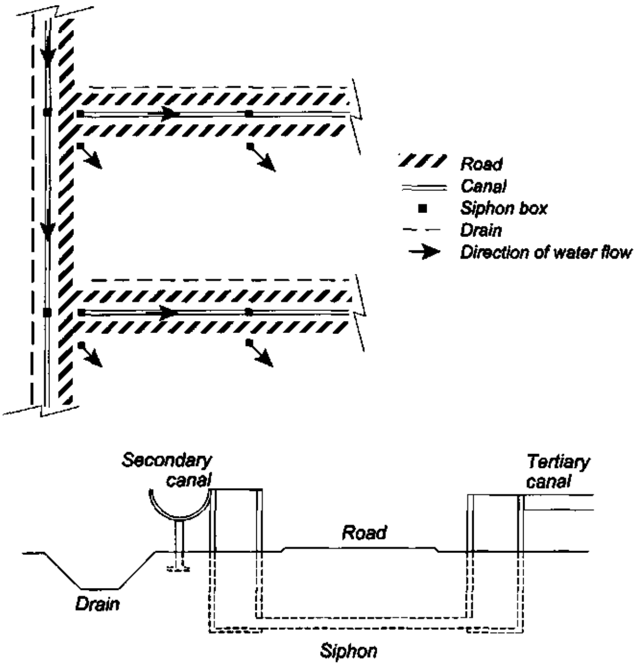


Figure 7.19. *Present* layout of Moroccan open canal irrigation systems (not to scale, after Jones 1994).

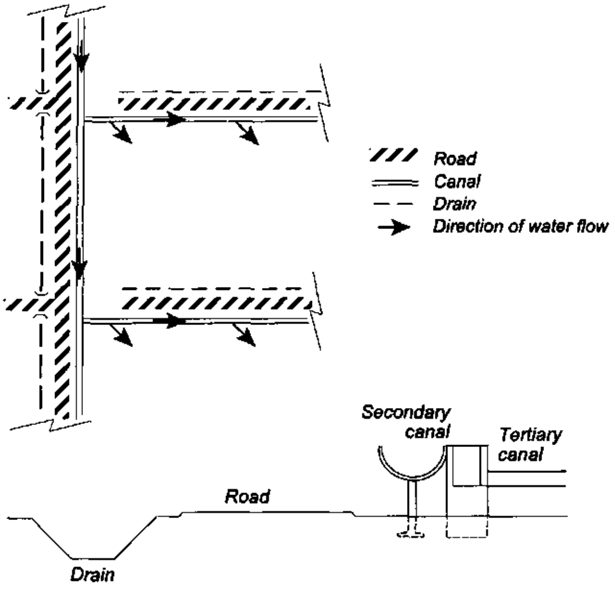


Figure 7.20. *Alternative* layout of Moroccan open canal irrigation systems (not to scale, after Jones 1994).

The periodic removal of the silt layer from the inverted siphons could help to control *Bulinus truncatus*, especially if the snail itself is removed mechanically too. In earlier brushing experiments this proved successful, but a later intervention consisting of emptying the siphons and removing the mud and stones from the bottom of the boxes was insufficient. The measure was carried out with the local water users association. Three times emptying and cleaning during the irrigation season had a limited immediate effect on *B.truncatus* snails and egg masses. The intervention could not keep the snail density low for a long period. More frequent emptying however, would require repeated inputs from a community that perceives no immediate benefit from these efforts.

A dark environment would reduce the available food resources and thus indirectly control *B.truncatus* populations, as was shown in laboratory experiments. The existing tertiary inverted siphons around a village in the Tessaout Amont irrigation system have been turned into dark environments by covering the siphon boxes with iron plates. Some of the iron plate covers were equipped with a moveable lid to leave the water in the siphon accessible to the villagers for domestic purposes. Covering was shown to be very effective in reducing *B.truncatus* populations, as both snails and egg masses were substantially reduced after the installation of the iron covers. The snails and egg masses of *B.truncatus* were also significantly lower in the covered siphon boxes than in control sites in the same year. Human water contact was reduced in the village and probably water contamination as well. The residents appreciated the covers and additionally reported a decrease in mosquitoes.

It was observed that the aquatic snails other than *B.truncatus* very rapidly built up to pre-intervention densities in the siphons. This can probably be explained by the higher vulnerability of the snail host for disturbances or through the indirect effect of reductions in the availability of the preferred food resources for *B.truncatus*.

Based on measurements in the Tessaout Amont irrigation system, Jones (1993) identified a critical mean annual water flow velocity in siphon boxes of $\overline{v_c}$= 0.042 m/s, below which no *B.truncatus* snails were found. Theoretically, adaptations in present standard inverted siphons or alternatively shaped siphons could be conceived that obtain a $\overline{v_c}$= 0.042 m/s with a flow rate Q of 0.03 m^3/s, the usual *main d'eau* in Morocco, flowing for 10% of the time. In practice however, this $\overline{v_c}$ value may not be sufficient. The boxes of 3 siphons in the Tessaout Amont irrigation system have been modified with concrete blocks, reducing their inner dimensions with 30% and creating a $\overline{v_c}$= 0.042 m/s. The modified siphons were repopulated very quickly however, and *B.truncatus* snails and egg masses were present within a month. If the $\overline{v_c}$ were doubled to a mean annual water flow velocity of 0.084 m/s, theoretical modified or alternative inverted siphons would have high energy head losses.

It could be that the critical value of $\overline{v_c}$ = 0.042 m/s is not high enough. Moreover, the concept of a mean annual flow velocity itself still needs more investigation. The general idea of a mean long term velocity limiting the development of *B.truncatus* populations has been confirmed in the length profile study in Section 6.2. However, the calculation of $\overline{v_a} = \Sigma vf$ might be too simple a model for the entire irrigation environment. Separate formulas might be required for larger and smaller secondary canals, for secondary and for tertiary inverted siphons and for other hydraulic structures.

In new open canal irrigation systems in Morocco, or if drastic rehabilitations are planned, a different system layout should be developed. The common access to the fields parallel to and crossing the canal should be changed in access from the drain side. The number of required inverted siphons would then be reduced substantially, which allows for other designs of siphons with higher flow velocities that prevent the development of *B.truncatus* as well as water contact. These alternative siphons are much less likely to become schistosomiasis transmission sites.

In existing Moroccan irrigation systems, covering the siphon boxes with iron plates might be the best environmental measure against schistosomiasis. At locations where water use from siphons is frequent, the covers can be equipped with moveable lids, provided that the users assume responsibility for closing the lids after each use. However, iron covers are expensive and if funds are limited, preference should be given to sites with high snail densities and intensive water use. At water use sites with low snail densities, the summer peak might be prevented by brushing the inner walls of the siphon box during the irrigation water flow to remove the snails, egg masses and the silt layer.

SUMMARY AND CONCLUSIONS

The impacts of irrigation and water resources development on health have been extensively reviewed in the literature. Most of the reported negative health impacts consist of water-related parasitic diseases such as malaria and schistosomiasis. Insight into the mechanisms of increased disease transmission is mostly restricted to the identification of certain critical characteristics. These features of irrigation systems would foster vector breeding or enhance human exposure. Less studied is the influence of irrigation development on health when the water, destined at agricultural crops, is used for other purposes. This may have positive as well as negative health impacts and is influenced by the availability of other water resources. An integrated concept is needed to consider the irrigation system as a separate dynamic man-made environment, used and influenced by people and interacting with parasites and vectors of disease.

The complex interactions between irrigation and health impacts can best be studied with the concept of *irrigation ecology*. In this thesis irrigation ecology is conceptualized as *an overall view for the analysis of health or other environmental impacts in irrigation systems. By distinguishing human, biological and irrigation environments, complex interactions can be identified in the overlap between the three of them.* These interactions determine whether a situation can develop that is favourable to the transmission of water-related diseases.

In an inter-disciplinary and inter-sectoral approach, the concept of irrigation ecology has been applied to a specific problem, the transmission and control of schistosomiasis in Morocco. Urinary schistosomiasis, the only form present in Morocco, is a parasitic disease, caused by the trematode worm *Schistosoma haematobium*, that needs the fresh water snail *Bulinus truncatus* as an intermediate host. The snail host lives in the water bodies within irrigation systems. People can acquire the disease through agricultural, domestic or recreational water contact. In absence of sanitation, infected persons may maintain the transmission by excreting worm eggs with their urine into the irrigation system.

In Morocco, the transmission of schistosomiasis has increased with the development of modern open canal irrigation systems. The Ministry of Health has been able to counteract this expansion with an effective National Schistosomiasis Control Programme. However, the risk of transmission is still present as the abundant breeding sites for *B.truncatus* are present in many irrigation systems. Within the overlap between the human, biological and irrigation environments in *irrigation ecology*, environmental control options have been identified to achieve a reduction of the transmission and eventually to eliminate the disease.

The oasis of Akka in southern Morocco is briefly presented as an example of the historical transmission sites for urinary schistosomiasis. Despite the availability of other water sources, many water use activities result in contact with snail breeding sites in the river bed. The transmission of schistosomiasis continues today, although at a low level. In this region, environmental control combined with health education might be the best schistosomiasis control strategy, as reflected in suggestions by the residents of three villages, obtained from a rapid rural appraisal. The appraisal has increased and activated the awareness of schistosomiasis and the communities in Akka oasis have already implemented some of their own recommendations.

Tessaout Amont

In Central Morocco, the Tessaout Amont irrigation system is an example of the construction of a large modern open canal irrigation system that has introduced urinary schistosomiasis into the Haouz plain, where there is already a long tradition of irrigation. The Tessaout Amont irrigation system has a typical Moroccan layout with upstream flow control and is entirely gravity-fed. Open trapezoidal primary canals supply water to elevated semi-circular concrete secondary and tertiary canals. At road crossings and at canal outlets, inverted siphons have been constructed to convey water below a road or track. These siphons consist of two square boxes connected by an underground pipe.

Water use, and water contact with it, in Tessaout Amont is regulated by the availability of water sources in the irrigation environment. In areas where the groundwater is deep, the rural population depends on the irrigation system to provide them with water for domestic purposes, which they sometimes store in reservoirs. Water allocation to meet crop water requirements and match water availability requires a rotational water distribution. This causes an almost permanent low flow in secondary canals and intermittent flow in tertiary canals, which completely dry out between irrigations. Nevertheless, most hydraulic structures remain filled with water. This standing water, in inverted tertiary siphons and other hydraulic structures, may be the only water source at hand for people living at some distance from a secondary canal.

Differences between the sources of water, with respect to quality, quantity and accessibility, determine the participation of different sex-age groups in the collection of water and in other water contact activities. As a result, exposure to possibly infective water and the consequent micro-epidemiology of schistosomiasis may contrast significantly between sex-age groups and between villages.

A cross-sectional snail survey in the Tessaout Amont irrigation system showed that *B.truncatus* was common in most sites, but was only sporadically (0.06%) infected with *S.haematobium*. *B.truncatus*, the intermediate snail host, was most frequently found in high densities in the numerous tertiary inverted siphons. The snail host was positively correlated with water depth and thickness of the silt layer, though the latter was biased by a few high density samples from drains. The preference of *B.truncatus* for tertiary siphon boxes could be explained by the availability of food resources in the form of microscopic algae, as stimulated by long periods of stagnation, evaporation and water use.

The different characteristics that make the siphon boxes ideal breeding sites for *B.truncatus* are inter-related and appear to depend on irrigation design, water management and water use activities. The relative location of hydraulic structures downstream of the canal head determines the exposure of each site to the rotational water flow. Both frequency and velocity of the water flow are higher in upstream parts of canals than in downstream reaches. An ecological length profile study was carried out of one secondary canal and four of its tertiaries to provide more information on location-specific characteristics of breeding sites for *B.truncatus*. This way, one ecological unit could be analyzed while minimizing the variability of other factors.

