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Integrated Project
Global Change and Ecosystems

Deliverable 5.2.3 - Annex B1

Participatory design and construction of on-farm wastewater treatment ponds for reuse in urban agriculture: Dzorwulu/Roman Ridge - Accra - Ghana.

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5.2.3 B: On technological and organizational innovations in Wastewater Reuse, and related guidelines
Work package 5.2

The aim of work package 5.2 is to contribute to a paradigm shift in wastewater management and sanitation towards a recycling-oriented closed loop approach. The work package is being implemented in three cities; Accra, Beijing and Lima, and includes the identification and integration of appropriate productive re-use of urban freshwater, storm and waste-water for agriculture into the policy and planning frameworks of these cities.

The deliverables of the work package follow a sequence of implementation. Based on a situation and stakeholder review (del. 5.2.1), working groups are formed, meet and are linked to the Learning alliances (del. 5.2.2), they receive training in multi-stakeholder action planning (del. 5.2.3 A), and are involved in, and informed on, specific research by consultants, MSc and PhD or action research linked to the demonstrations, (all under del. 5.2.4). Information has been disseminated in publications, magazines and newsletters (del. 5.2.5), and guidelines and related training material has been developed (del 5.2.3 B and C). The leading institutes here are ETC (WP coordinator), IWMI (Accra), IGSNRR (Beijing) and IPES (Lima), other institutions involved were WUR, IRC and NRI- GUEL.

As part of deliverable 5.2.3, this is on Wastewater treatment and reuse

Contributing products included in this document are:

5.2.3 BA 1: See 5.2.4 Ae2 Report of Demonstration: Design Considerations and Constraints in Applying On Farm Wastewater Treatment for Urban Agriculture
5.2.4 BA 2: See 5.2.5 Ac Guidance note for National Programme Managers and Engineers; Options for Simple On-Farm Water Treatment in Developing Countries: Third edition of the WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater in Agriculture and Aquaculture. IWMI, FAO, WHO, IDRC (IWMI contributed to this using SWITCH experiences also).

PARTICIPATORY DESIGN AND CONSTRUCTION OF ON-FARM WASTEWATER TREATMENT PONDS FOR REUSE IN URBAN AGRICULTURE

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EXECUTIVE SUMMARY

In Accra, Ghana, one of ten SWITCH focus cities, the LA through the working group on water use for urban agriculture, initiated participatory action research activities on technological innovations to minimise risks associated with urban water reuse for agriculture within the context of integrated urban water management. The purpose was to demonstrate the potential of on-farm wastewater treatment to minimize health risks associated with urban water reuse for agriculture. The Demo focuses on further development of existing farmers' practice of on-farm water storage ponds, for improved irrigation water quality and volume.

Urban agriculture has drawn attention of scientists, donor communities and international development agencies since its contribution to food security has been demonstrated. However, the current practices in urban farming continue to threaten health of consumers and farmers. Vegetables are often watered with wastewater from gutters or contaminated water bodies. Most of the time, farmers can only rely on this source of water. There's a need to find new ways to improve on-farm water quality.

This study component of the demo addresses the problem in an integrated manner. It focuses on farmers' constraints to propose sustainable and reproducible technical options. It is based on a participatory approach linking field observations and informal discussions with farmers. Water samples were analyzed for faecal coliform and helminth eggs. Research was held in Roman Ridge farming area, Accra, Ghana. Two different settings were investigated: 1) greywater derived from gutters in a ponds-trenches system; 2) individual ponds filled periodically with water pumped from a stream.

Analyses show a natural faecal coliform removal of about 2 log units from the wastewater source to the last pond in the case of ponds-trenches system. As for individual ponds, a removal of 1-1.5 log units is observed in two days. Helminth eggs are not a problem in the study area. Nutrients levels are very low, meaning that this water can't be seen as a fertilizer.

Lack of land tenure is the main constraint towards improvement of on-farm water quality. Besides, lack of space available, permanent demand of water, variability of water needs and watering schedule, walking distance to fetch the water, difficulty to dig deep ponds and trenches, risks of flooding, risks of nuisance for the neighbourhood and farmers' lack of financial resources are to be taken into account. This implies the following constraints for our design modifications: no lost of arable land, low cost, cheap and available materials, no solid infrastructure, same water fetching points and no impact on watering practices.

Options chosen consist of slight design modification favouring natural pathogen removal processes, i.e. increasing the volume of water, avoiding short-circuiting and hydraulic dead zones with baffles, improving water fetching points to avoid resiltation, introducing plug flow retention ponds between the source and the fetching points and creating retention ponds upstream in the drains. The two main aims are to increase the retention time of water and avoid recontamination of the water through resiltation or runoff.

Design modifications were implemented on-site and are currently being tested. Moreover, bacterial flows in the system are to be assessed. First observations point that runoff water from soil and manure may be as much a pathogen source as the wastewater itself. These parameters may be of relevance when doing risk assessment.

1 INTRODUCTION

1.1 CONTEXT

According to WHO guidelines (WHO 2006), pathogen contamination on vegetables from urban agriculture should be addressed through a multiple barrier approach, allowing via several interventions to achieve pathogen concentrations that do not threat human health. So far the WHO guidelines only give limited options for non-treatment options, such as choice of crops and drip irrigation. These options are applicable only under certain conditions. Till now, very few applicable solutions have been proposed. The research community is therefore encouraged to identify other methods which could be successful in a given local or regional context and to verify their risk reduction and adoption potential (Drechsel *et al.* 2008).

Too often, wastewater has been considered as the only source of contaminants on the farms. As intestinal parasites are concerned, many epidemiological studies only focus on the prevalence rate of parasites (presence/absence), which tend to disqualify quickly produce or water which could have acceptable pathogen levels. However, things are changing (Amoah *et al.* 2005; Keraita *et al.* 2007). Sources of contamination such as soils and manure are now taken into account in risk assessment method like QMRA (Franz *et al.* 2008; Seidu *et al.* 2008) and concepts like WHO multiple barrier approach give opportunity for reuse of originally contaminated water.

In Accra, Ghana, vegetables produced by urban agriculture are consumed by about 200,000 Accra residents daily (Obuobie *et al.* 2006). Amoah et al. (2007a) identified the farm as the main point of lettuce contamination. Besides irrigation water, contamination was also attributed to manure application and contaminated soil (Amoah *et al.* 2005). Urban farmers in Ghana perceived many of the risk reduction measures suggested in the international guidelines as unsuitable and identified simple and low-cost measures which they could easily adopt (Keraita *et al.* 2008a).

(Keraita *et al.* 2008a) found that only few farmers in Accra and Kumasi perceive the risks related to pathogen content in the water they use for irrigation. It is therefore very difficult to make them do efforts to improve water quality without incentives. The authors proposed incentives such as improved health to farmers, higher economic returns for safer vegetables and institutional support from government institutions. However, such incentives need further work and are only previewed for the middle to long-term.

In the same study, farmers identified among others the following key factors to be addressed to enhance the adoption of safer practices: (i) technical know-how on design of ponds and shallow wells, irrigation methods and scheduling; (ii) challenge of implementing the measures during water scarcity; (iii) need for measures which will not increase farmers' labor inputs; (iv) unwillingness and inability of farmers to put larger capital investments on measures. According to them, loss of income, level of investment needed, (market) incentives and land tenure appear key factors constraining or driving technology change in irrigated urban vegetable farming.

Dugout ponds are widely used in irrigated urban vegetable farming sites in Ghana (Keraita *et al.* 2008b). In most cases, they are used as intermediate water storage reservoirs filled either by surface runoff or by pumping water from polluted urban streams. Such reservoirs not only significantly reduce the walking distance to the stream, they also have a potential to reduce pathogens in irrigation water through die-off and sedimentation (Drechsel *et al.* 2008; Keraita *et al.* 2008b). However, farmers not only use independent dugout ponds. Very often, water is derived from gutters and ponds are linked together through trenches. This dynamic hasn't been studied yet, although very common and, if well designed, with an important potential for pathogen removal.

This study addresses the problem of on-farm water quality in an integrated manner. It investigates farmers' practical constraints and lays a basis for trials of appropriate and reproducible on-farm pond design modifications. It is based on an approach linking field observations and informal discussions with farmers. It enhances understanding of dynamics in ponds-trenches network and assesses natural pathogen removal efficiency in such a system, as well as in dugout ponds. Thus, two different settings were investigated: 1) greywater derived from gutters in a ponds-trenches system; 2) individual ponds filled periodically with water pumped from a polluted stream.

In the frame of the SWITCH project and the collaborative research between IWMI and EAWAG/Sandec it was proposed to develop a farm-based treatment technology which can be operated by farmers or group of farmers for treating the daily quantity of wastewater or polluted surface water needed for irrigation. Such technology is designed towards closing the loop of water and nutrients and reducing health and environmental impacts to acceptable levels.

1.2 OBJECTIVES

The main objective of this project is to design an on-farm wastewater treatment plant for irrigation reuse. Specific objectives are:

1. Farmers' motivation and preferences for on-farm treatment technology are identified
2. Participatory design criteria jointly defined with farmers
3. Operational and maintenance guidelines of selected technologies are known and accepted by farmers.
4. Treatment plant location and the detail construction plan are agreed with farmers.
5. A training program for enhancing farmers' operational and maintenance skill is proposed.
6. The methodological approach for participatory design is documented and published

2 PROJECT BACKGROUND

This study is carried out in the frame of SWITCH[1] project and it complements the RUAF[2] *From Seed To Table* (FSTT) project which globally aims at helping urban farmers to improve the quality of their products, to organize themselves and to gain institutional recognition.

The Dzorwulu-Roman Ridge area has been chosen as SWITCH demo site because of its large number of farmers (about 50), secure land for cultivation, huge range of market crops, secure water source, the existence of a farmer association on Dzorwulu side and the adoption by the farmers of improved technology. In addition, there has been long–term occupation of farmers due to the proximity of the land to high tension poles which has provided some protection against the land being developed for other purposes. Covering an area of 8.3 ha, this site is one of the largest urban agricultural sites in Accra. About 130 ponds are scattered on the site, some of which are linked together with trenches, and which are filled with wastewater derived from drains, stream water or pipe water.

Prior to this investigation, a baseline study has been conducted on the site, and a sampling campaign aiming to assess the differences in water quality between ponds receiving water from different sources and ponds with/without macrophytes has been conducted in November 2008. A PhD thesis (Amoah 2008) has investigated pathogen concentrations in the water and on the vegetables in Accra and Kumasi, from the field to the market, to understand the extent of contamination at each level in a perspective of multiple-barrier approach. Another has investigated potential improvements in farmers' practice (Keraita 2008). As a result, training material for good farming practices has been elaborated and is to be tested in the near future.

As a logical follow-up, this study now investigates on-farm wastewater treatment design using a participatory approach.

[1] Sustainable Water Management in the City of the Future: http://www.switchurbanwater.eu/
[2] Resource centers on Urban Agriculture and Food security: http://www.ruaf.org/

3 PRELIMINARY STEPS

3.1 UNDERSTANDING FARM WATER MANAGEMENT

Understanding farm water management implies first to understand where the water comes from and how it flows to the farms. In Dzorwulu/Roman Ridge farming area, we have three different settings:

1. Water comes from wastewater drains; drains are blocked with sand bags and the water derived in trenches towards the farms. This constitutes what we have called *networks*, a succession of trenches and ponds, which divides sometimes in different branches, which themselves can join again further, but which don't give an exit to water. Water flows according to the *communicating vessels principle* [3].
2. Water is pumped from a stream and poured directly into *individual ponds*. Stream water is also contaminated as it receives wastewater.
3. Farmers go and fetch water in the drain itself, which is blocked (often with sand bags) in different locations along the drain to make fetching easier. Water flows continuously, as in a stream.

Farmers choose the one or the other option according to their proximity to a drain or to the stream. In the farming area, flow rate in the drains is low, so that there's no other option than blocking it. On the contrary, water in the stream is abundant all year round. Farmers will always favour water flowing with gravity. Indeed, only few farmers own a pumping machine and fuel for pumping involves significant costs in farmers' budget. Moreover, length of the hosepipes is also a limiting factor.

Whereas setting 3 functions like a system of *ponds in series*, well known in wastewater treatment, it is not the case for setting 1. In such a setting, the ponds and trenches system functions as a single water body, with water flowing back and forth according to where it is withdrawn. Thus, hydraulically, setting 1 can't be described as a pond-in-series system, even if it shares some characteristics, in particular an improvement of the water quality the further the pond to the source.

3.2 SITUATION IN DZORWULU/ROMAN RIDGE FARMING AREA

In the first step, we have identified four different networks (setting 1), a number of individual ponds (setting 2) and two limited areas where water is fetched directly in the drains (setting 3). Networks 1 and 2 have the same water source, i.e. greywater derived from a drain which has been blocked by a dam. Network 1 consists of 14 ponds and divides in two branches. Network 2 is more complicated. There are many trenches, sometimes joining each other again. Network 4 works on the same principle, but the greywater source is different. It has turned out that what we had identified as Network 3 was in fact a mix of settings 1 and 3. Indeed, "Network 3" is a series of pond in a drain which brings very little water. Thus, water is also derived from Network 2. Farmers even say that most water comes from the latter network. This implies that there is continuous flow in parts of Network 2. Figure 1 shows the study site and the three "true" networks.

It shows how complex the networks can be. Network 2 is not flat. We can still say that part of Network 2 works with the communicating vessels principle, meaning that several ponds and

[3] The *communicating vessels principle* states that when recipients are linked together, whatever their shape and the mass of water they contain, the water level will always be the same in all the recipients (see § 6.3.1).

trenches are on the same level and act as a single water body. However, gravity also plays a role, bringing the water in and taking some water out. It means that the farmers in Network 2 have found a balance, managing the flow rates so that they always have sufficient water for themselves. Moreover, some have put in place earth floodgates to bring water to some lower ponds without emptying the main body of the network.

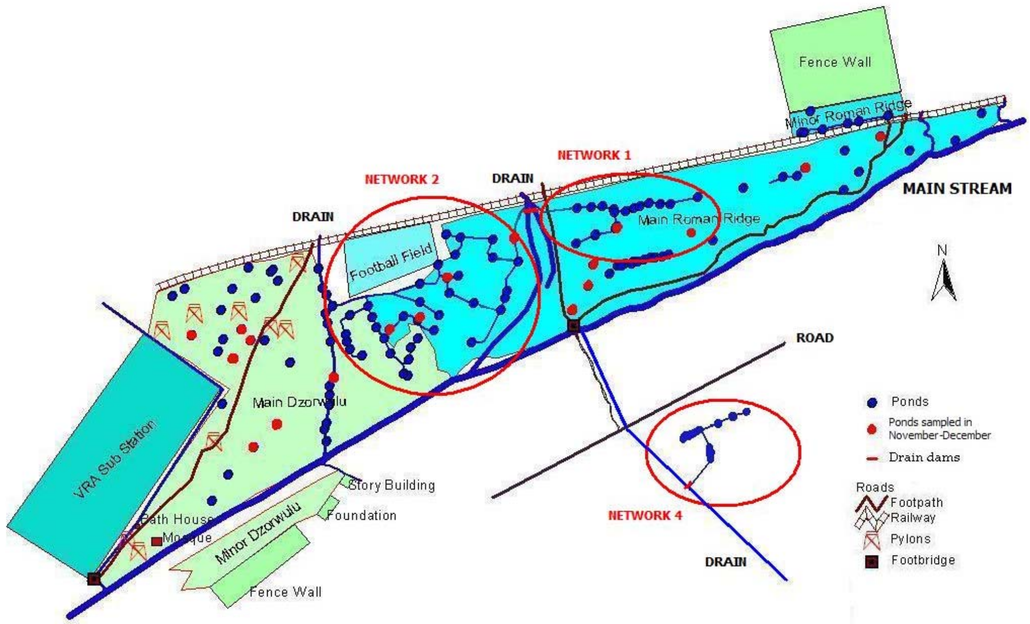


Figure 1: Study site – Dzorwulu / Roman Ridge farming area

3.3 CHOICE OF THE STUDY SITES

We have chosen ponds and networks who presented typical traits of one particular setting. Networks 1 and 4 have been chosen because they are typical of setting 1, and obey exclusively the *communicating vessels principle*. Network 4 has the further advantage to be controlled by a single farmer, making much easier the introduction of modifications. Moreover, the farmer often uses a pumping machine for watering, which leads to a very strong dynamic in the system. He also uses intensively organic manure, from pigs and chicken.

Individual ponds have been chosen according to their environment (high farming activity) and the farmers' will to cooperate. Thus, we have chosen two ponds, the first one from a farmer called Yussif (Pond Y) and the second one from a farmer called Haruna (Pond H).

Setting 3 has not been investigated, as very few farmers use water directly from the drains on this farming site.

3.4 COMPLEMENTS TO NOVEMBER SAMPLING CAMPAIGN

November sampling campaign aimed to compare water quality in ponds with different water sources (greywater from drains, stream water, pipe water), shaded and unshaded (with vegetation, Lemna or Pistia). However, contexts and water dynamics were not described, which made it very difficult to understand the variation of water quality observed. Our samplings were designed to bring the complementary information:

- Description of water dynamics
- Spatial analysis: ponds that are linked together are compared
- Water quality of the ponds is compared with water quality of the source
- Observation of environmental factors likely to influence water quality: watering practices, crop development stage, manure management, runoff.
- Understanding of water quality evolution on the short term: ponds are not sampled once a week, but every day. For individual ponds, sampling is made according to their cycle (empty-full-empty). Impact of watering practices is assessed.

Understanding of such complicated systems need integrated study.

4 METHODS

4.1 SAMPLING

4.1.1 Sampling points

Sampling points were selected according to the following criteria:

- Ability to show evolution of pathogen concentrations: we sampled the source, one pond in the middle of the network and the last pond.
- Farmers use it frequently: to draw conclusions, the pond sampled should be used daily and be surrounded by an important farming activity.
- Wish of the farmers to cooperate and to accept experiments and modifications of design.

In Network 1, two ponds were selected: P4-N1 (last pond in the network – this pond won't be modified. It should have the best water quality after the design modifications); P5-N1 (Figure 2). The samples representing the water source were taken in the first trench from the source, under the footpath bridge. Indeed, all the water in the dam doesn't come to Network 1. Taking the samples in this trench allows making sure that the sampled water is representative of the water arriving in the network.

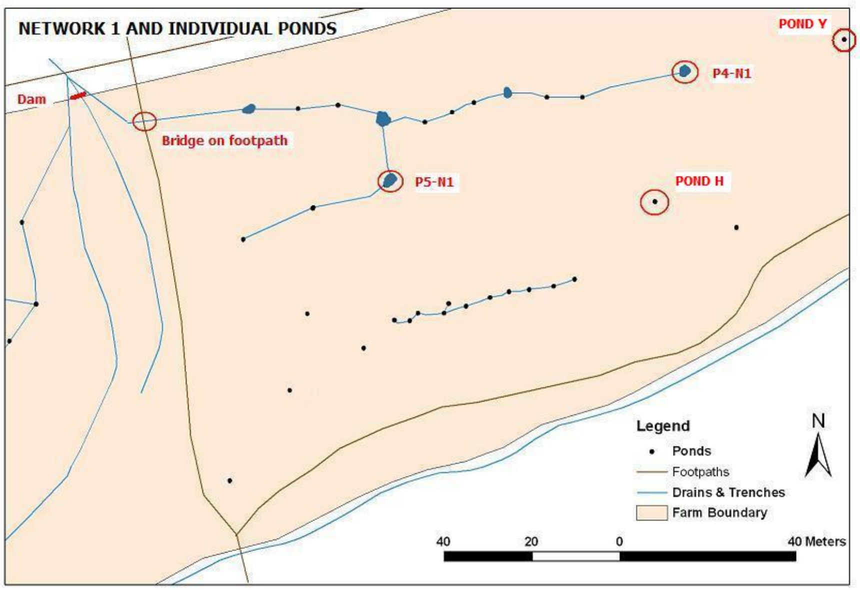


Figure 2: Sampling points in Network 1 and individual ponds

In Network 4, we sampled in the dam that blocks the drain (water source), in the second pond (P2-N4) and in the last pond of the network (P5-N4) (Figure 3).

We selected two individual ponds: Pond Y and Pond H (Figure 2).

Fifty-three samples were taken during this campaign: 25 for Network 1, 12 for Network 4, and 6 for each individual pond. Two additional samples were taken in Network 1 in the afternoon to get an idea of the situation, and two were taken in the dam, to compare with the values of the sampling point in the trench.

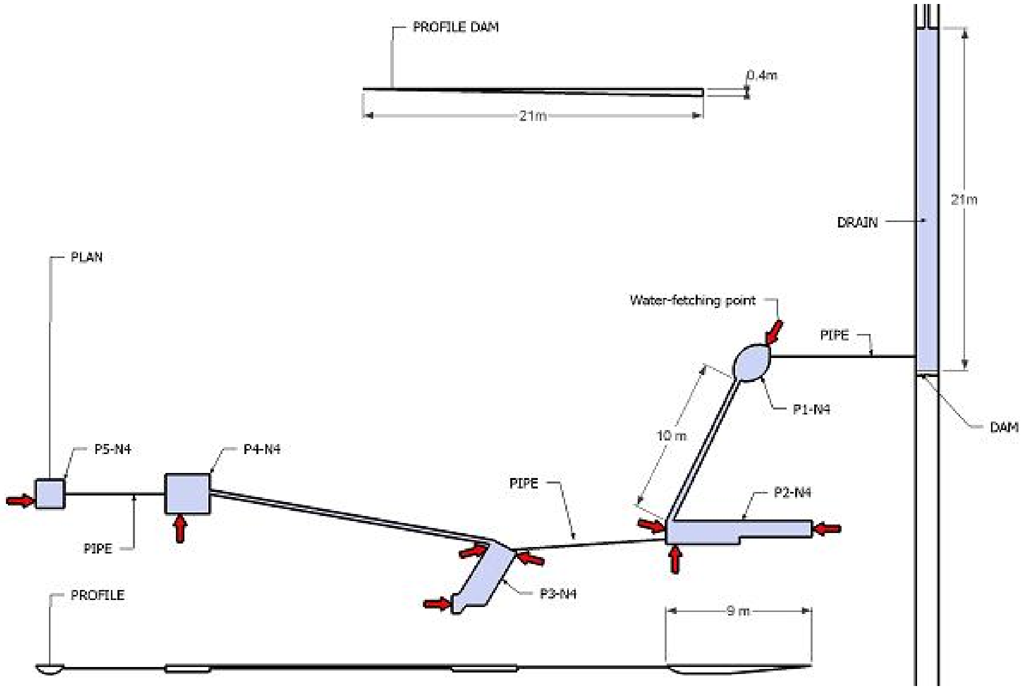


Figure 3: Sketch of Network 4 before modification

4.1.2 Time and way of sampling

In Network 1, samples were taken during five consecutive days. Time and way of sampling:

- *Before watering* (thus before 6.30 am), in the two selected ponds. Samples were taken 10 cm below water surface.
- *During watering*: water samples taken in the watering cans from the two selected ponds. (Note: the two selected ponds were used for watering during the sampling period)
- 1 sample in the water source, between 9 and 10 am (thus towards the end of the watering period)

The samples taken before watering give us the quality of the water after the longest retention time (over 12 hours) without disturbance in the ponds-trenches system. Then, the samples taken in the watering cans show the evolution of water quality through farmers' practices and modifications of dynamics in the network while watering.

In Network 4, samples were taken on two days, not consecutive. The idea was to get a first glance on the water quality in this network to see if it was adequate for further investigations, which has been the case. Time and way of sampling:

- 1 sample at each point before watering, 10 cm below water surface.
- 1 sample at each point at the end of morning watering session.

Time of sampling was determined according to farmers' schedule. When possible, samples were taken out of a watering can or hosepipe if pumping machine was used.

For individual ponds, sampling took place from the day water was pumped into the pond to the day the pond was empty again, thus one full cycle. Time and way of sampling:

- *Before pumping*, 1 sample from the residual water.

- *During pumping*, 1 sample out of the hosepipe, to assess the quality of water arriving in the pond (raw influent).
- When pumping was finished and the pond filled up, 1 sample was taken in the pond, 10 cm below the surface.
- After that, 1 sample was taken every day from the watering cans, during watering.

4.1.3 Parameters

The following parameters were analysed:

- On-site: *pH, Temperature, Conductivity*. These three parameters have been measured with a portable pH-meter.
- Microbiological analysis (done in IWMI laboratory by Mark Akrong): *Faecal coliforms, helminth eggs*.
- Chemical analysis (done in the Water Research Institute under responsibility of Collins Tay): *Dissolved oxygen (DO), Nitrate (NO_3), Ammonia (NH_4^+), Phosphate (PO_4)*. Nutrients were analyzed only for Network 4.

The Most Probable Number (MPN) method was used to determine faecal coliform counts. A set of triplicate tubes of MacConkey broth supplied by MERCK (MERCK1 KgaA 64271, Darmstadt, Germany) was inoculated with sub-samples from each dilution and incubated at 44°C for 24 to 48 hours (APHA-AWWA-WEF 2001). The number and distribution of positive tubes (acid or gas production or color change in both) were used to obtain the population of coliform bacteria in water samples from the MPN table. Helminth eggs were enumerated using the USEPA modified concentration method (Schwartzbrod 1998) identified using morphological features like shape, size and color. The Bench Aid for the Diagnosis of Intestinal Parasites (WHO 2004) was used for preliminary identification.