In the secondary canal, *B.truncatus* snails were collected in structures located at the terminal part of the canal only. The thickness of the silt layer, the algal cover and the degree of cover by macrophytes increase with distance from the head of the secondary canal. However, none of these characteristics is significantly correlated with *B.truncatus*.

In the tertiary canals the density of *B.truncatus* increased from the head end to the tail end of the canal. The highest frequencies and densities of the intermediate snail host were found in tertiary siphon boxes. Densities in the downstream tertiary and quaternary siphon boxes were significantly higher than in upstream boxes, probably because of differences in turbulence. The siphons are equally appropriate for the *S.haematobium* parasite, which may find a final human host through frequent water use activities at the siphon boxes. The tertiary inverted siphon has been conclusively identified as the main transmission site for urinary schistosomiasis in modern Moroccan open canal irrigation systems. The siphon provides a good starting point for focussed environmental schistosomiasis control to reduce snail host populations, water contact and water contamination. Several control options have been analyzed, theoretically as well as experimentally in the Tessaout Amont irrigation system.

An intervention consisting of emptying and cleaning all siphons three times around a village had a limited effect on *B.truncatus* snail and egg mass densities. The intervention could not suppress the snail population for long. More frequent emptying would require repeated inputs from a community that perceives no immediate benefit from these efforts.

Laboratory experiments have shown that a dark environment indirectly controls *B.truncatus* populations by reducing the available food resources. The tertiary inverted siphons around a village in the Tessaout Amont irrigation system have been turned into dark environments by covering the siphon boxes with iron plates. Some of the iron plate covers were equipped with a moveable lid to allow the villagers access for domestic purposes. Covering was shown to be very effective in decimating *B.truncatus* populations. Human water contact was reduced in the village and water contamination as well. The residents appreciated the covers and additionally reported a decrease in mosquitoes.

It was observed that aquatic snails other than *B.truncatus* very rapidly built up to pre-intervention densities in the siphons. This can probably be explained by the higher vulnerability of the snail host to disturbances, or through the indirect effect of reductions in the availability of the preferred food resources for *B.truncatus.*

Based on measurements in the Tessaout Amont irrigation system, Jones (1993) identified a critical mean annual water flow velocity in siphon boxes of $\overline{v_c}$ = 0.042 m/s, above which no *B.truncatus* snails were found. Theoretically, adaptations to the standard inverted siphons or alternatively shaped siphons could be conceived that obtain a $\overline{v_c}$ = 0.042 m/s with a flow rate Q of 0.03 m^3/s, the usual *main d'eau* in Morocco, flowing for 10% of the time. In practice however, this $\overline{v_c}$ value may not be sufficient. The boxes of 3 siphons in the Tessaout Amont irrigation system have been modified with concrete blocks to reduce their inner dimensions and create a $\overline{v_c}$ = 0.042 m/s. The modified siphons were repopulated very quickly and *B.truncatus* snails and egg masses were present within a month. If the $\overline{v_c}$ were doubled to a mean annual water flow velocity of 0.084 m/s, modified or alternative inverted siphons would have high energy head losses. These siphons could only be installed in a new layout of the Moroccan open canal irrigation systems.

The idea of a mean annual flow velocity needs more investigation. The general idea of a mean long term velocity limiting the development of *B.truncatus* populations has been confirmed in the length profile study. There, intermittent and low flow was shown to favour the development of snail host populations in hydraulic structures. The calculation of $\overline{v_c}$ as Σvf, the weighted average velocity, might be too simple a model for the entire irrigation environment. Separate formulas might be required for larger and smaller secondary canals, for secondary and for tertiary inverted siphons and for other hydraulic structures.

Recommendations

In many irrigated areas in Morocco, people literally depend on the irrigation system to provide them with water for domestic purposes, in traditional areas as well as in modern irrigation systems. The provision of an alternative water supply for consumption and for other purposes such as laundry and recreation, may substantially change present water contact behaviour. Rural water supply in sufficient quantities is thus an important measure in achieving environmental control of schistosomiasis and, probably, other water related diseases.

In existing Moroccan irrigation systems, covering the siphon boxes with iron plates was shown to be the best environmental measure against schistosomiasis. At locations where water use from siphons is frequent, the covers can be equipped with moveable lids, provided that the users assume responsibility for closing the lids after each use. However, iron covers are expensive and if funds are limited, preference should be given to sites with high snail densities and intensive domestic water use. At water use sites with low snail densities, the summer peak might be prevented by brushing the inner walls of the siphon box during the irrigation water flow to remove *B.truncatus* snails, egg masses and the silt layer.

Morocco's agricultural policy partly depends on expanding the irrigated area to the full potential by 2020, largely based on the current designs. Outbreaks of schistosomiasis could be prevented by incorporating environmental snail control measures in new irrigation systems. The standard layout should be modified by changing the common access to fields, parallel to and crossing the canal, into access from the drain side. The number of required siphons would thus be reduced substantially, which allows for other designs of siphons that control *B.truncatus* populations, requiring higher energy head losses to create high flow velocities. These alternative siphons are much less likely to become schistosomiasis transmission sites. However, a reduction in the number of siphons will diminish the quantity of water available for domestic purposes and alternative safe and sufficient water supply would also have to be integrated in the new irrigation environment.

The concept of *irrigation ecology* has been crucial in the identification of the important elements of schistosomiasis transmission in a Moroccan irrigation environment. Within this inter-disciplinary and inter-sectoral approach, rapid rural appraisal techniques may be useful in an initial phase, to help determine the relevant elements and interactions in the overlapping environments. From the analysis of the Moroccan situation and the interventions, implemented in the Tessaout Amont irrigation system, it is not possible to make a blue print for schistosomiasis control in other irrigation systems around the world. A specific advantage in Morocco is the effective schistosomiasis control programme that preceded the research on environmental control options. The general conclusion for environmental control in irrigation systems is that only locally obtained insights in the irrigation ecology of a particular disease can lead to effective and appropriate measures.

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APPENDICES

APPENDIX I - FRAME FOR INTERSECTORAL COLLABORATION PROPOSED BY THE MOROCCAN MINISTRY OF HEALTH

The following text is a personal translation of the chapter Collaboration intersectorielle in DEPS 1994:

"The actions by the Minister of Health on the reservoir of parasites and intermediate hosts will not be effective without the implication of other ministerial departments whose activities have an impact on the components of the problem. This concerns mainly the Ministry of Agriculture (MAMVA), the Ministry of Public Works (MTP), the Ministry of Education (MEN) and the Ministry of Interior and Information (i.e. local authorities and communities). Considering the tasks of these departments, their support as partners to the process of schistosomiasis elimination the Ministry of Health has committed itself to, is highly recommended to sustain its actions. The following fields of intervention have been identified:

Local communities and authorities

- Mobilise the population as usual, to facilitate mass health interventions;
- Support the public health actions by a contribution of logistical means and by taking care of the health team;
- Release credits for maintenance and cleaning of canals and ponds;
- Promote drinking water supply in the villages in order to reduce man-water contact (mobilization and organisation of water supply and distribution points such as wells, springs and public taps);
- Promote sanitation facilities and excavation of excreta and waste water.

Ministry of Agriculture

- Take the problem of schistosomiasis into account in the planning, design and implementation of irrigation systems;
- Maintain irrigation systems regularly (cleaning of canals, siphons etc);
- Spread, through agricultural extension workers, educational messages to the population to protect oneself against the disease;
- Participate in the execution of important drainage works and/or in the selection of suitable plants for the drying of water logged areas.

Ministry of Public Works
- Take the technical opinion of health authorities into account in each study on the health impact of dams;
- Participate in the application of preventive measures, adaptations and maintenance at water reservoirs and water courses to limit the establishment of intermediate snail hosts or to minimise the risk of disease transmission;
- Participate in important drainage and/or filling works that necessitate the use of Public Works machinery;
- Develop more drinking water supply programmes in endemic regions.

Ministry of National Education
- Communicate the total number of pupils in each grade to local health services at the start of the new school year;
- Facilitate access to schools to public health agents for the organization of case detection campaigns and treatment of infested pupils;
- Teach the planned course on schistosomiasis in the basic teaching programme each year;
- Organize training sessions at schools during case detection campaigns."

The above mentioned assignments partly build on existing fields of collaboration (Bennis & Bennouna 1995), but most of these are proposed for the first time by the Ministry of Health. With this initiative a basic condition for successful collaboration has been fulfilled: the presence of a formalized framework in the responsible ministry. Other conditions can be identified, such as mutual interests, a common understanding of the problem, and concrete activities.

APPENDIX II - SNAIL SAMPLING METHODOLOGY

For the sampling of snail populations in concrete irrigation canals and hydraulic structures, a drag scoop was used. The scoop consisted of a frame (0.1 * 0.1 m) supporting a wire mesh (0.8 mm) mounted on a 2 m long handle. It was used in siphon boxes and other deep structures to scrape the wall from the bottom to the surface on each side, thus scraping number of sides * 0.2 * water depth (m^2). For each sampling site in the canals, the bottom was scraped from the middle to the edge using the scoop at three positions with 1 m intervals.

The underlying assumption for this sampling technique is that in concrete habitats fresh water snails are restricted to the under water walls of the structure or canal, with only a few individuals floating on the water surface or hidden on the bottom. However, moderate numbers of snails were observed in the structures on floating organic material, especially reed leaves. These snails were included in the sample only when the floating material was accidentally captured in the drag scoop.

From the scooped number of snails, for each species the density in number of individuals/m^2 was calculated by dividing the number in the scoop by the sampled surface. Additionally, for siphon boxes in the length profile study, an estimation of the total snail population in the siphon was made.

In order to test the validity of the drag scoop method, a total snail count at the two boxes of a siphon on the tertiary canal RG1T9 was done on the 22th of April 1995. First a normal sample was taken in each of the two boxes. The snails were identified and counted on the spot. Then the siphon was emptied and all snails were removed. Most egg masses were left on the walls and counted from within the siphon box. The thick layer of mud on the bottom of the siphon was sieved and checked for snails as well. Now the estimated densities and total population of each snail species as based on the drag scoop sample could be compared with the *true* snail population in the box.

The real *density* in the siphon box has been calculated by dividing the total number of snails by the total under water surface of the walls and bottom (Table II.1). Similarly, the total *population* of snails in the box has been estimated by multiplying the number of snails in the drag scoop by the inner circumference of the box and divide this by the sampled width (Table II.2).

Table II.1. Sampled and total DENSITY (individuals/m^2) of snails in the tertiary siphon boxes RG1T9P18 and RG1T9P19 in the Tessaout Amont irrigation system.

	UPSTREAM BOX RG1T9P18		DOWNSTREAM BOX RG1T9P19	
SNAIL SPECIES	Sampled	Total	Sampled	Total
B.truncatus	24.2	18.4	39.3	84.5
L.peregra	3.5	4.4	0	1.7
L.truncatula	0.7	0.4	0	0
P.acuta	0	0	0	0.4
P.casertanum	0	84.2	0	2.3
All snails	28.3	107.4	39.3	89.4
Egg masses				
B.truncatus	26.2	143.6	24.6	100.6
L.peregra	4.8	2.4	2.9	1.9

Table II.2. Sampled and counted NUMBER of snails in the tertiary siphon boxes RG1T9P18 and RG1T9P19 in the Tessaout Amont irrigation system.

	UPSTREAM BOX RG1T9P18		DOWNSTREAM BOX RG1T9P19	
SNAIL SPECIES	Sampled	Counted	Sampled	Counted
B.truncatus	166	143	318	758
L.peregra	24	34	0	15
L.truncatula	5	3	0	0
P.acuta	0	0	0	4
P.casertanum	0	653	0	23
All snails	195	833	318	800
Egg masses				
B.truncatus	181	1114	200	903
L.peregra	33	19	24	17

The drag scoop seems unsuitable for the sampling of the bivalve snail *Pisidium casertanum*, because this species was found almost exclusively in the mud at the bottom of the siphon boxes. For *Bulinus truncatus* in siphon boxes the estimation of the total population seems a good indication of the true number of snails.

Later the experiment was repeated at two other siphons on the tertiary canal OGG2T0 in the same area of the Tessaout Amont irrigation system. Table II.3 shows the results in all siphon boxes for *B.truncatus* and the total snail population. Pearson's correlation coefficient between scooped and total population in the boxes was not significant for *Lymnaea truncatula* and could not be calculated for *Mercuria confusa* and *P.casertanum*. For all other species the correlation was significant (probability level $p<0.05$). For *B.truncatus* the correlation was highest

($p<0.01$); the estimated number of snails per siphon box appeared to be a slightly better indication of the true population than the use of density. For the total snail population this was opposite, while the predictive value of estimations based on the sample was less for all snails together than for *B.truncatus*. The drag scoop method has been compared to floating reed traps and a mark-recapture study in Laamrani et al (1999b).

Table II.3. Estimated (based on the Sample) and true (Total) snail populations in three siphons in the middle part of the Tessaout Amont irrigation system.

	DENSITY		NUMBERS OF SNAILS	
SIPHON BOXES	Sample	Total	Sample	Total
B.truncatus				
Upstream box RG1T9P18	24.2	18.4	166	143
Downstream box RG1T9P19	39.3	84.5	318	758
Upstream box OGG2T0P2	5.9	4.2	43	34
Downstream box OGG2T0P3	21.0	28.6	157	238
Upstream box OGG2T0P18	30.1	54.9	128	282
Downstream box OGG2T0P19	69.3	102.8	461	774
All snails[1]				
Upstream box RG1T9P18	28.3	23.2	195	180
Downstream box RG1T9P19	39.3	86.6	318	777
Upstream box OGG2T0P2	13.8	17.2	100	139
Downstream box OGG2T0P3	102.7	115.6	765	963
Upstream box OGG2T0P18	30.1	56.9	128	292
Downstream box OGG2T0P19	102.9	128.0	684	964

[1] All snails except *Pisidium casertanum*.

APPENDIX III - ADDITIONAL DATA FROM THE CROSS-SECTIONAL SNAIL SURVEY

In Section 6.1. data have been presented on *Bulinus truncatus*, 3 associated snail species and *Planorbarius metidjensis*. In this Appendix frequencies and densities of the other 4 snail species in the Tessaout Amont irrigation system are presented in the Tables III.1 and III.2 respectively. Details on the degree of vegetational cover can be found in Table III.3 for algae and in Table III.4 for macrophytes.

Table III.1. Frequencies of occurrence (%) of 4 snail species in 223 sampled habitats in the cross-sectional snail survey 1994/1995 in Tessaout Amont.

SAMPLED SITES	*Lymnaea truncatula*	*Melanopsis praemorsa*	*Mercuria confusa*	*Pisidium casertanum*
Primary canals	8	38	8	18
Secondary canals	8	46	21	21
Secondary siphons	4	3	4	9
Tertiary siphons	4	23		5
Quaternary siphons	18	18	18	9
Drains		17	8	17
Seguias	20	9	18	14
River Tessaout		20	20	

Table III.2. Mean snail density (individuals/m^2 in bold and standard deviation in small) of 4 snail species in 223 sampled habitats in the cross-sectional survey 1994/1995 in Tessaout Amont.

SAMPLED SITES	*Lymnaea truncatula*	*Melanopsis praemorsa*	*Mercuria confusa*	*Pisidium casertanum*
Primary canals	**2** 7.4	**15** 25.3	**0.3** 0.9	**1** 3.2
Secondary canals	**5** 23.5	**17** 45.8	**3** 9.7	**7** 20.9
Secondary siphons	**0.04** 0.18	**12** 47.3	**0.04** 0.2	**22** 104.2
Tertiary siphons	**0.1** 0.5	**13** 70.1	**0.3** 1.2	**3** 30.1
Quaternary siphons	**5** 15.1	**2** 6	**5** 13.8	**3** 9.5
Drains		**6** 17.8	**2** 5.8	**4** 9.1
Seguias	**0.5** 1.4	**15** 68.9	**10** 46.1	**2** 8.3
River Tessaout		**9** 19.4	**9** 19.4	

Table III.3. Frequency of occurrence (%) of 5 different classes of cover by algae in the cross-sectional snail survey 1994/95 in Tessaout Amont.

SAMPLED SITES	ABSENT	< 5 %	5 - 25 %	25 - 50 %	> 50 %
Primary canals	0	100			
Secondary canals	25	46	17	4	8
Secondary siphons	22	70	8		
Tertiary siphons	10	80	10		
Quaternary siphons	9	73	18		
Drains	17	58	8	17	
Seguias	27	55	18		
River Tessaout	0	60	20	20	

Table III.4. Frequency of occurrence (%) of 5 different classes of cover by macrophytes in the cross-sectional snail survey 1994/95 in Tessaout Amont.

SAMPLED SITES	ABSENT	< 5 %	5 - 25 %	25 - 50 %	> 50 %
Primary canals	85	15			
Secondary canals	54	25	13	8	
Secondary siphons	57	39			4
Tertiary siphons	41	47	9	2	1
Quaternary siphons	55	36	9		
Drains	33	9	17	33	8
Seguias	9	36	46	9	
River Tessaout	60		20		20

APPENDIX IV - ADDITIONAL DATA FROM THE LENGTH PROFILE STUDY

In Section 6.2. data from the length profile study have been presented on *Bulinus truncatus* only. In this Appendix frequencies (Table IV.1) and densities (Table IV.2) of the other snail species in Sector Dzouz are presented. In Table IV.3 the total snail population in siphon boxes is estimated. In addition, some data on habitat characteristics that have been summarized in Section 6.2, are displayed here in detail. The mean water depth in the sampled structures is mentioned in Table IV.4. Details on the degree of vegetational cover can be found in Table IV.5 for algae and in Table IV.6 for macrophytes.

Table IV.1. Frequency of occurrence (%) of 8 snails species in hydraulic structures on secondary canal RG7 and 4 tertiary canals RG7T2, RG7T7, RG7T15 & RG7T22 in Sector Dzouz.

SAMPLED SITES	N	*Lymnaea peregra*	*Lymnaea truncatula*	*Physa acuta*	*Ancylus fluviatilis*
Secondary canal RG7					
Upstream siphon box	17	35	12		
Downstream siphon box	19	74	21		
Long crested weir	21	47	32		
Division box	19	48	52	5	
Drop structure	6	50	83		
Tertiary canals					
Upstream siphon box	48	71	19	23	8
Downstream siphon box	48	83	23	38	10
Division box	14	21	7		
Drop structure	11	73		18	
Outlet	32	31	16	6	

SAMPLED SITES	N	*Melanopsis praemorsa*	*Mercuria confusa*	*Pisidium casertanum*
Secondary canal RG7				
Upstream siphon box	17	6		18
Downstream siphon box	19	21		5
Long crested weir	21	26	11	5
Division box	19	67	38	24
Drop structure	6	50		
Tertiary canals				
Upstream siphon box	48	42	4	4
Downstream siphon box	48	56	6	4
Division box	14	29	14	7
Drop structure	11	55		9
Outlet	32	13	3	

Table IV.2. Mean densities of 8 snail species in hydraulic structures in Sector Dzouz.

SAMPLED SITES	N	*Lymnaea peregra*	*Lymnaea truncatula*	*Physa acuta*	*Ancylus fluviatilis*
Secondary canal RG7					
Upstream siphon box	17	2.5	2.1		
Downstream siphon box	19	11.0	0.4		
Long crested weir	14	63.5	14.1		
Division box	18	143.3	44.9	6.9	
Drop structure	6	10.0	8.2		
Tertiary canals					
Upstream siphon box	48	22.7	0.4	3.1	0.8
Downstream siphon box	48	35.6	0.5	5.0	0.8
Division box	11	4.2	0.5		
Drop structure	11	41.5		0.4	
Outlet	14	14.6	16.8	3.2	

SAMPLED SITES	N	*Melanopsis praemorsa*	*Mercuria confusa*	*Pisidium casertanum*
Secondary canal RG7				
Upstream siphon box	17	0.1		0.2
Downstream siphon box	19	3.5		0.1
Long crested weir	14	4.6	1.0	0.3
Division box	18	175.2	25.9	91.3
Drop structure	6	113.4		
Tertiary canals				
Upstream siphon box	48	6.8	0.1	0.6
Downstream siphon box	48	6.3	0.3	0.0
Division box	14	33.9	10.0	8.2
Drop structure	11	42.8		1.9
Outlet	14	9.6	7.4	

Table IV.3. Average estimated number of snails in siphon boxes in Sector Dzouz.

SAMPLED SITES	N	*Lymnaea peregra*	*Lymnaea truncatula*	*Physa acuta*	*Ancylus fluviatilis*
Secondary upstream box	16	12	7		
Secondary downstream box	20	116	4		
Tertiary upstream box	49	87	2	8	1
Tertiary downstream box	42	176	3	12	5
Quaternary downstream box	8	156	6	76	1

SAMPLED SITES	N	*Melanopsis praemorsa*	*Mercuria confusa*	*Pisidium casertanum*
Secondary upstream box	16	1		1
Secondary downstream box	20	11		2
Tertiary upstream box	49	28	0	2
Tertiary downstream box	42	43	2	0
Quaternary downstream box	8	35		

Table IV.4. Mean water depth (m) in sampled structures in Sector Dzouz.

SAMPLED SITES	N	RG7	T2	T7	T15	T20	T22
Upstream siphon box	66	1.94	1.32	1.50	1.40	0.80	1.36
Downstream siphon box	71	1.81	1.21	1.13	1.48	1.09	1.47
Long crested weir	15	0.21					
Division box	28	0.30	0.30	1.10	0.50		
Drop structure	14	0.75	0.42	0.30	0.45	0.30	0.20
Outlet	5		0.12	0.16	0.04		0.72

Table IV.5. Frequency of occurrence (%) of 4 different classes of cover by algae in hydraulic structures in Sector Dzouz.

SAMPLED SITES	N	ABSENT	< 5 %	5 - 25 %	25 - 50 %
Secondary canal RG7					
Upstream siphon box	17	6	88		6
Downstream siphon box	20		90	10	
Long crested weir	15	7	67	27	
Division box	19	11	63	26	
Drop structure	5		67	33	
Tertiary canals					
Upstream siphon box	49	2	71	27	
Downstream siphon box	51	6	71	20	4
Division box	9		55	33	11
Drop structure	8		63	38	
Outlet	5	20	40	40	

Table IV.6. Frequency of occurrence (%) of 4 different classes of cover by macrophytes in hydraulic structures in Sector Dzouz.

SAMPLED SITES	N	ABSENT	< 5 %	5 - 25 %	> 25 %
Secondary canal RG7					
Upstream siphon box	17	71	29		
Downstream siphon box	20	80	20		
Long crested weir	15	80	7	13	
Division box	19	63		11	26
Drop structure	6	67	33		
Tertiary canals					
Upstream siphon box	49	47	49	4	
Downstream siphon box	51	57	33	10	
Division box	8	44	44	12	
Drop structure	8	63	37		
Outlet	5	60		20	20

APPENDIX V - ENERGY HEAD LOSS CALCULATIONS FOR TERTIARY INVERTED SIPHONS

The *equations in this Appendix have been applied to different* types *of siphons*, according to Idel'cik (1969). The basic lay out of an inverted siphon with streamlines is presented in Figure V.1. For each calculation, the applied equation is displayed when it is used for the first time and later its number is indicated at the right margin. For some of the factors used in the equation, the values have been established experimentally by Idel'cik (Tables V.1, V.2 and V.3).