Temperature, pH and DO are quite time-sensitive, because linked to sunlight and biological activity. To be able to make comparisons from day to day, it is thus very important that corresponding samples are taken at the same time every day.

4.1.4 Further observations

During the sampling campaign, the following environmental factors, likely to influence water quality, were observed: watering practices, crop development stage, manure management, runoff, dredging, weeding and rain. A heavy rain may completely change the conditions, as the water source is not the same anymore and inputs from surrounding soils are much more important. Thus, impact of rain should be studied apart.

Farmers were told not to weed nor dredge during the sampling period and to indicate farming activities during the period especially fertilizers or manure preparation and application.

4.2 Estimation of the theoretical retention time

The *theoretical retention time* is the ratio between the volume of water present in a water body and the volume of water withdrawn per day (§ 6.3.4). Consequently, these are the two volumes to estimate.

It was necessary to determine the retention time in ponds and ponds-trenches networks because it is the main factor impacting on pathogen removal. Indeed, the longer pathogens are

exposed to environmental factors, the more important the removal. As for helminths eggs, retention time in the system is to be compared with their settling time.

4.2.1 Estimation of the volume of water in the networks and ponds

The volume of the system has been estimated after measurement of the length, the width and the depth of the ponds and trenches. We can assume that such estimation is quite accurate.

The depths have been measured at different points in the ponds and trenches with a graded pole. The values given here are eye-estimations of the average value for the bottom depth. The ponds' shapes have been approximated through squares and circles. The approximations have been done to be slightly higher than the reality. A correction factor of 0.8 has then been applied to take into account the irregularities of the shapes. We have determined the value of the correction factor ourselves, according to what we have observed.

Consequently, the volume of water in the network has been calculated this way:

Volume of water = length x width x depth x 0.8

4.2.2 Estimation of the volume of water used per day

Three different methods have been used to estimate the volume of water used per day:

- METHOD 1: Observation during one full day. Watering cans are counted. As their capacity is known, it is easy to calculate the volume withdrawn during the day.

  Volume used per day = n° of watering cans x capacity of watering cans

- METHOD 2: Counting of the number of beds and the average number of watering cans used to water one bed.

  Volume/day = n° of beds x average n° of watering can/bed x capacity of watering cans

- METHOD 3: For individual ponds, divide the water volume of the pond when full by the number of days till it is empty.

  Volume used per day = volume of pond when full / number of days till empty

During our field work, only watering cans have been used. If a pumping machine is used instead of watering cans, the quantity of water applied should be calculated out of the flow rate of the pumping machine (liter/minute) and the duration of watering (minute). Then:

Volume of water withdrawn with a pumping machine = flow rate x time

IWMI Baseline Report for Dzorwulu/Roman Ridge farming area gives values for the capacity of watering cans, average number of watering cans used per bed and mean size of beds. Our measurements have confirmed these values, as shown in Table 1. To get accurate estimations, it is worth measuring it for each farm, as size of beds may vary as well as the number of watering cans used.

Table 1: Data for the estimation of volume used per day

	IWMI Baseline study	Dec-Jan study
Capacity of a watering can	15 liters	
Average number of watering cans used per bed	12	10
Average size of beds	15-20 m2	16 m2

Whereas it is quite easy to measure the volume used per day on a particular day, it is not easy to find without staying long on the field the yearly average volume or the maximal volume that is used. Indeed, the number of beds watered varies (they are not always cultivated) and the quantity of water applied per bed varies according to the maturation stage of the crop and

the use of watering cans or pumping machines. We observed that more water is applied when a pumping machine is used, as the effort is much less than for watering cans. It is important to know the worst case in order to guarantee a certain quality of water all year long.

In Network 1, this value can be estimated by putting the maximum number of beds in method 2 and the average number of watering cans used for mature crops. In this case, it seems relevant as pumping machines are hardly used. This is not the case in Network 4, for which further study is needed on days where the pumping machine is used.

We tried to assess the maximum watered area on the GIS maps[4] (see map in appendix). When we compared this with the total of the surface area of beds, we observed that the maximum watered surface is about half of the total surface related to one pond or network found with the GIS. This is due to the surface area taken by the footpaths, ponds and trenches themselves, resting areas and bush. To get an accurate estimation, we recommend counting the beds, as GIS may only give rough estimations.

4.3 PARTICIPATIVE APPROACH

Much time has been spent on the field and many *informal discussions* have been held with farmers. Interviews are often very difficult to hold, especially due to problems of understanding of the farmers, which leads to answers which are wrong or inaccurate. Moreover, farmers are often getting tired of formal interviews. Valuable information can only be gathered by observing practices on the field, spending time with the farmers, gaining confidence and, during the action, asking precise questions. One full day has been spent on the field and a lot of visits have been made, at different times of the day, as some farmers have sometimes another job during the day and come very early in the morning or in the late afternoon. Each time of the day on a farming area has its specificities.

In the course of the three months, all that we did has been explained to the farmers, often individually as we met them on their plots, in a language that they understand (English, Twi or French for people from Burkina). It is often better to talk individually to make sure that everybody understands and feels involved in the process. Forgetting one farmer may have negative consequences.

Then, for networks modifications, all the farmers have been gathered at a time we chose according to their working schedule. We have explained them what we intended to do, for them to react, suggest improvements, share the constraints they could see to our work and decide for the best moment to make the modifications.

[4] IWMI has GIS maps (Geographic Information System) of Dzorwulu/Roman Ridge site (see Gerald Forkuor). Surface areas can be measured directly, as the maps are georeferenced.

5 RESULTS OF JANUARY SAMPLING CAMPAIGN

Sampling in Roman Ridge has taken place from the 12th to the 16th January 2009 for Network 1, the 20th and 22nd January for Network 4, from the 20th to the 23rd January in Pond Y and from the 21st to the 26th January in Pond H.

5.1 NETWORK 1

5.1.1 Description

Network 1 is a network of 14 ponds, linked by a total of 170 meters of trenches (Figure 2). It divides into two branches and derives its water from a dam built with sand bags on a drain, close to a railway bridge. About 130 meters separate the source from the last pond of the network (P4, which has been sampled). The division takes place after about 75 meters, and the second branch is about 40 meters long. Most of the water is covered with water lettuce (Pistia). About 10 farmers [5] depend on water from Network 1, to whom one should add several labourers. The number of farmers can vary, as some are just lending a plot to well-established farmers. The first farmer that has been on this site, Mr Mamadou Daboné, is the leader of about half of Network 1 surface area and has lent part of it to his son and other relatives, whom we count also as full farmers. Characteristics of the network are given in Table 2 and detailed dimensions are given in the appendix.

Table 2: Characteristics of Network 1

Source of water	*greywater (dam on a drain)*
Number of farmers	~ 10
Number of ponds	14
Total length of trenches (m)	169.7
Total volume of water (m3)	43.3
in ponds	24.2
in trenches	19.1
Related farming area (ha)	~ 0.7
Related number of beds	~ 250
Max watered surface (ha)	~ 0.4
Average volume of ponds (m3)	1.7 *(1.1)**
Average depth of ponds (m)	0.4 *(0.04)**
Average width of trenches (m)	0.5 *(0.1)**
Average depth of trenches (m)	0.3 *(0.1)**

** Figures in parenthesis are standard deviations.*

Most of Network 1 is planted with salads, cabbages and carrots. However, during the rainy season, about half of it is planted with maize. According to the farmers, the soil is not very good. It is too sandy and gives crop which never grows big. Only one farmer owns a pumping machine, and he uses it very seldom to fetch water in the network.

Much time has been spent in Network 1, especially one full day, from dawn to dusk. It has allowed seeing the rhythm of the day and all the activities taking place on such a farming site. In particular, it has shown that farmers have very different watering schedules, depending on their other activities. Indeed, almost all of them have another job or other plots in a different area.

These different factors make it difficult to assess the quantity of water used per day. We have estimated it with the two methods described above: observation and counting watering cans

[5] Name of the Network 1 farmers: Mamadou Daboné (+Alphonse Iliasou), Mohammed Daboné (son), Issaka Daboné (brother of Mamadou), Zaccharia, Matthias, Abdullay, Cornelius, Haruna (+Nurudin, Nasil), Gofred.

during one day and calculation out of the number of beds and quantity of water used per bed (Table 3).

Table 3: Estimation of the volume of water used per day in Network 1

METHOD 1: counting of watering cans			
Volume of water used per day in Network 1 (13th Jan. 2009)			
Morning:	4710 L		
Afternoon:	9480 L		
TOTAL:	***14190 L***	***=***	***14.19 m3***

METHOD 2: counting of beds and n° of watering cans used per bed			
Volume of water used per day in Network 1 if all the beds are watered:			
Number of beds:	250		
Average n° of w.c. used per bed:	10		
Average capacity of a w.c.:	15 L		
TOTAL:	***37500 L***	***=***	***37.5 m3***

We can see that the results given by the two methods are very different. It is due to the fact that, on the 13th January, a lot of beds still didn't have crop on them. The value given by the second method will be retained to assess the retention time. It is certainly overvalued for most of the time but is still representative of a significant period throughout the year.

5.1.2 Contamination extent

Concentrations in faecal coliforms and helminth eggs in Network 1 have been found to be quite close to WHO standards[6] (Table 4). Average concentrations are 3.5 logMPN/100mL (stdev: 0.6) for faecal coliforms and 0.2 eggs/liter (stdev: 0.5) for helminths inside the network. Concentrations in the network are quite stable. On the contrary, concentrations in the water source (dam) are higher and more variable. Figure 4 illustrates the results and Figure 5 shows how they are distributed.

Table 4: Faecal coliforms and helminth eggs results for Network 1

	FAECAL COLIFORMS (logMPN/100mL)			HELMINTHS (n°of eggs / L)		
	Average *(5 samples)*	**StDev**	***Max value***	**Average** *(5 samples)*	**StDev**	***Max value***
Greywater source (GS1)	5.7	1.1	*7.4*	1.6	2.6	*6*
P5-N1 /B	3.7	0.8	*4.6*	0	0	*0*
P5-N1 /D	4.0	0.7	*4.6*	0.4	0.9	*2*
P4-N1 /B	3.0	0.4	*3.4*	0.4	0.5	*1*
P4-N1 /D	3.3	0.2	*3.6*	0	0	*0*

B = Before irrigation - D = During irrigation - P = Pond - N = Network

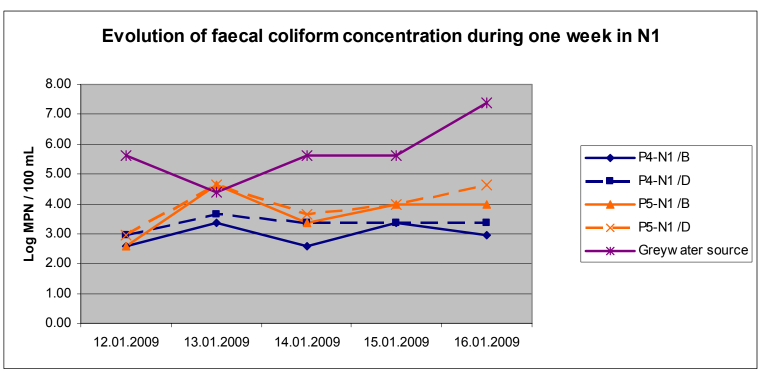
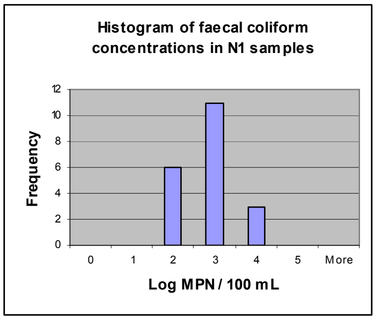


Figure 4: Graph of faecal coliform results in Network 1

[6] About 3 logMPN/100mL for faecal coliforms, corresponding to concentrations usually coming out of waste stabilization ponds, and 1 egg/liter for helminthes (WHO 2006)



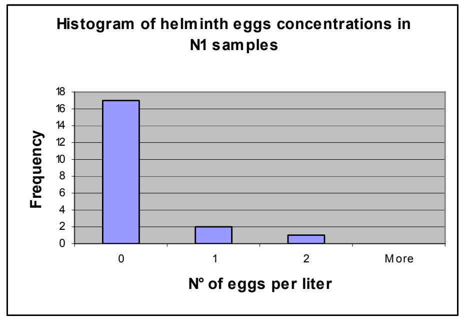


Figure 5: Histograms of faecal coliform and helminth eggs concentrations in N1

P5 had already been sampled during the November-December sampling campaign (Table 5). Six samples were taken for faecal coliform analysis, in the morning, every week on Wednesday. Helminthes were analyzed in the water and in the sediments (three samples each, every two weeks, at the same time as for faecal coliform). Values are slightly higher than that observed during January campaign. Twice, no helminth egg was found in the water, but an event with 5 eggs/liter was observed. There's no explanation for that, as no observation was made.