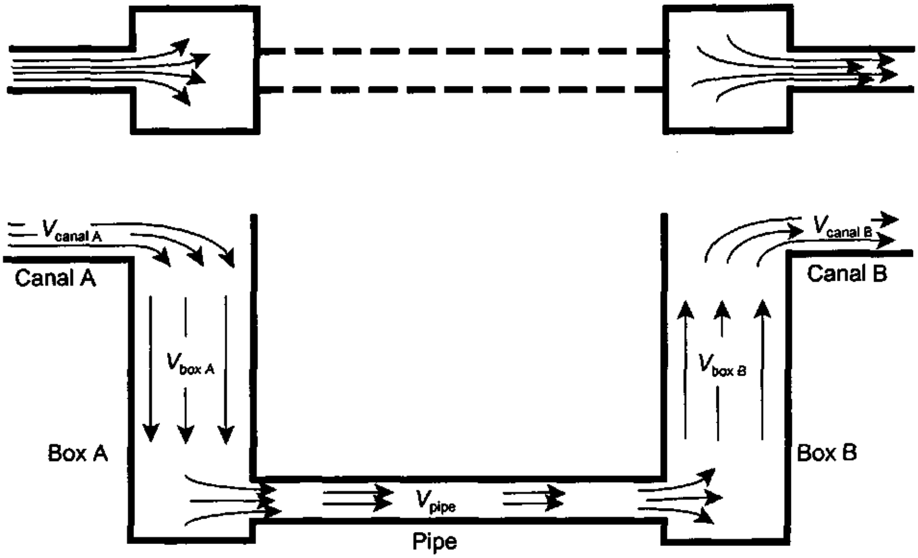

Figure V.1. Diagram of an inverted siphon with bending, diverging and converging streamlines (not to scale).

Symbols used in this Appendix

A_0	Wetted area (m^2) before converging or diverging.
A_1	Wetted area (m^2) after converging or diverging.
b	Width (m) of conduit before the bend.
C_1	Constant factor depending on the ratio y/b (Table V.2).
C_2	Constant factor depending on the bend J(Table V.3).
J	Bend (°).
g	Accelleration due to gravity = 9.8 m/s^2.

k_n	Factor, calculated from Reynolds number RE, depending on the hydraulic roughness *n*.
k_{RE}	Factor, calculated from λ_{RE} (Table V.1).
l	Length (m) of conduit.
n	Hydraulic roughness (m) or mean height of irregularities of the conduit wall; $n = 0.0025$ m for armed concrete.
Q	Flow rate (m^3/s).
r	Radius (m) of circular conduits.
R'	Hydraulic diameter (m) = 4 * hydraulic radius; $R' = 2r$ for circular conduits and $R' = 2 \, [\, (y^*b) \, / \, (y+b) \,]$ for rectangular conduits.
RE	Reynolds number, depending on v, R' and υ.
s	Slope.
v	Mean water velocity (m/s), calculated as Q / A.
y	Water depth (m) in conduit before the bend.
ΔH	Energy head loss (m).
λ_{RE}	Factor, calculated from Reynolds number RE.
ρ	Specific mass (kg/m^3); $\rho = 1000$ kg/m^3 for water.
υ	Viscosity of water.
ζ_M	Constant factor depending on the bend J (Table V.3).

Table V.1. Determination of λ_{RE} (Idel'cik 1969).

RE			$2 \cdot 10^3$	$3 \cdot 10^3$	$4 \cdot 10^3$	$5 \cdot 10^3$	$6 \cdot 10^3$	$8 \cdot 10^3$
λ_{RE}			0.052	0.045	0.041	0.038	0.036	0.033
RE	10^4	$1.5 \cdot 10^4$	$2 \cdot 10^4$	$3 \cdot 10^4$	$4 \cdot 10^4$	$5 \cdot 10^4$	$6 \cdot 10^4$	$8 \cdot 10^4$
λ_{RE}	0.032	0.028	0.026	0.024	0.022	0.021	0.020	0.019
RE	10^5	$1.5 \cdot 10^5$	$2 \cdot 10^5$	$3 \cdot 10^5$	$4 \cdot 10^5$	$5 \cdot 10^5$	$6 \cdot 10^5$	$8 \cdot 10^5$
λ_{RE}	0.018	0.017	0.016	0.015	0.014	0.013	0.013	0.012
RE	10^6	$1.5 \cdot 10^6$	$2 \cdot 10^6$	$3 \cdot 10^6$	$4 \cdot 10^6$	$5 \cdot 10^6$		$8 \cdot 10^6$
λ_{RE}	0.012	0.011	0.011	0.010	0.010	0.009		0.009
RE	10^7	$1.5 \cdot 10^7$	$2 \cdot 10^7$	$3 \cdot 10^7$			$6 \cdot 10^7$	$8 \cdot 10^7$
λ_{RE}	0.008	0.008	0.008	0.007			0.007	0.007

Table V.2. Determination of C_1 (Idel'cik 1969).

y / b	C_1
0.25	1.10
0.50	1.07
0.75	1.04
1.0	1.00
1.5	0.95
2.0	0.90
3.0	0.83
4.0	0.78
5.0	0.75
6.0	0.72
7.0	0.71
8.0	0.70

Table V.3. Determination of ζ_M and C_2 (Idel'cik 1969).

J (°)	ζ_M	C_2
0	0	
20	0.05	2.50
30	0.07	2.22
45	0.17	1.87
60	0.37	1.50
75	0.63	1.28
90	0.99	1.20
110	1.56	1.20
130	2.16	1.20
150	2.67	1.20
180	3.00	1.20

For all calculations the same Reynolds number and associated values have been used:

RE = $Q/u = 0.03 / 10^{-6} = 3.00 \cdot 10^4$

λ_{RE} = 0.024 (Table V.1)

k_{RE} = $45\ \lambda_{RE} = 45 * 0.024 = 1.08$

$n_{armed\ concrete}$ = 0.0025 m

k_n (for $RE < 4 \cdot 10^4$) = 1,0

V.1. Standard tertiary siphon

Flow rate Q = 0.03 m^3/s

Canals A & B = ½ ⌀ 0.4 m, r = 0.2 m, s = 0.006, freeboard = 0.04 m

Upstream box A = 0.8 * 0.8 * 2 m^3 (inner dimensions)

Downstream box B = 0.8 * 1.1 * 2 m^3 (inner dimensions)

Pipe = 8 m, ⌀ 0.4 m, r = 0.2 m, s = 0.006

$A_{canal\,A} = A_{canal\,B}$ $= ½\pi r^2 - 2r * \text{freeboard} = ½\pi\ 0.2^2 - 2 * 0.2 * 0.04$

$= 0.0628 - 0.016 = 0.0468\ m^2$

$v_{canal\,A} = v_{canal\,B}$ $= Q / A_{canal\,A} = 0.03 / 0.0468 = 0.641$ m/s

$A_{box\,A}$ $= y\,b = 0.8 * 0.8 = 0.64\ m^2$

$v_{box\,A}$ $= Q / A_{box\,A} = 0.03 / 0.64 = 0.047$ m/s

$R'_{box\,A}$ $= 2\,[\,(y\,b) / (y + b)\,] = 2\,[\,(0.8 * 0.8) / (0.8 + 0.8)\,]$

$= 2\,(0.64 / 1.6) = 0.8$ m

A_{pipe} $= \pi r^2 = \pi\ 0.2^2 = 0.126\ m^2$

v_{pipe} $= Q / A_{\text{pipe}} = 0.03 / 0.126 = 0.239$ m/s
R'_{pipe} $= 2r_{\text{pipe}} = 2 * 0.2 = 0.4$ m
$A_{\text{box B}}$ $= y\,b = 1.1 * 0.8 = 0.88$ m^2
$v_{\text{box B}}$ $= Q / A_{\text{box B}} = 0.03 / 0.88 = 0.034$ m/s
$R'_{\text{box B}}$ $= 2\,[\,(y\,b) / (y + b)\,] = 2\,[\,(1.1 * 0.8) / (1.1 + 0.8)\,]$
$= 2\,(0.88 / 1.9) = 0.926$ m

$\boldsymbol{\Delta H_{\text{tot}} = 4\,\Delta H_{\varepsilon} + 4\,\Delta H_{\text{bending}} + 3\,\Delta H_{\text{friction}}}$

ΔH_{ε} (4x)

$$\Delta H_{outflow} = (1 - \frac{A_0}{A_1})^2 \frac{v^2}{2g} \tag{1a}$$

<u>From canal A into box A (diverging)</u>
$A_0 = A_{\text{canal A}} = 0.0468$ m^2
$A_1 = A_{\text{box A}} = 0.64$ m^2
$v = v_{\text{canal A}} = 0.641$ m/s
$\Delta H_{\text{outflow A}} = (1 - 0.0468/0.64)^2 * 0.641^2/19.6 =$
$0.0859 * 0.021 = 0.0180$ m

$$\Delta H_{inflow} = 0.5(1 - \frac{A_1}{A_0}) \frac{v^2}{2g} \tag{1b}$$

<u>From box A into pipe (converging)</u>
$A_0 = A_{\text{box A}} = 0.64$ m^2; $A_1 = A_{\text{pipe}} = 0.126$ m^2
$v = v_{\text{box A}} = 0.047$ m/s
$\Delta H_{\text{inflow pipe}} = 0.5\,(1 - 0.126/0.64) * 0.047^2/19.6 =$
$0.402 * 0.0001 = 0.00005$ m

<u>From pipe into box B</u> (1a)
$A_0 = A_{\text{pipe}} = 0.126$ m^2; $A_1 = A_{\text{box B}} = 0.88$ m^2
$v = v_{\text{pipe}} = 0.239$ m/s
$\Delta H_{\text{outflow pipe}} = (1 - 0.126/0.88)^2 * 0.239^2/19.6 = 0.734 * 0.003 = 0.0021$ m

<u>From box B into canal B</u> (1b)
$A_0 = A_{\text{box B}} = 0.88$ m^2; $A_1 = A_{\text{canal B}} = 0.0468$ m^2
$v = v_{\text{box B}} = 0.034$ m/s
$\Delta H_{\text{inflow B}} = 0.5(1 - 0.0468/0.88) * 0.034^2/19.6 = 0.473 * 0.00006 = 0.00003$ m

$\Delta H_{\varepsilon} = \Delta H_{\text{outflow A}} + \Delta H_{\text{inflow pipe}} + \Delta H_{\text{outflow pipe}} + \Delta H_{\text{inflow B}} = 0.0202$ m

Δ $\boldsymbol{H_{bending}}$ (4x)

$$\Delta H_{bending} = k_n k_{RE} C_1 C_2 \zeta_M \frac{v^2}{2g} \quad (2)$$

<u>1. From canal A into box A</u>

$v = v_{canal\ A} = 0.641$ m/s

$y / b = y_{canal\ A} / b_{canal\ A} = 0.16 / 0.4 = 0.4$

$C_1 = 1.08$ (Table V.2)

$\angle = 90°$; $\zeta_M = 0.99$ and $C_2 = 1.2$ (Table V.3)

$\Delta H_{bending\ 1} = 1.0 * 1.08 * 1.08 * 1.2 * 0.99 * (0.641)^2/19.6 = 0.0290$ m

<u>2. From box A into pipe</u> (2)

$v = v_{box\ A} = 0.047$ m/s

$y / b = y_{box\ A} / b_{box\ A} = 0.8 / 0.8 = 1$; $C_1 = 1$ (Table V.2)