Table 5: Results of November-December sampling for pathogens in P5-N1

	N° of samples	Average	StDev	*Max value*
Faecal coliforms (Log MPN/100mL)	6	**4.4**	0.7	*5.4*
Helminths in water (n° eggs/L)	3	**1.7**	2.9	*5*
Helminths in sediments (n° eggs/10g dry sediment)	3	**3.3**	1.5	*5*

These three samples are the only ones we have for helminthes in sediments in Network 1. It shows that at the middle of the network, the concentrations are low, which tend to prove that helminth eggs settle upstream. However, more samples would be needed in Network 1 to assess exactly where sedimentation takes place.

5.1.3 Extent of faecal coliform natural removal

We have observed a difference of about 2 logMPN/100mL faecal coliform between the source and P5, which lies about 65 meters from the source (Table 6). Concentrations in P4, which lays about 55 meters further from the source, are about 0.6 logMPN/100mL lower than in P5. Even if P4 doesn't lie in the same branch of the network as P5, we assume that concentrations in P4 are similar to those at the same distance in P4's branch.

Table 6: Differences of water quality along Network 1

Sampling points compared	AVERAGE FAECAL COLIFORM CONCENTRATION DIFFERENCE (logMPN/100mL) *(5 samples)*	*StDev (logMPN/100mL)*
Greywater Source and P4/B	2.8	*1.2*
Greywater Source and P5/B	2.0	*1.4*
P5/B and P4/B	0.7	*0.5*
Greywater Source and P4/D	2.4	*1.2*
Greywater Source and P5/D	1.8	*1.2*
P5/D and P4/D	0.6	*0.5*

B = Before irrigation - D = During irrigation - P = Pond

These results tend to confirm the hypothesis that, in this type of network, the length of the way the water has to go through has an important impact on removal efficiency.

5.1.4 Impact of watering practices

The watering practices seem not to have an important effect on the quality of water. Our samples show an average of only 0.4 logMPN/100mL more faecal coliforms during watering (Table 7).

Table 7: Impact of watering on water quality in Network 1

Difference of FC concentration before/during irrigation	AVERAGE (logMPN/100mL) *(5 samples)*	*StDev (logMPN/100mL)*
P4	0.4	*0.3*
P5	0.3	*0.3*

Two samples that have been taken in P4 and P5 in the late afternoon show concentrations of 4.63 log units. The quality seems to decline a little bit during the day. This could be attributed to mixing with water coming from the source. However, more samples would be needed to find a definitive explanation.

5.1.5 Dissolved oxygen

Dissolved oxygen (DO) concentrations are quite low, as shown in Table 8 and in Figure 6. Most of the time, there's no DO in the water source, testifying of anaerobic conditions and explaining the bad smell we observed. It is to be mentioned that most of the network is covered with Pistia, inclusive P5-N1. P4-N1 is not covered with Pistia, but was shaded at the time of sampling. The presence of Pistia has an influence over dissolved oxygen concentrations.

Table 8: Results of dissolved oxygen concentrations in Network 1

	AVERAGE (mg/L) *(5 samples)*	StDev (mg/L)
Greywater source	0.1	*0.1*
P5-N1 /B	0.7	*0.1*
P5-N1 /D	0.8	*0.2*
P4-N1 /B	1.2	*0.2*
P4-N1 /D	1.7	*0.2*

B = Before irrigation - D = During irrigation - P = Pond - N = Network

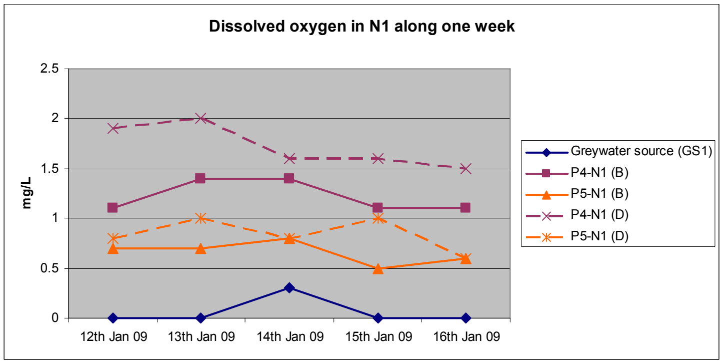


Figure 6: Graph of dissolved oxygen results in Network 1

The concentrations are increasing the further we stand in the network. It seems that they are increasing linearly, as suggests Figure 7.

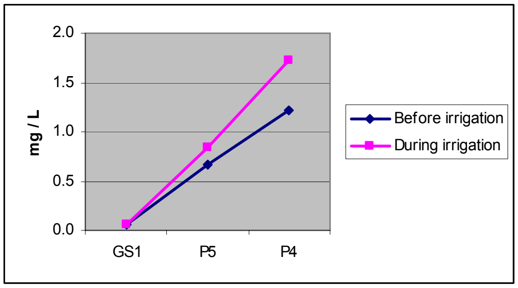


Figure 7: Graph showing dissolved oxygen evolution along Network 1

5.1.6 Temperature, pH, conductivity and others

Values of temperature, pH and conductivity are in the range of what is normally found in greywater (Table 9).

Table 9: Results of temperature, pH and conductivity in Network 1

	Temperature (°C)			pH			Conductivity (µS/cm)		
	Average *(5 samples)*	StDev	*Max value*	Average *(5 samples)*	StDev	*Max value*	Average *(5 samples)*	StDev	*Max value*
Greywater source (GS1)	27.5	0.9	*28.4*	7.3	0.1	*7.4*	1023	41	*1062*
P5-N1 / B	27.2	0.3	*27.5*	6.9	0.2	*7.1*	1004	45	*1071*
P5-N1 / D	27.2	0.4	*27.8*	6.9	0.2	*7.1*	985	19	*1017*
P4-N1 / B	26.6	0.3	*26.9*	7.3	0.1	*7.5*	1002	46	*1068*
P4-N1 / D	26.9	0.5	*27.5*	7.2	0.2	*7.3*	1025	39	*1058*

B = Before irrigation - D = During irrigation - P = Pond - N = Network

5.2 NETWORK 4

5.2.1 Description

Network 4 is essentially the network of one very dynamic farmer, Kwame, even though the furthest part of it is used by another young farmer, Selassie. Kwame has dug the system and has the total control over it. He has built a dam with sand bags in the drains, and dug a hole in the concrete wall for a pipe to lead the greywater into the first pond. The system feeds four other ponds, linked together with trenches or pipes (Figure 3). All the ponds have different configuration, but most of them have stones at the fetching points. Pond 2 is characterized by a very low slope. Excess water should arrive into it and, in case of heavy rain, Kwame has dug a channel to direct the water back into the drain, with, again, a hole in the drain's concrete wall. In Network 4, water level is closer to ground level as in Network 1. A big difference is that trenches are much smaller. Network characteristics are given in Table 10 and detailed dimensions are given in the appendix.

Table 10: Characteristics of Network 4

Source of water	*greywater (dam on a drain)*
Number of farmers	2
Number of ponds	5
Total length of trenches (m)	52.6
Total volume of water (m3)	11.9
in ponds	10.7
in trenches	1.2
Related farming area (ha)	~ 0.3
Related number of beds	110
Max watered surface (ha)	~ 0.16
Average volume of ponds (m3)	2.1 *(0.7)**
Average depth of ponds (m)	0.4 *(0.1)**
Average width of trenches (m)	0.3 *(0.1)**
Average depth of trenches (m)	0.15 *(0)**

** Figures in parenthesis are standard deviations.*

Kwame grows mostly cabbage. He owns a pumping machine that he uses as soon as the crop permits (younger crop don't stand heavy pumping machine irrigation, salads either). However, during the sampling campaign, only watering cans have been used, as cabbage was less than two weeks old.

As we didn't spend one full day on Network 4, only the second method has been used to assess the volume of water used per day. It has been assessed for the situation observed on the 22nd January and for the case when all the beds are watered (Table 11).

Table 11: Estimation of the volume of water used per day in Network 4

METHOD 2: counting of beds and n° of watering cans used per bed			
Volume of water used per day in Network 4 (22nd Jan 09):			
Number of beds:	65		
Average n° of w.c. used per bed:	10		
Average capacity of a w.c.:	15 L		
TOTAL:	***9750 L***	***=***	***9.75 m3***
Volume of water used per day in Network 4 if all the beds are watered:			
Number of beds:	110		
TOTAL:	***16500 L***	***=***	***16.5 m3***

As the total volume of water in the network is 11.4 m^3, we see that the retention time can be less than one day. Moreover, we have made the calculation considering that watering cans were used. If pumping machine is used, the volume of water would probably be even higher. It means that the farmer is sometimes using raw water from the dam. Deepening of the system is necessary to be able to avoid direct use of source water or even to separate the system from the source during the watering period while providing sufficient water to the farmer.

5.2.2 Contamination extent

In Network 4, samples have been taken for two days, in order to get a first idea of the contamination extent. Confirming the observations (in particular, the dark colour, smelly character of the water, presence of a small dump directly upstream and even traces of dies), water quality is much lower than in Network 1, as shown in Table 12. Average concentrations are 5.7 logMPN/100mL (stdev: 0.7) for faecal coliforms, with values reaching 6.6 logMPN/100mL in Pond 2. The source is even more contaminated, with an average of 7.2 logMPN/100mL (stdev: 0.6).

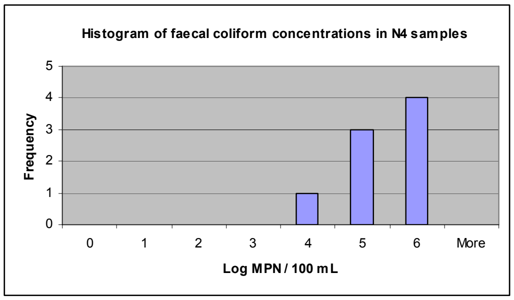
However, as in Network 1, helminthes seem not to be a problem, with an average of 0.1 egg/liter (stdev: 0.4) found in the network and 1 egg/liter (stdev: 0.8) in the source.

Results distribution is giving in Figure 8.

Table 12: Faecal coliforms and helminth eggs results for Network 4

	FAECAL COLIFORMS (logMPN/100mL)			HELMINTHS (n°of eggs / L)		
	Average *(2 samples)*	StDev	*Max value*	Average *(2 samples)*	StDev	*Max value*
Greywater source /B	7.0	0.5	*7.4*	1.0	0	*1*
Greywater source /D	7.5	0.7	*8.0*	1.0	1.4	*2*
P2-N4 /B	6.4	0.3	*6.6*	0	0	*0*
P2-N4 /D	6.3	0.1	*6.4*	0	0	*0*
P5-N4 /B	4.9	0.4	*5.2*	0	0	*0*
P5-N4 /D	5.4	0.0	*5.4*	0.5	0.7	*1*

B = Before irrigation - D = During irrigation - P = Pond - N = Network



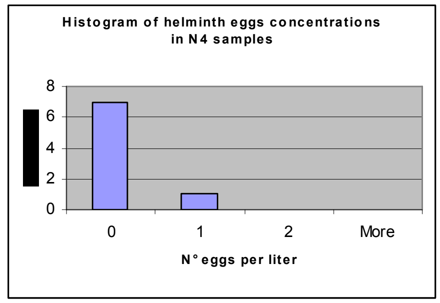


Figure 8: Histogram of faecal coliform concentrations found in Network 4

5.2.3 Extent of faecal coliform natural removal

These few samples show the same as in Network 1: the quality improves the further the pond to the source. More than 2 log units difference are observed between the source and the last pond of the network (P5) (Table 13).

Table 13: Differences of water quality along Network 4

Sampling points compared	20.01.2009 (logMPN/100mL)	22.01.2009 (logMPN/100mL)	AVERAGE (logMPN/100mL)
Greywater Source and P2 (B)	0.75	0.46	**0.60**
P2 and P5 (B)	1.46	1.54	**1.50**
Greywater Source and P2 (D)	1.79	0.59	**1.19**
P2 and P5 (D)	0.80	1.00	**0.90**

B = Before irrigation - D = During irrigation - P = Pond

5.2.4 Impact of watering practices

As in Network 1, water quality doesn't vary significantly during the watering period (Table 14).

Table 14: Impact of watering on water quality in Network 4

Difference of FC concentration before/during irrigation	20.01.2009 (logMPN/100mL)	22.01.2009 (logMPN/100mL)	AVERAGE (logMPN/100mL)
P2/D minus P2/B	-0.46	0.20	**-0.13**
P5/D minus P5/B	0.20	0.75	**0.48**

B = Before irrigation - D = During irrigation - P = Pond

5.2.5 Dissolved oxygen

Results show that there is no dissolved oxygen in the source and in Pond 2 (Table 15). This confirms the anaerobic character of these two water bodies, presupposed after the observation of strong H_2S smell. DO is present in small quantity in Pond 5, showing a slight improvement in water quality towards the end of the network. On the contrary to Network 1, there's no macrophyte here.

Table 15: Results of dissolved oxygen concentrations in Network 4

	20th Jan 09 (mg/L)	22nd Jan 09 (mg/L)
P2-N4 /B	0	0
P2-N4 /D	0	0
P5-N4 /B	0.4	0.4
P5-N4 /D	1.3	1
Greywater source /B	0	0
Greywater source /D	0	0

B = Before irrigation - D = During irrigation - P = Pond - N = Network

5.2.6 Nutrients

Nutrients levels are quite low (Table 16), which is normal for a greywater. Indeed, urine is the main nitrogen contributor to domestic wastewater. Phosphorous may come from detergents, but, in our case, concentrations found are low, even compared to regions where non-phosphorous detergents are used (Morel and Diener 2006).

Table 16: Results of nutrient concentrations in Network 4

	NO3-N (mg/L)			NH4-N (mg/L)			PO4-P (mg/L)		
	Average (2 samples)	StDev	*Max value*	Average (2 samples)	StDev	*Max value*	Average (2 samples)	StDev	*Max value*
Greywater source /B	<0.001	*VTS*	*<0.001*	3.4	1.2	*4.3*	1.4	0.1	*1.5*
Greywater source /D	*VTS*	*VTS*	*1.0*	3.9	2.0	*5.3*	3.6	0.2	*3.7*
P2-N4 /B	<0.001	*VTS*	*<0.001*	1.3	0.7	*1.8*	2.3	0.2	*2.4*
P2-N4 /D	*VTS*	*VTS*	*0.7*	3.8	0.9	*4.5*	2.8	0.7	*3.3*
P5-N4 /B	<0.001	*VTS*	*<0.001*	1.6	0.7	*2.1*	2.0	0.6	*2.4*
P5-N4 /D	2.3	0.3	*2.5*	5.7	2.4	*7.4*	2.1	0.8	*2.7*

B = Before irrigation - D = During irrigation - P = Pond - N = Network - VTS = Values Too Small

5.2.7 Temperature, pH, conductivity

In Network 4 as well, values of temperature, pH and conductivity are quite in the norm for wastewater (Table 17). Conductivity is half time higher than in Network 1, which correlates with the degree of contamination of the water.

Table 17: Results of temperature, pH and conductivity in Network 4

	Temperature (°C)			pH			Conductivity (µS/cm)		
	Average (2 samples)	StDev	*Max value*	Average (2 samples)	StDev	*Max value*	Average (2 samples)	StDev	*Max value*
Greywater source /B	24.5	1.0	*25.2*	7.1	0.1	*7.1*	1633	124	*1721*
Greywater source /D	24.6	1.4	*25.6*	7.1	0.1	*7.2*	1503	69	*1552*
P2-N4 /B	23.4	1.4	*24.4*	7.4	0.2	*7.5*	1508	66	*1555*
P2-N4 /D	24.4	2.6	*26.2*	7.4	0.0	*7.5*	1529	34	*1553*
P5-N4 /B	24.3	1.1	*25.1*	7.5	0.1	*7.5*	1532	3	*1534*
P5-N4 /D	24.1	1.1	*24.9*	7.5	0.0	*7.5*	1528	0	*1528*

B = Before irrigation - D = During irrigation - P = Pond - N = Network

5.3 INDIVIDUAL PONDS

5.3.1 Description

Individual ponds are ponds which stand alone and are fed with water pumped from the stream or drain nearby. Most of the time, individual ponds are used by only one farmer who bears the cost of filling and maintaining it. Fuel for the pumping machine is costly so that other farmers can't go and fetch water freely from such ponds as it is the case in the networks.

The two chosen individual ponds, Pond Y and Pond H, have very different shapes but about the same volume of water and same depth (Table 18). Pond Y has a very geometric shape, with, on two sides, proper stairs made out of stones to fetch the water. On the contrary, Pond H is quite long with low slopes leading to the fetching points, forcing the farmers to walk into the pond to fetch the water. This has an obvious effect on resiltation. We have also observed that, if both ponds are quite turbid, Pond Y has a more greenish colour and is more prone to runoff from the surrounding fields.

Table 18: Characteristics of the individual ponds under study

	Pond Y	Pond H
Water source	*Stream*	*Stream*
Length (m)	4.2	*Irregular shape*
Width (m)	3.9	*Irregular shape*
Surface (m2)	16.4	17.0
Depth when full (m)	0.9	0.9
Volume of water when full (m3)	11.8	12.3
(calc. with corr. factor = 0.8)		
Max. watered surface (m2)	314	350
Max. n° of beds watered	22	25

The water is pumped from the stream at irregular intervals, but with an average of 3 to 5 days. During our sampling campaign, Pond Y was emptied in three days and Pond H in four days. The time the farmers need to exhaust the water depends on the number of beds under cultivation as well as the maturation stage of the crop. Besides, farmer at Pond H also uses to fetch water in Network 1, which is not Pond Y farmer's case.

To estimate the volume of water used per day, it seems sufficient to divide the volume when full by the number of days till the pond is empty.

5.3.2 Contamination extent

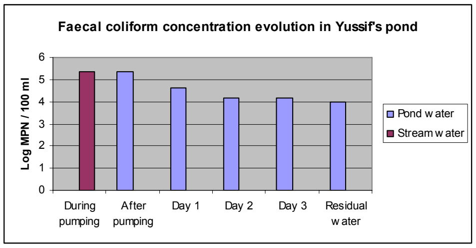
The individual ponds are filled with water from the stream. Samples have been taken just before pumping, just after, and out of the hosepipe (thus reflecting the quality of the stream-water poured into the pond). Then, one sample has been taken every day short after the watering period (Table 19).

Table 19: Faecal coliform, helminth eggs and DO results for the individual ponds

	Time of sampling		Water depth (cm)		Faecal coliforms (logMPN/100mL)		Helminths (n° eggs/L)		DO (mg/L)	
	Yussif	Haruna	Yussif	Haruna	Yussif	Haruna	Yussif	Haruna	Yussif	Haruna
Water source (STREAM)	7.15 am	11.30 am			5.38	4.88	0	2	5.1	5.6
Before pumping (POND)	7.00 am	11.15 am	40	25	3.97	3.63	0	0	7.7	0.8
After pumping	11.45 am	1.10 pm	90	90	5.38	5.38	0	0	8.7	6.2
Day 1	8.40 am	11.25 am	75	65	4.63	3.63	6	0	6.2	1.6
Day 2	7.45 am	9.40 am	60	60	4.18	3.63	3	0	6.4	1.2
Day 3	9.30 am		30		4.18		0		5.3	
Day 4										
Day 5		9.35 am		15		3.97		0		2

We observe that faecal coliform concentrations in the stream are significantly higher than WHO recommendations for irrigation water, with concentrations of about 5 logMPN/100mL.

Logically this is also the concentration in the pond just after pumping. However, we then observe a rapid reduction, lasting one day in Pond H and two days in Pond Y, leading to a value remaining quite stable for the following days (Figure 9). This value is 4.2 logMPN/100mL for Pond Y and 3.6 for Pond H. Further study would be needed to know which factors determine this value.



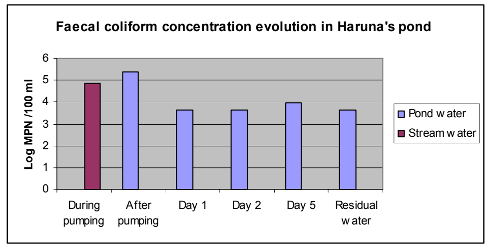


Figure 9: Graphs of faecal coliform concentrations in two individual ponds

As described above, the morphology of the two ponds is quite different. Pond Y is equipped with stairs, but may be more prone to runoff from surrounding fields. Pond H doesn't have stairs, so that the boys have to walk into the pond, which has a low slope. The resiltation is much more important, but there's no runoff from surrounding fields. However, it is not possible yet to relate definitively the concentrations observed with one of these factors.

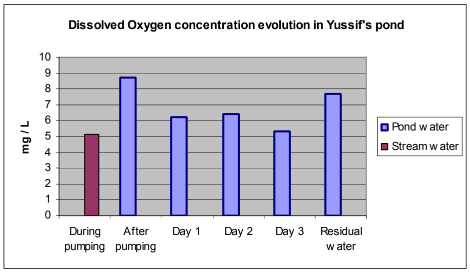
Pond H has already been sampled in the November-December sampling campaign (Table 20). Six samples were taken for faecal coliform analysis, in the morning, every week on Wednesday. Helminths were analysed in the water and in the sediments (three samples each, every two weeks, at the same time as for faecal coliform). Faecal coliform concentrations were lower than that found in January campaign. This could be explained by the fact that all the samples of Nov-Dec had been taken before the watering period (as boys working around Pond H are watering in the late morning). Numbers of helminth eggs found in the water and in the sediment are very low.

Table 20: Results of November-December sampling for pathogens in Pond H

	N° of samples	Average	StDev	*Max value*
Faecal coliforms (Log MPN/100mL)	6	**3.2**	0.3	*3.6*
Helminths in water (n° eggs/L)	3	**0.3**	0.6	*1*
Helminths in sediments (n° eggs/10g dry sediment)	3	**1.0**	1.0	*2*

5.3.3 Dissolved oxygen

DO concentrations are very different in both ponds (Table 19). Pond Y has between 5.3 and 7.7 mg/L DO, and Pond H between 0.8 and 2.0 mg/L (Figure 10). In the latter, DO level is only increased when stream water is added, but the concentration drops to its previous level within one day. We have observed a more greenish colour in Pond Y, showing a more important photosynthetic activity. This can explain the difference in DO level. However, we still haven't any explanation for DO sudden drop in Pond H, and why the two ponds behave differently. It could have been that farmer at Pond H adds some fertilizing agent in the water, which would imply a sudden DO depletion. However, he said he didn't do it.



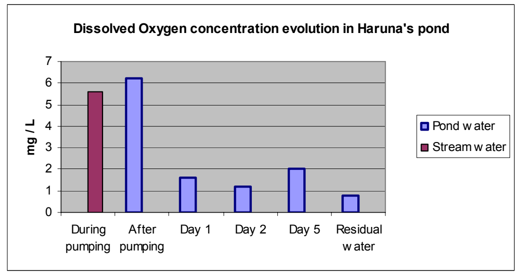


Figure 10: Graphs of dissolved oxygen concentrations in two individual ponds

5.3.4 Temperature, pH, conductivity and others

Stream water is characterized by a lower conductivity than greywater from the drains (Table 21). Temperature and pH are related with the time of sampling. However, we see that pH is higher in Pond Y, which is another proof of a higher biological activity than in Pond H.

Table 21: Results of temperature, pH and conductivity for the individual ponds

	Time of sampling		Water depth (cm)		Temperature (°C)		pH		Conductivity (µS/cm)	
	Yussif	Haruna	Yussif	Haruna	Yussif	Haruna	Yussif	Haruna	Yussif	Haruna
Water source (STREAM)	7.15 am	11.30 am			24.4	28.9	7.7	7.5	894	879
Before pumping (POND)	7.00 am	11.15 am	40	25	25.0	26	9.1	7.3	914	949
After pumping	11.45 am	1.10 pm	90	90	27.7	29.4	7.9	7.8	899	883
Day 1	8.40 am	11.25 am	75	65	24.8	26.2	8.0	7.4	910	903
Day 2	7.45 am	9.40 am	60	60	23.7	24.2	7.9	7.2	921	912
Day 3	9.30 am		30		23.0		7.9		944	
Day 4										
Day 5		9.35 am		15		25		7.4		965

6 DESIGN MODIFICATIONS

6.1 AIMS OF MODIFICATIONS

The solutions we propose in this study have two main aims: *increase the retention time of the water* in the individual ponds and networks, in order to favor the natural removal processes of pathogens, and *avoid recontamination of the water*. We can detail the proposed solutions as follows:

- *Increase the volume of ponds and networks*: the larger the volume, the longer the retention time.
- *Avoid short-circuiting and hydraulic dead zones*: very often in networks, water flows directly from the inlet of a pond to the outlet, without mixing well in the whole water body. Consequently, we observe rapid flow of contaminated water through the network, whereas large volumes, called *hydraulic dead zones*, are let undisturbed. This has a very significant influence on the real retention time we can count with as far as pathogen removal is concerned[7].
- *Favor plug flow at the entry point of the networks*: whereas it is advantageous to have well-mixed water inside the network, we have tried to keep the water unmixed as long as possible before it enters the network. The reason for this is that pathogen removal obey a *first order kinetic* law (see below), which means that the higher the concentration of pathogens, the higher the removal rate. The best way to do it is to channel the water, thus tending to the so-called *plug flow* (see below).
- *Upstream action*: as space is often limited on the farming areas, trying to treat the water upstream as much as possible can be a very valuable option. In the case where wastewater is derived from a drain, several dams can be built, thus imitating ponds in series, which makes the retention time longer and allows sedimentation.
- *Avoid resiltation*: ponds contain very often pathogen-rich sediments. Resiltation due to farming practices can ruin treatment efforts. Building proper stairs allows the farmers not to tread directly into the sediments, and proper pond depth allows sediments not to be aspired upwards when water is withdrawn.
- *Avoid runoff into the ponds*: soil on such farms contains high pathogen levels (Amoah 2008, Keraita 2008), due partly to irrigation water, but especially to organic manure. Farmers often drain excess water on their field into the ponds. This should be avoided by deriving elsewhere or building small dikes around the ponds.