$\Delta H_{bending\ 2} = 1.0 * 1.08 * 1 * 1.2 * 0.99 * (0.047)^2/19.6 = 0.00014$ m

<u>3. From pipe into box B</u> (2)

$v = v_{pipe} = 0.239$ m/s

$y / b = 1$; $C_1 = 1$

$\Delta H_{bending\ 3} = 1.0 * 1.08 * 1 * 1.2 * 0.99 * (0.239)^2/19.6 = 0.0037$ m

<u>4. From box B into canal B</u> (2)

$v = v_{box\ B} = 0.034$ m/s

$y / b = y_{box\ B} / b_{box\ B} = 1.1 / 0.8 = 1.375$; $C_1 = 0.98$ (Table V.2)

$\Delta H_{bending\ 4} = 1.0 * 1.08 * 0.98 * 1.2 * 0.99 * (0.034)^2/19.6 = 0.00007$ m

$\Delta H_{bending} = \Delta H_{bending\ 1} + \Delta H_{bending\ 2} + \Delta H_{bending\ 3} + \Delta H_{bending\ 4} = 0.0329$ m

Δ $\boldsymbol{H_{friction}}$ (3x)

The Darcy-Weissbach equation (3):

$$\Delta H_{friction} = \lambda_{RE} \frac{l}{R'} \cdot \frac{\rho v^2}{2g}$$

<u>Box A</u>

$R' = R'_{box\ A} = 0.8$ m

$l = l_{box\ A} = 2$ m

$v = v_{box\ A} = 0.047$ m/s

$\Delta H_{friction\ A} = 0.024 * 2/0.8 * 1 * (0.047)^2/19.6 = 0.0000068$ m

Box B (3)

$R' = R'_{\text{box B}} = 0.926$ m; $l = l_{\text{box B}} = 2$ m; $v = v_{\text{box B}} = 0.034$ m/s

$\Delta H_{\text{friction B}} = 0.024 * 2/0.93 * 1 * (0.034)^2/19.6 = 0.000003$ m

Pipe (3)

$R' = R'_{\text{pipe}} = 0.4$ m; $l = l_{\text{pipe}} = 8$m; $v = v_{\text{pipe}} = 0.239$ m/s

$\Delta H_{\text{friction pipe}} = 0.024 * 8/0.4 * 1 * (0.24)^2/19.6 = 0.00141$ m

$\Delta H_{\text{friction}} = \Delta H_{\text{friction A}} + \Delta H_{\text{friction B}} + \Delta H_{\text{friction pipe}} = 0.0014$ m

Total energy head loss through a standard tertiary siphon:

$$\begin{aligned} \Delta H_{tot} &= \Delta H_{\varepsilon} + \Delta H_{bending} + \Delta H_{friction} \\ &= \mathbf{0.0202} + \mathbf{0.0329} + \mathbf{0.0014} = \mathbf{0.0545\ m} \end{aligned}$$

V.2. Standard tertiary siphon with reduced dimensions to obtain *v* = 0.42 m/s

Discharge Q = 0.03 m^3/s
Canals A & B = ½ ⌀ 0.4 m, $r = 0.2$ m, $s = 0.006$
Box A = Box B = 0.2 * 0.35 * 2.0 m^3 (inner dimensions)
Pipe = 9.5 m, ⌀ 0.4 m, $r = 0.2$ m, $s = 0.006$

Total energy head loss through a standard tertiary siphon with reduced dimensions (v_{box} = 0.429 m/s):

$$\begin{aligned} \Delta H_{tot} &= \Delta H_{\varepsilon} + \Delta H_{bending} + \Delta H_{friction} \\ &= \mathbf{0.0064} + \mathbf{0.0550} + \mathbf{0.0052} = \mathbf{0.0666\ m} \end{aligned}$$

V.3. Alternative U-shaped tertiary siphon to obtain *v* = 0.42 m/s

Flow rate Q = 0.03 m^3/s
Canals A & B = ½ ⌀ 0.4 m, $r = 0.2$ m, $s = 0.006$
Pipe A = pipe B = 3 m, ⌀ 0.3 m (standard diameter), $r = 0.15$ m, $s = 1$
Horizontal pipe = 6 m, ⌀ 0.3 m (standard diameter), $r = 0.15$ m, $s = 0.006$

Total energy head loss through an alternative U-shaped tertiary siphon (v_{pipe} = 0.424 m/s):

$$\begin{aligned} \Delta H_{tot} &= \Delta H_{\varepsilon} + \Delta H_{bending} + \Delta H_{friction} \\ &= \mathbf{0.0040} + \mathbf{0.0172} + \mathbf{0.0088} = \mathbf{0.0300\ m} \end{aligned}$$

V.4. Alternative V-shaped tertiary siphon to obtain $v = 0.42$ m/s

Flow rate Q = 0.03 m^3/s
Canals A & B = ½ ⌀ 0.4 m, $r = 0.2$ m, $s = 0.006$
Pipe A = pipe B = 6 m, ⌀ 0.3 m (standard diameter), $r = 0.15$ m, $s = 1$

Total energy head loss through an alternative V-shaped tertiary siphon (v_{pipe} = 0.424 m/s):

$$\begin{aligned} \Delta H_{tot} &= \Delta H_{\varepsilon} + \Delta H_{bending} + \Delta H_{friction} \\ &= \mathbf{0.0040} + \mathbf{0.0227} + \mathbf{0.0088} = \mathbf{0.0355\ m} \end{aligned}$$

V.5. Standard tertiary siphon with reduced dimensions to obtain $v = 0.85$ m/s

Flow rate Q = 0.03 m^3/s
Canals A & B = ½ ⌀ 0.4 m, $r = 0.2$ m, $s = 0.006$
Box A = box B = 0.175 * 0.2 * 2.0 m^3 (inner dimensions)
Pipe = 9.5 m, ⌀ 0.4 m, $r = 0.2$ m, $s = 0.006$

Total energy head loss through a standard tertiary siphon with reduced dimensions (v_{box} = 0.857 m/s):

$$\begin{aligned} \Delta H_{tot} &= \Delta H_{\varepsilon} + \Delta H_{bending} + \Delta H_{friction} \\ &= \mathbf{0.0256} + \mathbf{0.1279} + \mathbf{0.0209} = \mathbf{0.1744\ m} \end{aligned}$$

V.6. Alternative U-shaped tertiary siphon to obtain v = 0.85 m/s

Flow rate Q	= 0.03 m^3/s
Canals A & B	= ½ ⌀ 0.4 m, r = 0.2 m, s = 0.006
Pipe A = pipe B	= 3 m, ⌀ 0.2 mm (standard diameter), r = 0.1 m, s = 1
Horizontal pipe	= 6 m, ⌀ 0.2 mm (standard diameter), r = 0.1 m, s = 0.006

Total energy head loss through an alternative U-shaped tertiary siphon (v_{pipe} = 0.955 m/s):

$$\begin{aligned} \Delta H_{tot} &= \Delta H_{\varepsilon} + \Delta H_{bending} + \Delta H_{friction} \\ &= 0.0084 + 0.0558 + 0.0670 = 0.1312 \text{ m} \end{aligned}$$

LIST OF USED TERMS, ABBREVIATIONS AND SYMBOLS

A	Wetted area (m^2).
Anopheles	Mosquito species that can be a vector of malaria.
AUEA	*Association des Utilisateurs des Eaux Agricoles*, Water Users Association, group of irrigating farmers responsible for operation and maintenance of their part of the irrigation system.
Bilharzia	Schistosomiasis.
Bulinus truncatus	Also abbreviated as *B.truncatus*, fresh water snail species that is the intermediate host of *Schistosoma haematobium* in Morocco.
Cercaria	Final larval stage of *Schistosoma* worm which emerges from the snail intermediate host, capable of infecting man or other mammals through the skin.
CMV	*Centre de Mise en Valeur*, agricultural exploitation centre.
DEPS	*Direction d'Epidémiologie et des Programmes Sanitaires (MSP)*, Department of Epidemiology in the Moroccan Ministry of Health.
ΔH	Energy head loss (m), energy lost as the result of friction or other forces (ICID 1996).
MAD	Moroccan currency, the dirham.
MAMVA	*Ministère d'Agriculture et de Mise en Valeur Agricole*, Moroccan Ministry of Agriculture.
MEN	*Ministère d'Education Nationale*, Moroccan Ministry of Education.
Metfia	Partly underground reservoir for the storage of (irrigation) water for domestic purposes.

Miracidium	Embryo larva of *Schistosoma* worm, hatched from the egg. It invades the body of a snail for multiplication.
MSP	*Ministère de Santé Publique*, Moroccan Ministry of Health.
MTP	*Ministère des Travaux Publics*, Moroccan Ministry of Public Works.
ONI	*Office National d'Irrigation*, National Irrigation Office in Morocco.
ORMVA	*Office Régionale de Mise en Valeur Agricole*, Regional Agricultural Office in Morocco.
ORMVAH	*ORMVA du Haouz*, Regional Agricultural Office for the Haouz Region, responsible for the Tessaout Amont irrigation system.
Prevalence	Rate of infection or proportion of the population with a disease. In the case of schistosomiasis, the proportion of individuals with *Schistosoma* eggs in their urine or faeces (WHO Expert Committee 1993).
p	Probability factor, should be below 0.05 for statistical significance.
Q	Flow rate (m^3/s).
Schistosomiasis	Also referred to as Bilharzia or snail fever. It is a chronic, debilitating parasitic disease caused by a trematode worm of the genus *Schistosoma*, with freshwater snails acting as intermediate hosts.
Schistosoma haematobium	Trematode worm that lives pair-wise in the veins around the human bladder and constantly produces eggs that are excreted with the urine, causing urinary schistosomiasis.
Seguia	Traditional, earthen irrigation canal in Morocco.

SGRID	*Service de Gestion des Réseaux d'Irrigation et du Drainage*, department in ORMVA, responsible for the management of irrigation and drainage systems, further referred to as Irrigation Board.
SIAAP	*Service d'Infrastructure d'Activités Ambulatoires Provinciales*, provincial department in the Ministry of Health, responsible for providing infrastructure for ambulant activities.
SMP	*Service des Maladies Parasitaires (MSP)*, Service of Parasitic Diseases in the Moroccan Ministry of Health.
Urinary schistosomiasis	Schistosomiasis caused by *Schistosoma haematobium*.
v	Mean water flow velocity (m/s), calculated as Q / A.
v_f	Flushing velocity (m/s), minimum velocity that is required to flush out snails or silt.
$\overline{v}_a$	Mean annual flow velocity (m/s), calculated as Σvf, with f being the time frequency (fraction) of the flow with a certain v (Jones 1993).
$\overline{v}_c$	Critical mean annual flow velocity (m/s), above which no *B.truncatus* snails are found (Jones 1993).
Vector	Animal, often insect, transmitting infection from person to person or from infected animals to people (Cairncross & Feachem 1993).
Vector-borne disease	Disease spread by insects which either breed in water or bite near water (Cairncross & Feachem 1993).
Water-related vector-borne disease	Parasitic diseases that are transmitted by a vector or have an intermediate host that is dependent on water for its development.
WUA	Water Users Association (see AUEA).