6.2 CONSTRAINTS

We have imposed ourselves several constraints when planning the modifications, for them to be sustainable and reproducible by every farmer on their own:

- *No lost of arable land*: most farmers own very small plots. Thus it is important for the modifications to involve the smallest land uptake as possible.
- *Low cost*: proposed modifications should be affordable to the farmers.
- *Cheap and locally available materials*: different materials have been looked at in the course of the project. Finally, the cheapest and most available ones have been tested (wood and plastic sheets).

[7] See example in Shilton, A. and Harrison, J. (2003b). Guidelines for the Hydraulic Design of Waste Stabilisation Ponds. Palmerston North, Massey University. §3.3

- *Same water fetching points*: farmers always try to walk the shortest distance to get water. Current fetching points are, in a way, an optimization of this walking distance. We assume that it is not possible to make farmers give up fetching points for others further than the current ones, as carrying water in watering cans in quite a tiring task. Thus, we've planned the modification in order to keep all of them.
- *No impact on watering practices*: watering times and the way to water (watering cans or pumping machine) are highly variable, in time and in space, as it depends on the type of crops, their development state and the other activities of the farmers. This can't be changed. This also means that the modified system should be able to provide sufficient water in any situation.

6.3 PRINCIPLES FOR WATER DYNAMICS AND PATHOGEN REMOVAL

6.3.1 Communicating vessels

Communicating vessels are an illustration of the so-called in physics *hydrostatic paradox*, which states that when recipients are linked together, whatever their shape and the mass of water they contain, the water level will always be the same in all the recipients (Figure 11). This principle lies on Pascal's law[8].

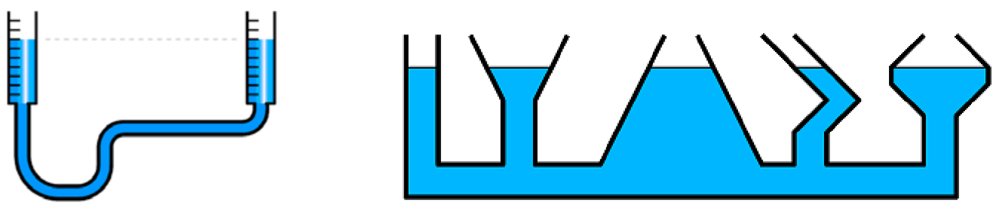


Figure 11: Two illustrations of the *communicating vessels* principle

It means that if water is added in or withdrawn from one of the recipients, remaining water will flow between the recipients until the water level is the same in all of them[9]. In our case, it means that, in a network, the level of water will be the same everywhere as long as the ponds are linked together. Water level of the whole network is determined by the water level of the source, i.e. the level of the dam in a drain. Farmers have understood this principle very well.

When a farmer withdraws water from a pond in a network, the water level will go down in the whole network. Water level can be maintained constant only if the same amount of water arrives in the drain. In the same manner, if a dam breaks, water will flow from the network into the drain, because the reference level will still be the one of the drain.

6.3.2 Plug flow

There are two theoretical extremes of flow behaviour: *plug flow* and *completely mixed flow*.

The concept of *plug flow* assumes that there is no mixing or diffusion as the water moves through a pond or a channel. One can imagine water divided into packets (*plugs*), flowing one after the other without interacting one with the other (Figure 12). Alternatively, *completely mixed flow* assumes the water is instantaneously fully mixed upon entering a pond. These theoretical flow extremes are known as *ideal flows*.

[8] Pascal's law: $P = \rho gh + P_a$ (P is the hydrostatic pressure (Pa); ρ is the liquid density (kg/m^3); g is gravitational acceleration (m/s^2); h is the height of liquid above (m); P_a is the atmospheric pressure (Pa))
[9] An animation can be seen under this weblink: http://upload.wikimedia.org/wikipedia/commons/2/20/ANIMvasicomunicanti.gif

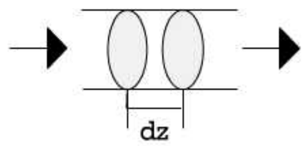


Figure 12: Illustration of *plug flow*

Because plug flow conditions mean that the pathogen concentration is not diluted by mixing, then for first order kinetics removal rate, the higher concentration means that the rate of treatment is faster and, therefore, the overall efficiency is better.

6.3.3 First order kinetics removal rate

When a reaction has a first order kinetics removal rate, in our case the removal of faecal coliforms, it means that the rate of removal is proportional to the pathogen concentration remaining at that time. This is a non-linear relationship because the pathogen concentration is decreasing over time.

6.3.4 Hydraulic retention time

The so-called *theoretical* hydraulic retention time (HRT) is the ratio of the volume of water present in a pond or network (m^3) and the average flow rate (m^3/day). In reality, the HRT is often very different to the theoretical one, for the reasons already mentioned above:

- hydraulic dead zones
- hydraulic short-circuiting

In addition to these problems concerning the hydraulic efficiency of a system, it is important to keep in mind that flow rates are highly variable and that ponds get filled with sediments or sludge with time, reducing the volume of water.

In our context, it is not the *theoretical* HRT that matters, but what is called the *mean* HRT. A way to assess the mean HRT is to conduct a tracer study.

6.3.5 Factors explaining faecal coliform die-off

The major environmental factors influencing mortality of bacteria in waste stabilization ponds are solar intensity, temperature, pH and dissolved oxygen (Curtis *et al.* 1992a; Curtis *et al.* 1992b; Mayo and Kalibbala 2007). Other factors are sedimentation of the faecal bacteria adsorbed onto settleable solids or contained within flocs of settleable solids, predation by free-living protozoa and micro-invertebrates and death due to starvation and senescence (Mara 2003). According to (Curtis *et al.* 1992a), the ability of light to damage faecal coliforms is highly sensitive to dissolved oxygen concentrations, with humic substances acting as sensitizers. Bacteria are then damaged in a process called *photooxidation*. Curtis et al (1992b) found that light can only have an impact on FC if complemented by high dissolved oxygen concentrations and a high pH, that the tendency of algae to impede light penetration is offset by their ability to raise the pH and DO and that the visible light is more important than UV. Indeed, light may only have a direct effect in the first few millimetres of water in often turbid water bodies.

Various attempts to model faecal coliform die-off in ponds have been made (Marais 1974; Qin *et al.* 1991; Curtis *et al.* 1992a; Mayo 1995; Mayo and Kalibbala 2007; Hipsey *et al.* 2008). Parameters to be put in have been widely discussed, but definitive explanation of actual phenomena taking place in ponds still has not been found. (Mayo and Kalibbala 2007)

showed in an attempt to model faecal coliform mortality in water hyacinth ponds in tropical climates that solar intensity and pH were the key factors when water hyacinths ponds have a large exposed surface area. Attachment of bacteria to water hyacinths played a major role in ponds fully covered with water hyacinths. On the contrary, sedimentation was not found to be a major factor. Until now, no equation is available to predict faecal coliform removal in waste stabilization ponds.

Direct removal through UV light is not important in ponds because these rays are almost wholly absorbed in the first few millimeters of the pond (Mara 2003). Thus, removal of faecal coliform is influenced by a complex interaction of light, pH, DO and other substances called *sensitizers*.

6.3.6 Influence of pH

In ponds, pH values ≥ 9.3 induce very rapid faecal bacteria die-off (Parhad and Rao 1974; Pearson *et al.* 1987)[10]. High pH is induced by algae photosynthetic activity, and thus is a light-mediated factor. Highest values are found on sunny days close to the pond surface, which is therefore where the most rapid faecal bacterial die-off occurs. High pH kills faecal bacteria by making them unable to maintain their optimal intracellular pH of 7.4-7.7.

6.3.7 Influence of dissolved oxygen

As a result of the photosynthetic activities of the pond algae, there is a diurnal variation in the concentration of dissolved oxygen[11]. After sunrise, the dissolved oxygen level gradually rises, in response to photosynthetic activity, to a maximum in the mid-afternoon, after which it falls to a minimum during the night when photosynthesis ceases and algal and bacteria respiratory activity consumes oxygen. The position of the depth limit at which the dissolved oxygen concentration reaches zero similarly changes, as does the pH.

Dissolved oxygen can only damage faecal bacteria in the presence of light and a dissolved sensitizer such as the humic substance gilvin (Curtis *et al.* 1992b; Davies-Colley *et al.* 2000). Gilvin is present in almost all waters, including wastewater. The light-oxygen-gilvin damage is enhanced by intracellular pH values >7.7, so the pond algae are crucial for the die-off of faecal bacteria in WSP: they produce high dissolved oxygen levels and induce high in-pond pH values which induce an intracellular pH >7.7, which in turn and in conjunction with high light intensities (>~500 W/m^2) achieves rapid faecal bacterial die-off. The way in which the combination of high light intensity, high dissolved oxygen, high pH and gilvin kills faecal bacteria appears to be as follows: gilvin absorbs the light and then reacts with oxygen to form oxygen radicals (e.g. hydrogen peroxide) which damage the cell membrane and so cause the cell to die; and the high pH enhances cell damage in the way explained above.

6.3.8 Helminth eggs removal

Eggs and cysts are removed by *sedimentation*. Settling velocities are given in Table 22. It means that most eggs are removed in the first ponds, or even in the source, where there's one or several dams in a drain.

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[10] In Mara, 2003, p.140.
[11] See Mara, 2003, p.115.

Table 22: Settling velocities of helminth eggs and cysts

Parasite	Settling velocity (m/h)
Ascaris	0.65
Trichuris	1.53
Hookworms	0.39
Giardia	0.02
Cryptosporidium	0.004

6.3.9 Inputs and influences affecting pond hydraulics

The treatment efficiency of pond systems is often compromised by poor hydraulic design. Inputs and influences affecting pond hydraulics are, according to (Shilton and Harrison 2003b):

- *Flow rate*: higher flow rates increase inlet momentum
- *Inlet size*: smaller inlets increase the inlet velocity and so the inlet momentum
- *Inlet position and orientation*: defines the way the inlet momentum is introduced into the main body of the pond, and as a result influences the main flow pattern. Poorly considered positioning of the inlet and the outlet may create hydraulic short-circuiting problems. For example, it has become recognized that the momentum from the inlet will cause the influent to swirl around the pond. Should this influent circulate around past the outlet then short-circuiting will occur.
- *Outlet position*: sets distance from the inlet and therefore the time for the main flow to reach the outlet. Outlet positioning can be considered as a secondary function after the design of the inlet and the baffles and would be placed in a dead/shielded zone out of the main flow path to achieve maximum efficiency.
- *Pond geometry and baffles*: strongly influence flow patterns and defines the degree of "channeling"
- *Temperature / density effects*: may influence the channeling and circulation of the main flow.

Shilton and Harrison (2003a) tested different baffles configuration, and found that configuration shown in Figure 13, with stub baffles, was giving good results for small expense (Shilton and Harrison 2003a). Figure 14 shows how a pulse of contaminated water diffuses in the pond. Once the inlet baffle has dissipated the inflow momentum, the concentration radiates evenly out from the opposite corner of the pond towards the outlet. The fact that short baffles give as good results as long baffles is attributed to a reduction of channeling effect that the longer baffles create.

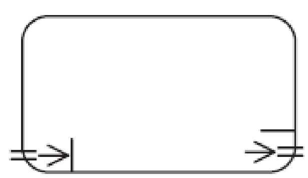


Figure 13: Stub baffles according to Shilton and Harrison

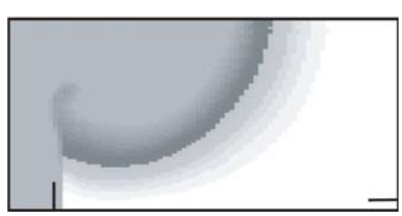


Figure 14: Modeling of a coliform pulse diffusion in a pond with baffles

Shilton and Harrison also give a good example of the impact of short-circuiting: if a pond treats a wastewater containing 7 cfu[12]/100mL, and that, on the water coming, 1% of the water only receives a 60% treatment because of short-circuiting, the discharge concentration will be 41,000 cfu instead of 1,000 cfu if short-circuiting was avoided.