SAMENVATTING EN CONCLUSIES

De invloed van irrigatie en de exploitatie van watervoorraaden op de gezondheid is uitgebreid beschreven in de literatuur. De meeste gerapporteerde invloeden op de gezondheid bestaan uit water-gerelateerde parasitaire ziekten zoals malaria en schistosomiasis. Inzicht in de mechanismen, die zorgen voor een toename van de overdracht van ziekten, is meestal beperkt tot de identificatie van bepaalde kritieke eigenschappen. Deze kenmerken van irrigatiestelsels zouden het broeden van ziekte-overbrengers (vectoren) of menselijke blootstelling aan ziekten bevorderen. Minder bestudeerd is de invloed van irrigatie-ontwikkeling op de gezondheid waarbij water dat bestemd is voor landbouwgewassen, gebruikt wordt voor andere doeleinden. Dit kan zowel positieve als negatieve effecten op de gezondheid hebben. Dit watergebruik wordt beïnvloed door de beschikbaarheid van alternatieve waterbronnen. Een geïntegreerd concept is nodig om het irrigatiesysteem te beschrijven als een aparte en dynamische omgeving, die gemaakt, gebruikt en beïnvloed wordt door mensen in interaktie met parasieten en vectoren.

De complexe interacties tussen irrigatie en effecten op de gezondheid kunnen het beste bestudeerd worden met het concept *irrigatie-ecologie*. In dit proefschrift wordt irrigatie-ecologie geconceptualiseerd als *een totaaloverzicht voor de analyse van effecten van irrigatiestelsels op de gezondheid of het milieu. Door het onderscheiden van een menselijke, biologische en irrigatie-omgeving, kunnen complexe interacties worden geïdentificeerd in de overlap tussen deze drie.* Deze interacties bepalen of zich een situatie kan ontwikkelen die gunstig is voor de overdracht van water-gerelateerde ziekten.

Het irrigatie-ecologieconcept is in een interdisciplinaire en inter-sectoriële benadering toegepast op een specifiek probleem: de overdracht en bestrijding van schistosomiasis in Marokko. Urinaire schistosomiasis, de enige vorm present in Marokko, is een parasitaire ziekte, veroorzaakt door de trematode worm *Schistosoma haematobium*, die de zoetwaterslak *Bulinus truncatus* nodig heeft als tussengastheer. De gastheerslak leeft in open water in irrigatiestelsels. Mensen kunnen de ziekte oplopen door agrarisch, huishoudelijk of recreatief watercontact. In afwezigheid van sanitaire voorzieningen kunnen geïnfecteerde personen de besmettingscyclus voortzetten door met hun urine wormeneieren in het irrigatiestelsel te brengen.

De besmetting met schistosomiasis in Marokko is toegenomen met de ontwikkeling van moderne irrigatiestelsels met open kanalen. Het Ministerie van Gezondheid heeft deze uitbreiding kunnen tegengaan met een effectief Nationaal Schistosomiasis Bestrijdings Programma. Het risico van besmetting bestaat echter nog steeds met de alom aanwezige broedplaatsen voor *B.truncatus* in veel irrigatiestelsels. In de overlap tussen de menselijke, biologische en de irrigatie-omgeving binnen *irrigatie-ecologie*, zijn opties voor fysieke bestrijding geïdentificeerd om een vermindering van besmetting te bereiken en uiteindelijk de ziekte uit te roeien.

De Akka-oase in zuidelijk Marokko wordt kort gepresenteerd als een voorbeeld van een historische besmettingsplaats voor urinaire schistosomiasis. Ondanks de beschikbaarheid van andere waterbronnen, resulteren veel watergebruiksactiviteiten in contact met slakkenbroedplaatsen in de rivierbedding. De overdracht van schistosomiasis gaat daardoor vandaag de dag nog steeds door, zij het op een laag niveau. In deze regio is fysieke bestrijding in combinatie met gezondheidsvoorlichting waarschijnlijk de beste bestrijdingsstrategie tegen schistosomiasis. Dit wordt ook weerspiegeld in de suggesties van inwoners van drie dorpen, verkregen door een *rapid rural appraisal*. De studie heeft de mensen aktief bewust gemaakt van schistosomiasis en de gemeenschappen in de Akka-oase hebben al enkele van hun eigen aanbevelingen in praktijk gebracht.

Tessaout Amont

In Centraal Marokko is het irrigatiestelsel Tessaout Amont een voorbeeld van de aanleg van een groot irrigatiestelsel met open kanalen, waardoor urinaire schistosomiasis is geïntroduceerd in de Haouzvlakte, waar al eeuwen geïrrigeerd wordt. Het Tessaout Amont irrigatiestelsel heeft de typerende Marokkaanse opzet met bovenstrooms gereguleerde waterstroom en is volledig gevoed door zwaartekracht. Open trapeziumvormige primaire kanalen vervoeren water naar halfronde betonnen secondaire en tertiaire kanalen op pootjes. Bij wegkruisingen en velduitlaten zijn duikers gebouwd om het water onder de weg of piste door te leiden. Deze duikers bestaan uit twee vierkante bakken verbonden door een ondergrondse pijp.

Watergebruik, en daarmee watercontact, in Tessaout Amont wordt bepaald door de beschikbaarheid van watervoorraden in de irrigatie-omgeving. In gebieden met diep grondwater, is de rurale bevolking afhankelijk van het irrigatiestelsel om hen te voorzien van water voor huishoudelijke doeleinden, dat zij soms opslaan in reservoirs. De toewijzing van het beschikbare water om in de gewasbehoeften te voorzien, leidt tot een waterverdeling waarbij boeren om de beurt water krijgen. Dit veroorzaakt een vrijwel permanente kleine waterstroom in de secondaire kanalen en een afwisselende stroom in de tertiaire kanalen, die volledig uitdrogen tussen de irrigatiebeurten. De meeste waterbouwkundige werken daarentegen, blijven gevuld met water. Dit stilstaande water in duikers en in andere kunstwerken, kan de enige watervoorraad onder handbereik zijn voor de mensen die op enige afstand van een secondair kanaal wonen.

Verschillen tussen de watervoorraden, voor wat betreft kwaliteit, kwantiteit en toegankelijkheid, bepalen de deelname aan het waterhalen en andere watercontactactiviteiten van verschillende sexe-leeftijdsgroepen. Als gevolg daarvan kan de blootstelling aan mogelijk geïnfecteerd water en daarmee de micro-epidemiologie van schistosomiasis, significant contrasteren tussen de sexe-leeftijdsgroepen en tussen dorpen.

Een *cross-sectional snail survey* in het Tessaout Amont irrigatiestelsel toonde aan dat *B.truncatus* algemeen aanwezig was op de meeste plaatsen, maar slechts sporadisch (0.06%) geinfecteerd met *S.haematobium*. *B.truncatus*, de tussengastheerslak, werd het vaakst gevonden met hoge dichtheden in de vele tertiaire duikers. De gastheerslak was positief gecorreleerd met waterdiepte en met dikte van de sliblaag, hoewel dat laatste vertekend was door enkele monsters uit drains met hoge slakkendichtheden. De voorkeur van *B.truncatus* voor tertiare duikerbakken kan worden verklaard door de beschikbaarheid van voedsel in de vorm van microscopische algen, die gestimuleerd worden door lange perioden van stilstand, verdamping en watergebruik.

De verschillende kenmerken die de duikers ideale broedplaatsen maken voor *B.truncatus* hangen met elkaar samen en blijken bepaald te worden door irrigatie-ontwerp, waterbeheer en watergebruik. De relatieve positie van waterbouwkundige werken stroomafwaarts van het begin van het kanaal bepaalt de blootstelling van elke plek aan de afwisselende waterstroom. Zowel de frequentie als de snelheid van de stroom zijn hoger in stroomopwaartse delen van kanalen dan stroomafwaarts. Een ecologische studie van een lengteprofiel is uitgevoerd in één secondair kanaal en vier van zijn tertiairen om meer informatie te verkrijgen over lokatie-specifieke karakteristieken van *B.truncatus*-broedplaatsen. Zo werd een ecologische eenheid geanalyseerd terwijl de variatie van andere factoren minimaal bleef.

In het secondaire kanaal werden alleen *B.truncatus* slakken gevonden in kunstwerken aan het eind van het kanaal. De dikte van de sliblaag, de bedekkingsgraad van algen en de mate van bedekking door macrofyten namen toe met de afstand van het begin van het secondaire kanaal. Geen van deze kenmerken is echter significant gecorrelleerd met *B.truncatus*.

In de tertiarire kanalen nam de dichtheid van *B.truncatus* toe van het begin naar het eind van het kanaal. De hoogste frequenties en dichtheden van de tussengastheerslak werden gevonden in de tertiaire duikerbakken. Dichtheden in de benedenstroomse tertiaire en quaternaire bakken waren significant hoger dan in de bovenstroomse bakken, waarschijnlijk door verschillen in turbulentie. De duikers zijn eveneens geschikt voor de *S.haematobium* parasiet, die een definitieve menselijke gastheer kan vinden door het veelvuldige watergebruik bij de duikerbakken. De tertiaire duiker is hiermee afdoende geïdentificeerd als de belangrijkste besmettingsplaats voor urinaire schistosomiasis in moderne Marokkaanse irrigatiestelsels met open kanalen. De duiker vormt een goed uitgangspunt voor lokatie-specifieke fysieke schistosomiasisbestrijding om de gastheerslakkenpopulatie, water contact en waterbesmetting te reduceren. Verschillende opties voor bestrijding zijn geanalyseerd, theoretisch zowel als experimenteel in het Tessaout Amont irrigatiestelsel.

Een interventie bestaande uit het drie maal legen en schoonmaken van alle duikers rond een dorp had een beperkt effect op de dichtheid van *B.truncatus* slakken en eipakketjes. De maatregel kon de slakkenpopulatie niet lang onderdrukken. Vaker legen zou herhaalde inzet vragen van een gemeenschap die geen direkt voordeel ziet van deze inspanningen.

Laboratoriumexperimenten hebben aangetoond dat een donkere omgeving *B.truncatus* indirekt bestrijdt door vermindering van de beschikbare voedselbronnen. De tertiaire duikers rond een dorp in het Tessaout Amont irrigatiestelsel zijn in een donkere omgeving veranderd door de duikerbakken af te dekken met ijzeren platen. Sommige van de platen werden uitgevoerd met een beweegbaar deksel zodat de dorpelingen toegang hielden tot het water voor huishoudelijk gebruik. Het afdekken bleek erg effectief te zijn in het decimeren van *B.truncatus* populaties. Menselijk watercontact werd gereduceerd in het dorp en waterbesmetting ook. De bewoners waardeerden de deksels en rapporteerden ook een vermindering van het aantal muggen.

De waterslakken anders dan *Bulinus truncatus* bleken erg snel tot pre-interventiedichtheden op te bouwen in de duikers. Dit kan waarschijnlijk worden verklaard door de grotere kwetsbaarheid van de gastheerslak voor verstoringen, of door het indirekte effect van een afname in de hoeveelheid beschikbaar voedsel voor *B.truncatus*.

Gebaseerd op metingen in het Tessaout Amont irrigatiestelsel identificeerde Jones (1993) een kritische gemiddelde jaarlijkse stroomsnelheid in duikerbakken van $\overline{v_c}$ = 0.042 m/s, waarboven geen *B.truncatus* slakken gevonden werden. Theoretisch kunnen aanpassingen aan de standaard duikers of alternatief gevormde duikers bedacht worden die een $\overline{v_c} = 0.042$ m/s bereiken met een debiet Q van 0.03 m^3/s, het gebruikelijke *main d'eau* in Marokko, stromend voor 10% van de tijd. In de praktijk echter, kan deze $\overline{v_c}$ waarde onvoldoende zijn. De bakken van 3 duikers in het Tessaout Amont irrigatiestelsel werden aangepast met betonblokken om hun binnenmaten te verkleinen en een $\overline{v_c} = 0.042$ m/s te creëren. De veranderde duikers werden erg snel herbevolkt en *B.truncatus* slakken en eipakketjes waren aanwezig binnen een maand. Als de $\overline{v_c}$ verdubbeld zou worden tot een gemiddelde jaarlijkse stroomsnelheid van 0.084 m/s, zouden veranderde of alternatieve duikers erg hoge energiehoogteverliezen hebben. Deze duikers zouden alleen geinstaleerd kunnen worden in een nieuwe opzet van de Marokkaanse irrigatiestelsels met open kanalen.