6.4 PROPOSED SOLUTIONS

6.4.1 Deepening of networks

Networks and ponds should be dug as deep as possible to increase the volume of water in the network (thus the retention time) and reduce resiltation.

A depth of 60 cm for the ponds has been chosen as a trade-off between the capacity of the farmers to dig, and the wish to avoid resiltation. Keraita sets that this depth will be sufficient to reach the latter target (Keraita *et al.* 2008b). In the case of Network 1, where there's an about 40 cm difference between the ground and the water level, the bottom of the pond would then be about 1m below ground level.

As for the trenches, the depth of 40 cm seems to be the maximum achievable compared to their width. It is also the maximum depth observed currently.

6.4.2 Improvement of water fetching points

Currently, farmers use to tread into the water to a depth of about 30 cm to be able to fill their watering cans comfortably (especially regarding the tension in their back). In most cases, they have already put stones at the points they fetch water, in order not to slip or tread into mud. However, the shallowness of the ponds makes resiltation unavoidable.

The original idea was to build stairs with a final platform at a depth of 30 cm, everything with concrete slabs (*dimensions 40 x 30 x 8 cm*). Around this platform, the pond depth would drop at once to 60 cm (Figure 15). Thus, resiltation would be much reduced.

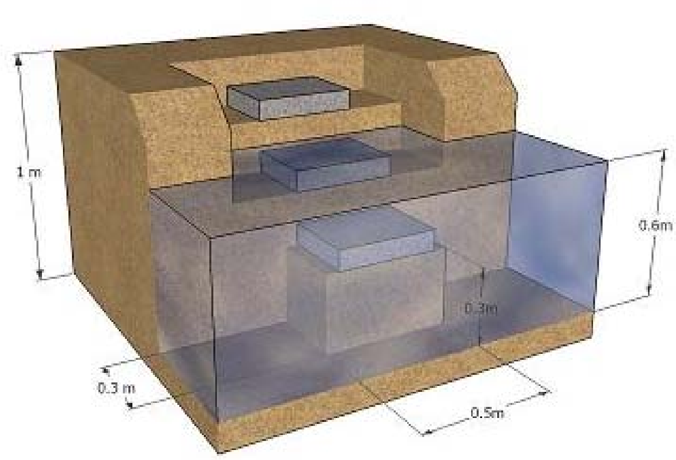


Figure 15: Improved fetching point – first design

[12] *cfu : colony forming unit*. Measure indicating the number of microorganisms capable of multiplying in a sample.

Practice has brought small changes to this design. As materials are concerned, farmers have proposed to use very strong and cheap blocks from demolished building for the stairs, and to add concrete to bind these blocks together (Picture 1). This makes the whole thing more sustainable by avoiding the blocks to slide on the mud.

Picture 1: Previous and improved fetching point – final design

6.4.3 New retention ponds

Retention ponds have been added before the first water fetching point in the networks. We can distinguish two types:

- *Modification of the trench leading the water from the drain to the network*: it can be widened to a width of 1.5 meters, which generally doesn't imply much space lost for farming and allows creating, for a pond of 10 meters length, a plug flow channel of 30 meters length (see modifications in networks 1 and 4). This type of pond is called *retention pond* because it increases the water volume in the network without being used by the farmers.
- *Construction of new dams in the drain*: these are upstream measures. Water is retained outside the network.

The ideal would be to dig proper retention ponds, able to contain water for two to three watering days, before the source and the first water fetching point, but, in our case, space was not available for such thing.

6.4.4 Baffles

Baffles are placed for three aims:

- avoid short-circuiting
- increase the mixing inside the network
- encourage plug flow before entering the networks

To avoid short-circuiting, *full-height baffles* have been placed strategically in the ponds. via tracer studies and computer modeling. Shilton and Harrison's results have been taken as an example for our design (Shilton and Harrison 2003b) (see §6.3.9).

Full-height baffles have also been used to reduce as much as possible the extent of *hydraulic dead zones*, that is, spaces of stagnant water which can't be counted as part of the retention

volume. They have been placed in some of the ponds, according to their shape. Besides, *plunging and immersed baffles* have been proposed to favor vertical mixing of water in the deeper trenches (Figure 16). Our practice has shown that they can be placed if trenches have a minimal depth of 40 cm, which is currently the maximum depth encountered. Otherwise the effort is too big compared to the profit expected.

The different baffles have been positioned so as not to disturb the farmers, and their number has been reduced at the strict minimum. That's the reason why only one plunging baffle followed by one immersed baffle has been recommended in the trenches before each pond. The distance between them has been intuitively set at 2 meters. However, we still haven't placed any plunging or immersed baffles, as no channel has reached the minimal depth.

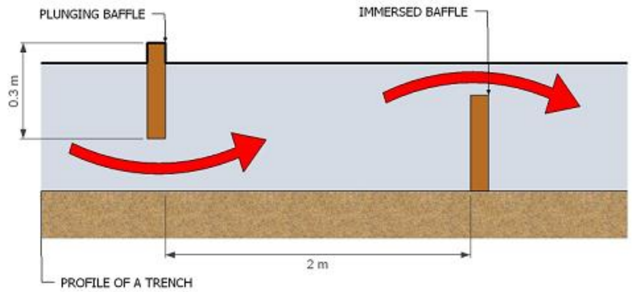


Figure 16: Plunging and immersed baffles

Long full-height baffles (up to 10 meters) have been placed in the retention ponds to favor plug flow.

Materials chosen are redwood (planks of 4 m. length and 30 cm. width) and corrugated plastic sheets, used alternatively. For example, in our case, baffles for plug flow have been made out of plastic sheets, and shorter baffles in ponds have been made out of wood. However, this is not a rule. Each material has its characteristics (especially the width), fitting best to water depth, bottom configuration, or simply economic calculation, making the choice depend only of particular setting (see §8.1). Their life span and relative impact on water quality is still to be assessed.

6.4.5 Temporary separation of source and network

According to communicating vessels principle, water comes from the source when water is withdrawn from the network, thus bringing higher pathogen concentrations. We have thought about ways to close the water arrival during the watering period with a kind of floodgate between the source and the network. In order to function, this type of system must meet the following requirements:

- The volume of water in the network is sufficient for one day watering.
- The network can fill up to its original level in less than six hours (so that the water can rest at least for six hours during the night). The latter factor depends on the flow rate in the wastewater drain.
- Farmers using water from the network are organized so that they know who should open and close the floodgate and when.

Attention should be paid to the following points:

- The water level in the network should always be sufficient to avoid resiltation.
- The water should have already at least one day retention time before entering the network (in dams in the drain or specially constructed retention ponds). Otherwise,

untreated wastewater will fill the network and have only six hours at night for pathogen removal, which is totally insufficient.

It is really not easy to find a balance with the constraints of the field. Experience in N4 is described in the corresponding chapter below.

In Network 1, it is not possible to implement currently such system, as the volume of water is not sufficient for one day and the volume of water in the dam not sufficient to fill up the network quickly. An intermediate alternative is planned, with the placing of one immersed baffle at the entrance of the network to reduce the inflow. Thus, if a lot of water is withdrawn from the network at the same time, there won't be important current induced. One could also think to close the entrance punctually when the water is fetched from the two first ponds.

6.4.6 Multiplication of individual ponds

Farmers use to pump water from the stream into the individual ponds once or twice a week. Then, they use the water until the pond is empty. The only way to let the water untouched for several days is to build one or two other ponds to be used successively, i.e., if the farmer has two ponds, he will leave the first one full while using the second one till empty, and then switch to the first one while filling the second one again and leaving it untouched.

The two problems encountered are the availability of space and the need to dig the ponds in such a way that the farmers don't have to walk more to fetch the water. This means that the ponds have to be dug one against the other. Lack of space and appropriate distance to fetching points make it very difficult to have more than two ponds together. That's why we chose to modify single ponds into two ponds only.

6.5 MODIFICATIONS IN NETWORK 1

In Network 1, a new design has been proposed for the whole network, but only the retention pond with plug flow has been already realized. For the rest of the modifications, we are waiting for a window in the farming schedule to be able to dry part of the network and put excavated materials on the nearby beds.

6.5.1 Plug flow retention pond in N1

The field configuration has allowed adding a new pond between the source (dam) and the first water fetching point. This pond is 10 m long, 2 m wide and 40 cm deep. Long full-height baffles made out of corrugated plastic sheets have been placed in the length of the pond, to make water circulate for 30 meters before carrying on (Figure 17 and Picture 2). This implies more exposure to removal factors for faecal coliforms, and a longer distance for helminth eggs sedimentation.

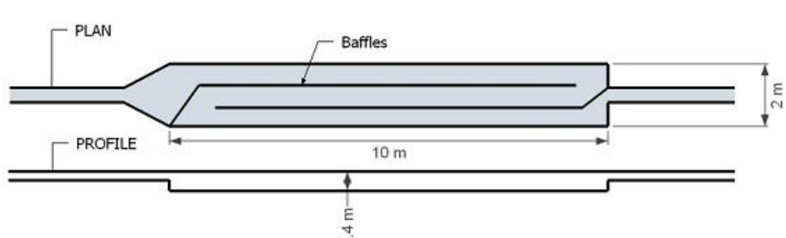


Figure 17: Plug flow retention pond in Network 1

Picture 2: Plug flow retention pond in Network 1

6.5.2 Remaining modifications

As soon as necessary conditions for working are present, the whole system will be deepened a bit, to a depth of 40 cm for the trenches and 60 cm for the ponds. With a width of about 60 cm, the trenches will act as further retention spaces. Baffles will be added and the fetching points will be improved. Three sequences of the plan are given in Figure 18. They show the eight first ponds after the source. Similar modifications will be made on the rest of the network, with fewer baffles towards the two ends. The red arrows represent the places where the farmers fetch water. These fetching points are already equipped with some stones for the farmers to tread on.

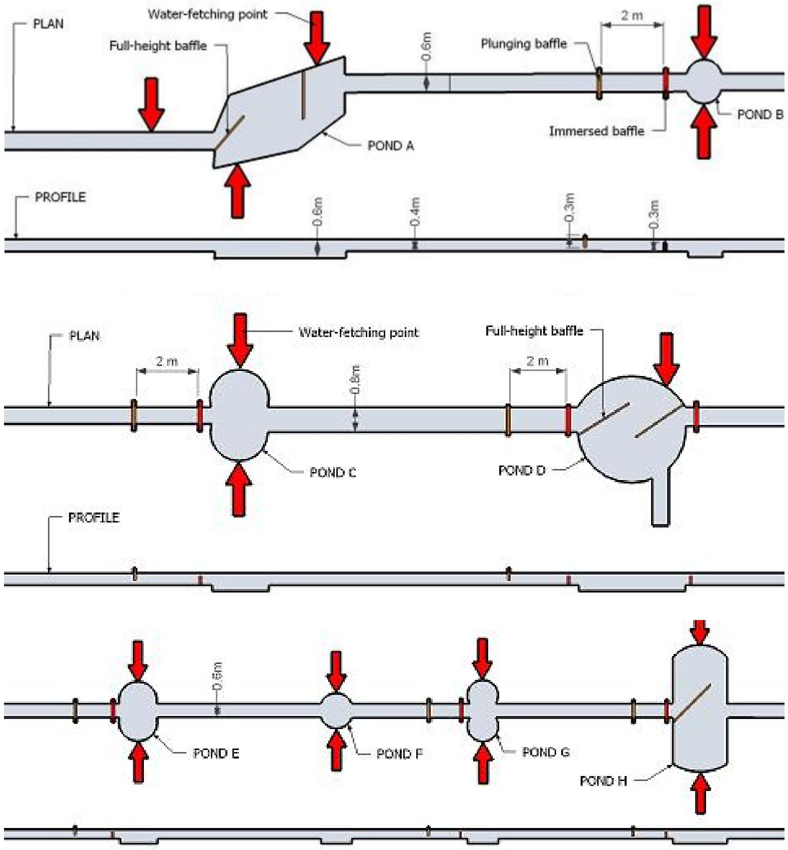


Figure 18: Planned modifications in Network 1

The plug flow retention pond will be partially closed with an immersed baffle. In theory, the best thing would be to separate it completely from the network during the watering period. However, the volume of the network is not sufficient for not allowing a constant flow of new water entering the system. Besides, many farmers work in the network, which makes a common management not easy. Thus, an immersed baffle reduces the flow without blocking it completely.