Het idee van een gemiddelde jaarlijkse stroomsnelheid verdient meer onderzoek. Het algemene idee van een gemiddelde lange termijnsstroomsnelheid die de ontwikkeling van *B.truncatus* populaties beperkt, is bevestigd in de lengteprofielstudie. Daar bleek een afwisselende lage waterstroom de ontwikkeling van gastheerslakken in kunstwerken te bevorderen. De berekening van $\overline{v_c}$ als Σvf de gewogen gemiddelde snelheid, is wellicht een te eenvoudig model voor de hele irrigatie-omgeving. Waarschijnlijk zijn afzonderlijke formules nodig voor grote en kleinere secondaire kanalen, voor secondaire en tertiaire duikers en voor andere kunstwerken.

Aanbevelingen

In vele geirrigeerde gebieden in Marokko, zijn mensen letterlijk afhankelijk van het irrigatiestelsel om hen van water voor huishoudelijk gebruik te voorzien, in traditionele gebieden zowel als in moderne irrigatiestelsels. Het verschaffen van alternatieve watervoorziening voor de consumptie en voor andere doeleinden zoals wassen en recreatie, zal het huidige watercontactgedrag aanzienlijk veranderen. Rurale watervoorziening in voldoende hoeveelheden is daarom een belangrijke maatregel om fysieke bestrijding te bereiken van schistosomiasis en waarschijnlijk ook van andere water-gerelateerde ziektes.

In bestaande Marokkaanse irrigatiestelsels, bleek het afdekken van duikerbakken met ijzeren platen de beste fysieke maatregel tegen schistosomiasis te zijn. Op plaatsen waar frequent watergebruik vanuit duikers plaats vindt, kunnen de afdekplaten uitgerust worden met beweegbare deksels, mits de gebruikers de verantwoordelijkheid nemen om de deksels na elk gebruik te sluiten. Maar ijzeren afdekplaten zijn duur en wanneer de fondsen beperkt zijn, moet de voorkeur worden gegeven aan plaatsen met hoge slakkendichtheden en intensief huishoudelijk watergebruik. Op watergebruikplaatsen met lage slakkendichtheden zou de zomerpiek voorkomen kunnen worden door het borstelen van de binnenkant van de duikerbakken gedurende de irrigatiewaterstroom om *B.truncatus* slakken, eipakketjes en de sliblaag te verwijderen.

Marokko's landbouwpolitiek hangt deels af van de uitbreiding van het geïrrigeerde gebied tot het volle potentieel in 2020, grotendeels gebaseerd op het huidige ontwerp. Oplevingen van schistosomiasis kunnen worden voorkomen door het verwerken van fysieke slakkenbestrijdingsmaatregelen in nieuwe irrigatiestelsels. De standaard opzet moet worden aangepast door de gebruikelijke toegang tot de velden, parallel aan en over het kanaal, te veranderen in toegang van de drainkant. Het benodigde aantal duikers zou zo aanzienlijk verminderd worden, hetgeen andere ontwerpen mogelijk maakt van duikers, die *B.truncatus* populaties bestrijden maar meer energiehoogte nodig hebben om hogere snelheden te bereiken. Deze alternatieve duikers worden waarschijnlijk geen besmettingsplaatsen van schistosomiasis. Maar een vermindering van het aantal duikers zal de hoeveelheid water, die beschikbaar is voor huishoudelijk gebruik, reduceren en alternatieve veilige en voldoende watervoorzieningen zouden ook in de nieuwe irrigatie-omgeving moeten worden geïntegreerd.

Het concept van *irrigatie-ecologie* is cruciaal geweest in de identificatie van de belangrijke elementen van de overdracht van schistosomiasis in een Marokkaanse irrigatie-omgeving. Binnen deze interdisciplinaire en intersectoriële benadering, kunnen *rapid rural appraisal* technieken nuttig zijn in een beginfase, om de relevante elementen en interacties in de overlappende omgevingen te helpen bepalen. Van de analyse van de Marokkaanse situatie en de interventies die in het Tessaout Amont irrigatiestelsel geimplementeerd zijn, is het niet mogelijk om een blauwdruk te maken voor de bestrijding van schistosomiasis in andere irrigatiestelsels in de wereld. Een specifiek voordeel in Marokko was het effectieve bestrijdingsprogramma dat vooraf ging aan het onderzoek naar opties voor fysieke bestrijding van schistosomiasis. De algemene conclusie voor fysieke bestrijding in irrigatiestelsels is dat alleen lokaal verkregen inzichten in de irrigatie-ecologie van een bepaalde ziekte kunnen leiden tot effectieve en toepasselijke maatregelen.

SOMMAIRE ET CONCLUSIONS

L'impact de l'irrigation et du développement des ressources en eau sur la santé a fait l'objet de nombreuses revues bibliographiques. La plupart des effets néfastes mentionnés sont surtout l'apparition et l'extension des maladies liées à l'eau, en particulier des maladies parasitaires telles que le paludisme et la schistosomiase. Les réflexions sur les mécanismes entraînant le déclenchement et l'intensification de la transmission de ces maladies ont été généralement réduites à l'identification de certaines particularités critiques. Cettes caractéristiques des réseaux d'irrigation favorisent la création des gîtes de reproduction des population de vecteurs ou ont plutôt induit une exposition accrue de l'hôte humain aux maladies en question. Alors que peu d'attention a été accordée à l'influence du développement de l'irrigation sur la santé quand l'eau destinée aux cultures est utilisée à d'autres fins. En fait, ceci peut avoir aussi bien un effet négatif ou plutôt positif sur la santé suivant la disponibilité ou non d'autres ressources en eau. D'où le besoin de considérer le réseau d'irrigation comme étant un environnement artificiel à part, mis en place, exploite et influence par l'homme et qui est en interaction permanente avec les parasites et les vecteurs de maladies.

Une meilleure approche de la complexité des interactions irrigation-santé pourrait se faire à travers le concept d'*écologie de l'irrigation*. Dans la présente thèse, écologie de l'irrigation est conceptualisé comme étant *une vue globale qui permet une analyse intégrale des effets des réseaux d'irrigation aussi bien sur la santé que sur l'environnement. La distinction entre trois environnements séparés: l'environnement humain, l'environnement biologique et l'environnement d'irrigation elle-même, permet de mettre en exergue les interactions complexes situées dans les zones de chevauchements entre les différents niveaux.* Et se sont justement ces interactions qui feront qu'une situation serait favorable ou non à la transmission de maladies eau-dependantes.

Dans une approche interdisciplinaire et intersectorielle, le concept *écologie de l'irrigation* a été appliqué à la résolution d'un problème spécifique qui est celui de la transmission de et la lutte contre la schistosomiase au Maroc. La schistosomiase urinaire seule forme de bilharziose connue au Maroc, est une maladie parasitaire due à un ver plat de la classe des trématodes connu sous le nom de *Schistosoma haematobium.* Son cycle évolutif dépend de la présence d'un mollusque d'eau douce, *Bulinus truncatus* qui joue le role d'hôte intermédiaire. Le mollusque colonise certains habitats du réseau d'irrigation où la population humaine contracte la maladie lors d'activités agricoles, domestiques ou récréatives induisant un contact avec l'eau infestée. Le manque d'assainissement fait que des personnes atteintes pourraient entretenir la transmission en excrétant des oeufs du parasite dans le réseau d'irrigation à travers les urines.

Au Maroc, la transmission de la schistosomiase a été accrue suite au développement des réseaux modernes aux conduits ouverts. Le Ministère de la Santé a pu maîtriser la situation en limitant l'extension de la maladie grâce a un programme national de lutte contre la schistosomiase. Cependant, le risque de transmission demeure potentiel compte tenu de la large distribution de l'hôte intermédiaire, *B.truncatus,* dans de nombreux réseaux d'irrigation. Dans le cadre *écologie d'irrigation,* au chevauchement de l'environnement humain, biologique et de l'irrigation des mesures de lutte environnementales ont été identifiées et mises sur pied dans le but de réduire la transmission de la schistosomiase voire même de l'éliminer.

L'exemple de l'oasis d'Akka au sud du Maroc est décrit brièvement comme étant un exemple typique des foyers séculaires de transmission de la schistosomiase urinaire dans le pays. Malgré la disponibilité de ressources en eau, de nombreuses utilisations d'eau ont lieu au niveau des gîtes a mollusques dans le lit de la rivière d'Akka. Par conséquent, la transmission continue à ce jour, bien que son niveau soit relativement faible. Dans cette région particulière, la synergie entre la lutte environnementale et l'éducation pour la santé serait la meilleure stratégie, comme l'ont souligné les représentants de trois villages, lors d'une étude par évaluation rurale rapide. Cette étude a suscité l'intérêt croissant des villageois dans le contrôle de la maladie au point que certaines des recommandations des villageois déjà avaient été mises en place par leur propre initiative.

Tessaout Amont

Au Maroc central, le réseau d'irrigation de Tessaout Amont est un exemple type d'un système grande hydraulique dont la mise en place a été derrière l'apparition de la schistosomiase dans la plaine du Haouz oriental ou l'irrigation est une pratique ancestrale. Le réseau de Tessaout Amont a la conception typique des réseaux gravitaires modernes au Maroc, avec un contrôle en amont de la mise en eau. Des canaux primaires de section trapézoïdale alimentent en eau des canaux secondaires et tertiaires semi-circulaires et surélevés. A la sortie des canaux, ainsi que pour céder le passage aux pistes et routes, des siphons ont été construits. Ce sont des ouvrages comprenant un puisard amont et un puisard aval liés par une buse souterraine.

Dans le périmètre irrigue de Tessaout Amont, les utilisations de l'eau aussi bien que les contacts homme-eau sont conditionnés par la disponibilité de sources d'eau dans l'ensemble de l'environnement d'irrigation. Dans les zones où les eaux souterraines sont profondes, la population rurale dépend surtout de l'eau destinée à l'irrigation pour couvrir ses besoins en eau pour les activités domestiques. Dans certains cas, cette eau est stockée dans des réservoirs. Afin de subvenir aux besoins en eau des cultures compte tenu de la disponibilité de l'eau dans le barrage, la distribution de l'eau se fait par rotation. Ce qui fait que les canaux secondaires sont mis en eau presque en permanence, alors que la mise en eau est intermittente dans les canaux tertiaires qui sont complètement secs en dehors des périodes d'irrigation. Tandis que la plupart des ouvrages hydrauliques restent remplis d'eau stagnante après irrigation. Cette eau stagnante dans les siphons de canaux tertiaires ainsi que dans d'autres structures hydrauliques pourrait être la seule source d'eau accessible à la population qui dans beaucoup de cas se trouve loin des canaux secondaires.

La différence entre les sources en eau en terme de qualité, de quantité et d'accessibilité, est un facteur déterminant la participation des diverses tranches d'âge des deux sexes dans la collecte de l'eau et des autres activités induisant les divers contacts avec l'eau. Par conséquent, l'exposition à l'infestation et la micro-épidémiologie de la schistosomiase qui en découle pourrait différer substantiellement entre les deux sexes, les différentes tranches d'âge, et d'un village a un autre.

Une étude transversale de la distribution des mollusques dans le périmètre de Tessaout Amont a montré que *B.truncatus* colonise la plupart des habitats prospectés. Cependant la prévalence de l'infestation par *S.haematobium* est très sporadique (0.06%). Les densités les plus élevées de *B.truncatus*, l'hôte intermédiaire, ont été le plus souvent notées au niveau de nombreux siphons des canaux d'irrigation. Une corrélation positive a été notée entre cet hôte mollusque et la profondeur de ses habitats ainsi qu'avec l'épaisseur des dépôts d'argile. Néanmoins, cette dernière corrélation pourrait être biaisée par la considération des quelques échantillons prélevés au niveau des drains. La prédilection de *B.truncatus* pour les puisards des canaux tertiaires serait due à la disponibilité de la nourriture sous forme d'algues microscopiques dont la croissance est favorisée par les longues périodes de stagnation de l'eau, de l'évaporation et des utilisations de l'eau.

Les différentes caractéristiques qui font des puisards des habitats favorables pour *B.truncatus* sont interdépendantes et apparemment sont liées a la conception et la gestion du réseau d'irrigation ainsi qu'aux différentes utilisations de l'eau. La localisation relative des structures hydrauliques vers l'amont ou l'aval du canal détermine l'exposition de ces structures à la mise en eau. La fréquence et la vélocité sont souvent élevées dans les parties amonts du canal. Un profil en long écologique au niveau d'un canal secondaire et quatre de ses canaux tertiaires a permis d'obtenir des données plus détaillées sur les caractéristiques des habitats de *B.truncatus.* En sélectionnant un seul secondaire, qui constitue l'unité écologique, les paramètres pouvant constituer une source de variabilité dans étude transversale ont été réduite.

Dans le canal secondaire, *B.truncatus* a été trouvé uniquement dans les structures situées dans la partie terminale du canal. L'épaisseur des dépôts sur les bordures, la surface couverte par la flore algale et par les macrophytes augmente avec la distance de la sortie du canal secondaire. Cependant, aucune corrélation significative n'a été trouvée entre ces paramètres et la densité de *B.truncatus.*

Dans les canaux tertiaires, la densité de *B.truncatus* augmentait de la sortie du canal à sa partie terminale. Les densités et les fréquences les plus élevées d'hôte intermédiaire ont été notées au niveau des puisards tertiaires. Dans les puisards aval des canaux tertiaires et quaternaires, les densités de *B.truncatus* étaient significativement plus élevées en comparaison avec les puisards amont des mêmes canaux. Ceci peut être dû à la différence de turbulence. Les siphons sont également des sites favorables a *S.haematobium* qui a de grandes chances de rencontrer hôte définitif lors des contacts humains avec l'eau des puisards occasionné par les diverses utilisations. En effet ces puisards ont été identifiés comme étant les sites principaux de transmission de schistosomiase urinaire dans les périmètres irrigués modernes au Maroc. Les siphons constituent donc un bon point de départ pour la lutte environnementale focale contre la schistosomiase par réduction des populations de mollusques, du contact homme-eau et de la contamination de l'eau des puisards. Plusieurs options de lutte ont été analysées aussi bien d'un point de vue théorique qu'au travers d'expériences menées dans le réseau d'irrigation de Tessaout Amont.

Une intervention, consistant à vidanger et nettoyer tous les siphons autour d'un village à trois reprises au cours d'une compagne d'irrigation, a eu un effet limité sur la densité de *B.truncatus* et celle de ses oeufs. L'intervention n'a pas pu déloger les populations de mollusques pour une longue durée. De ce fait, des vidanges répétées sont sollicités alors que la communauté ne voit pas les bénéfices immédiats de tels efforts.

Une étude sous les conditions du laboratoire a montré qu'un environnement obscur permet une réduction indirecte des populations de *B.truncatus* par réduction des ressources trophiques disponibles. Les puisards des siphons autour d'un village au périmètre irrigué de Tessaout Amont ont été couverts par des tôles en fer afin de les rendre obscures en permanence. Certains de ces couvertures étaient mobiles afin de permettre à la population d'utiliser l'eau des siphons à des fins domestiques. Ces couvertures étaient très efficaces dans la réduction des populations de *B. truncatus*. Elles ont également diminué le contact des villageois avec l'eau, soit pour y attraper la schistosomiase ou pour la contaminer. Les villageois appréciaient les couvertures et en plus ont rapporté une réduction des moustiques.

Les mollusques autres que *B.truncatus* ont pu accroître leur densité à des niveaux comparables à la période avant les interventions aux siphons. Ceci pourrait s'expliquer par la grande vulnérabilité par le mollusque hôte intermédiaire à l'égard des perturbations elles-mêmes ou par les effets indirects sur la disponibilité de la nourriture préférée de *B.truncatus*.

Sur la base de mesures effectuées dans le réseau d'irrigation de Tessaout Amont, Jones (1993) avait identifié une vélocité moyenne annuelle critique dans les siphons qui est de $\overline{v_c}$ = 0.042 m/s, au-delà de laquelle aucun spécimen de *B.truncatus* n'a été collecte. Théoriquement, des ajustements aux siphons standards ou bien des siphons de forme alternative peuvent être conçus pour obtenir la $\overline{v_c}$ = 0.042 m/s avec un débit Q de 0.03 m/s, qui est équivalent à une main d'eau au Maroc, et une mise en eau 10% du temps. Cependant en pratique, cette valeur de $\overline{v_c}$ peut ne pas suffire. Les dimensions des puisards de 3 siphons du réseau d'irrigation de Tessaout Amont ont été réduites, par utilisation de briques en ciment fixées sur les bordures internes des puisards, pour obtenir une vitesse de $\overline{v_c}$ = 0.042 m/s. Les puisards redimensionnés ont été vite repeuplés par *B.truncatus* et ses oeufs ont été collectés en un mois après la mise en place des modifications. Si la vélocité moyenne annuelle de l'eau avait doublé, et $\overline{v_c}$ = 0.084 m/s, les siphons modifiés ou alternatives auraient une plus grande perte de charge. Ce sont donc des structures qui ne peuvent être mises en place que dans un nouveau plan des systèmes d'irrigation en projection au Maroc.

L'idée d'une vélocité moyenne annuelle nécessite plus d'investigation. L'idée générale d'une vélocité moyenne à long terme pouvant limiter le développement des populations de *B.truncatus* a été confirmée lors de l'étude du profil en long. En effet, dans les ouvrages hydrauliques où les débits étaient faibles et la mise en eau intermittente, les populations de *B.truncatus* avaient tendance à être plus abondante. Le calcul de $\overline{v_c}$ comme étant Σvf, la valeur moyenne pondérée de la vélocité, serait alors un modèle trop simple pour inclure tout l'environnement de l'irrigation. Des équations différentes seraient nécessaires pour les grands ou petits canaux secondaires, pour les siphons secondaires et tertiaires, ou pour d'autres ouvrages hydrauliques.

Recommandations

Dans plusieurs regions irriguées du Maroc, la population dépend complètement du réseau d'irrigation en tant que source d'approvisionnement en eau pour usage domestique aussi bien dans les périmètres modernes que traditionnels. De ce fait, la présence d'une source d'eau alternative permettant l'approvisionnement en eau de table et pour d'autres besoins tels que la lessive et les activités récréatives pourrait influencer substantiellement le schéma de contact actuel avec l'eau. L'approvisionnement du monde rural en eau en quantités suffisantes est par conséquent une mesure clé dans le succès de la lutte contre la schistosomiase et probablement, d'autres maladies liées à l'eau.

Dans les systèmes d'irrigation actuels au Maroc, la couverture des siphons à l'aide de tôles en fer a été la meilleure mesure de lutte environnementale contre la schistosomiase parmi celles testées. Dans les situations où l'usage de l'eau des siphons est fréquent, les couvertures peuvent être mobiles à condition que les usagers assument la responsabilité de les fermer après chaque utilisation. Néanmoins, le coût d'une telle intervention étant élevé et dans les cas où les fonds sont limités, la priorité doit être donnée aux sites ayant une densité de *B.truncatus* élevée et une utilisation intensive de l'eau à des fins domestiques. Au niveau des sites de faible densité, le pic de densité de l'été pourrait être prévenu par brossage des bordures internes des puisards lors des lâchés d'eau afin de déloger le *B.truncatus* et ses oeufs en même temps que les dépôts sur les bordures.

Le plan de développement de l'agriculture au Maroc projette l'extension des zones irriguées au potentiel total du pays vers 2020 essentiellement sur la base de la conception actuelle. Les épidémies de schistosomiase peuvent être prévenues en incorporant les mesures de lutte environnementales contre les mollusques dans les ouvrages d'irrigation en perspective. La conception de base doit donc être modifiée en remplaçant l'accès aux champs, parallèle ou perpendiculaire au canal, par un accès du côté des drains. Le nombre de siphons nécessaires va alors diminuer énormément et permettra d'introduire des siphons conçus pour prévenir le développement de *B.truncatus*, avec une haute perte de charge pour créer une vélocité élevée.

Ces siphons alternatifs ont beaucoup moins de chance de devenir, à leur tour, des sites de transmission de la schistosomiase. Cependant, une diminution du nombre de puisards va systématiquement réduire le nombre de points d'eau disponibles pour couvrir les besoins domestiques de la population. C'est pourquoi, une telle approche doit prévoir la mise en place d'une provision alternative d'eau qui doit être intégrée dans le nouvel environnement de l'irrigation.

Le concept *écologie de l'irrigation* a été crucial dans l'identification des éléments-clés dans la transmission de la schistosomiase dans un environnement irrigué au Maroc. Dans le cadre de cette approche interdisciplinaire et intersectorielle, les méthodes d'évaluation rurale rapide peuvent être d'une grande utilité dans une première phase, pour aider à identifier les éléments-clés et les interactions dans les environnements chevauchants. A partir de l'analyse de la situation au Maroc, et des interventions mises en place dans le réseau d'irrigation de Tessaout Amont, il serait impossible de faire des extrapolations pour l'ensemble des périmètres partout dans le monde. Il va sans dire qu'un avantage particulier dans le cas du Maroc est l'existence préalable d'un programme de contrôle dont le succès dans le domaine de lutte environnementale a précédé la présente recherche. La conclusion générale concernant la lutte environnementale dans les périmètres irrigués est que seules les réflexions locales obtenues dans des conditions écologiques propres à chaque contexte d'irrigation sont susceptibles d'identifier les mesures efficaces de lutte contre une maladie donnée.

CURRICULUM VITAE

Eline Boelee was born on August 4, 1966 in Leiden, the Netherlands. In 1974 the family moved to Hilversum, where Eline finished secondary school at the Comenius College in 1984. After two years of several temporary jobs she started at Wageningen Agricultural University in tropical rural engineering. From the second year on, she did additional biological and entomological subjects to acquire insight into health impacts of irrigation and water supply. Practical field work in 1990 was carried out in Ivory Coast on the relation between malaria mosquitoes and land use. The associated laboratory tests were done at Nijmegen Catholic University, where courses in Philosophy were attended as well. Thesis field research has been carried out in farmer-managed irrigation systems in Portugal, after which the MSc-degree was attained in November 1992. After writing a research proposal, Eline was invited to participate in the EU-funded project on environmental control of schistosomiasis in Mediterranean irrigation. During the three years of the project from June 1994 to 1997, she worked for the Laboratory of Parasitology of Leiden University both in Morocco and the Netherlands. After data gathering and analysis, this PhD thesis was written in Wageningen from 1997 to 1999. During this last period, she worked part-time as an assistant-researcher at the Career Services of the Royal Agricultural Society. Presently Eline Boelee is working as a researcher in the Health and Environment Programme of the International Water Management Institute in Sri Lanka.

"By involving engineers with human health and disease vectors, the aim is not to turn them into entomologists or epidemiologists. Rather, it is to turn out better engineers - better because they are more fully aware of the impacts of their activities, better because they can more effectively use their engineering for the good of mankind, and better because they will more willingly and comfortably cooperate with those of other professional disciplines." (Bahar 1988)