6.5.3 Expected impact of the modifications on the retention time

We estimated the volume of water in the network after modification. Table 23 shows the difference before and after. Overall, the volume would be increased by more than 60%. We also observe that volume of water in the trenches is very significant in this case. They act as water reservoirs.

Table 23: Volumes of water in Network 1 before and after modifications

	VOLUME OF WATER IN N1	
	Before modifications	After modifications
In the ponds (m3)	24.2	43.1
In the trenches (m3)	19.1	27.9
TOTAL	***43.3***	***71.0***

The corresponding *theoretical* retention times (Table 24) were calculated.We can realistically hope to reach a three-day theoretical retention time for most of the time.

Table 24: Theoretical retention times in Network 1 before and after modifications

	THEORETICAL RETENTION TIME (days)	
	Before modifications	After modifications
With vol. withdrawn = 14.2 m3 *(13th Jan)*	3.0	5.0
With vol. withdrawn = 37.5 m3 *(Hyp: all the beds are watered)*	1.2	1.9

It should be noticed that the modifications in design not only intend to increase the *theoretical* retention time, but also the *mean* retention time, while trying to reduce as much as possible the volume of *hydraulic dead zones*.

6.6 MODIFICATIONS IN NETWORK 4

A bigger impact on water quality can be achieved in Network 4, as the concentration in pathogens is about 2 log units higher than in Network 1.

Apart from water quality, the difference in Network 4 is that it is operated by only two farmers, the first one controlling alone the water supply. Whereas in Network 1 it seems not easy to separate the system from the source during the watering period, this can be done in Network 4. Moreover, Network 4's drain configuration allows adding one dam upstream, which is not the case for Network 1.

Otherwise, the modifications are the same: deepening of the pond and trenches; full-height baffles according to the network configuration, plug flow retention pond and improved fetching points (Figure 19). Plunging and immersed baffles have not been installed, because the trenches were not as wide and deep as in Network 1. Specific modifications are detailed in the following paragraphs.

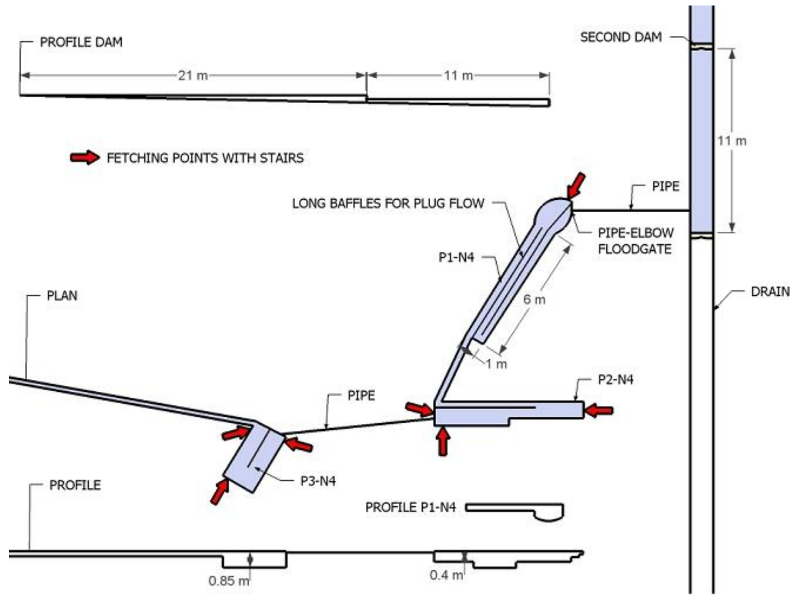


Figure 19: Sketch of the main modifications in Network 4

6.6.1 Floodgate system

In Network 4, a pipe leads the water from the drain (which is blocked by a dam) and the first pond. To be able to stop the water entering the network when desired, we have installed an elbow at the end of this pipe. A removable piece of pipe can then be pushed into the elbow to stop the water, or taken away to let the water flow freely, as illustrated in Figure 20 and Picture 3. This system is based on the communicating vessels principle.

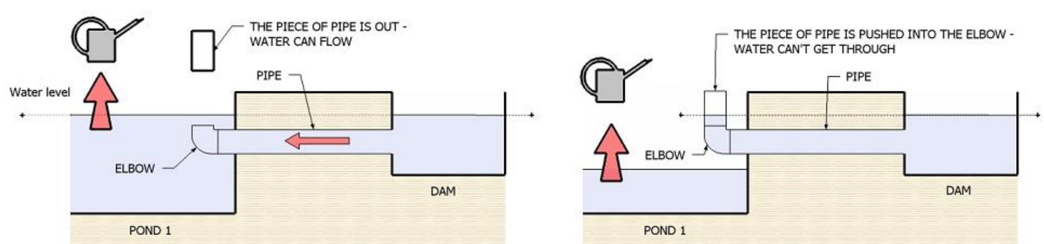


Figure 20: Sketch of floodgate system used in Network 4

Picture 3: Pipe-elbow floodgate system in Network 4

This design has been chosen because it is very easy to push the piece of pipe from above into the elbow, even if the elbow is under water; it can be done without putting hands in the water.

At first, we had thought of sticking the piece of pipe to the elbow, and rotate the elbow around the main pipe, as shown in Figure 21. When turned towards the ground, it would have let the water flow free. When turned towards the sky, the configuration is the same as the chosen option. We haven't chosen this system because it is quite inconvenient to turn the elbow when it is under water.

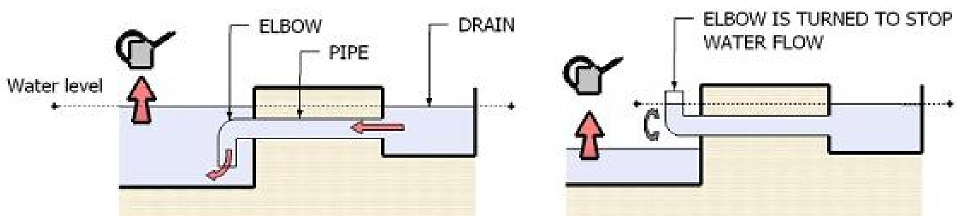


Figure 21: Sketch of the floodgate system with an elbow in the pipe

6.6.2 Plug flow pond

A plug flow retention pond has been dug out of Pond 1 and the trench to Pond 2 (Picture 4). This pond brings several advantages:

- The water has to flow for 20 meters before reaching the first fetching point. Before, the water was directly flowing from the dam to the fetching point. As in Network 1, the plug flow nature of the pond should increase the pathogen removal rate.
- It increases the available volume of water in the network.

The extension dug in the trench is about 6 m long for 1.1 m large and 0.6 m depth. This corresponds to an additional volume of water of about 4 m^3. More than 16 meters baffles have been installed, out of wood for Pond 1 main body and out of plastic sheets for the extension.

Picture 4: Baffles and plug flow retention pond in Network 4

6.6.3 Baffles

Long full-height baffles have been positioned in Pond 2 (Picture 5) and Pond 3 (Picture 6) (see also Figure 19). In these two ponds, inlet and outlet were very close to each other, creating important short-circuiting and huge hydraulic dead zones. The baffles prevent the two phenomena by forcing the water to flow through the whole pond. They have been made out of redwood.

As said above, baffles have also been placed in Pond 1 to tend towards plug flow.

Picture 5: Modified Pond 2 in Network 4

Picture 6: Modified Pond 3 in Network 4

6.6.4 Upstream action

A second dam has been built in the drain. It has been made out of sand bags, like the current one. The two dam volumes will act as two retention ponds in series. The number of dams and the distance to the first one have been constrained by the fact that there is a small informal settlement upstream. The stagnant water of the pond should not come up to this height, for hygiene and health reasons.

Unfortunately, it seems that, with the second dam upstream, the *readily available water* (Figure 22) in the first dam is not always sufficient. The farmer, Kwame, has removed some sand bags, which means a return to original configuration (only one retention pond). This issue should be further studied. In all case, it shows that farmers' constraints are key factors to undertake successful action.

This issue has made us introduce the concept of *readily available water*, in pink colour on Figure 22. This is the sum of water from the source and the network that the farmer can count with during a watering period. When this water is finished, he can only count with the wastewater flow coming from the drain. In Network 4, as a consequence to communicating vessel principle, water can't be expected anymore as soon as the level of the water in the source-network system comes down below the outlet (in this case, a pipe). Then, only water remaining in the network can be used and the wastewater flow arriving in the drain. When everything's finished, the wastewater flow, quite low in our case, may be much less than the flow withdrawn from the network, leading to watering problems for the farmer.

Figure 22: Concept of *Readily Available Water* in a dam with outlet to a farm

In conclusion, if upstream action is to be undertaken in a drain, one has to make sure that the quantity of water is sufficient. This quantity can only be increased by digging the network further, or, in this case, in placing the outlet a little bit lower, but not so low that sediments would be out of water (which could launch bad smell and put helminth eggs in resiltation if the water comes back and forth).

6.6.5 Remodeling of Pond 2

Before modification, Pond 2 had a very low slope, which led the farmers to walk for one or two meters into the pond to fetch the water, causing important resiltation. The pond has been dug deeper with the construction of stairs to a 30 cm depth. At first, we intended to dig all of it to a homogenous depth. However, as the clayey soil was hard, we could only dig the sloping parts to a depth corresponding to a 50 cm water level, whereas the central part of the pond has been restored to its depth corresponding to 90 cm of water. Even if it is not as deep as wished, the depth achieved is sufficient to reduce resiltation significantly. Besides, the volume of the pond is doubled.

6.6.6 Fetching points

The fetching points of ponds 1, 2 and 3 have been improved with stairs out of blocks and cement. The stairs have been built by the farmers themselves.

6.6.7 Impact of the modification on the retention time

The deepening of the network has doubled the retention time as can be seen in Table 25 and Table 26. New dimensions of ponds and trenches are given in the appendix. However, we can see that, during important watering, water in the network would be just sufficient. Indeed, there's always a part of the water volume which is not used. It also means that the drain should then provide about 10 m^3 before the next day. Further investigation would be needed to see how this can be dealt with.

Table 25: Volumes of water in Network 4 before and after modifications

	VOLUME OF WATER IN N4	
	Before modifications	**After modifications**
In the ponds (m3)	10.7	20.4
In the trenches (m3)	1.2	3.1
TOTAL	***11.9***	***23.5***

Table 26: Theoretical retention times in Network 4 before and after modifications

	THEORETICAL RETENTION TIME (days)	
	Before modifications	**After modifications**
With vol. withdrawn = 9.75 m3 *(22ndJan)*	1.2	2.4
With vol. withdrawn = 16.5 m3 *(Hyp: all the beds are watered)*	0.7	1.4

6.7 MODIFICATIONS IN INDIVIDUAL PONDS

Modification of two ponds has been planned: Pond Y (Figure 23) and Pond H (Figure 24). Finally, work could only be done in Pond Y, as the brother of the farmer in Pond H didn't give any space for the extension of his pond. A second pond similar to Pond Y has been dug next to it (Picture 7) and new stairs have been built by the farmers, with cement and tools provided through the project.

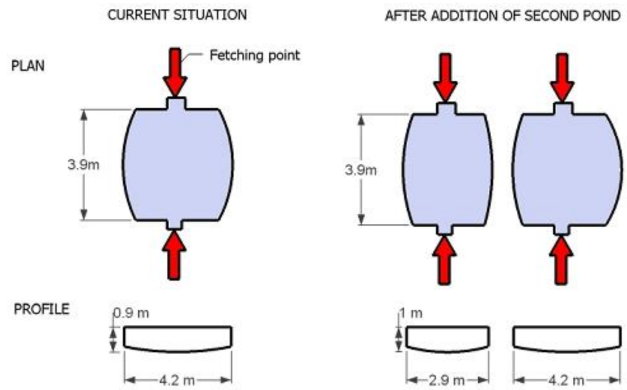


Figure 23: Sketch of modifications planned with Pond Y

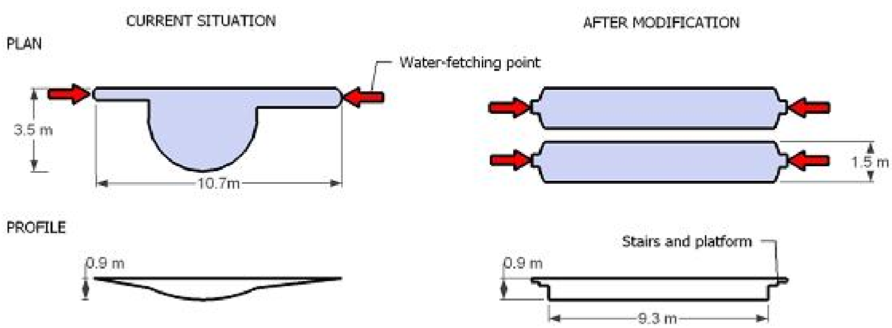


Figure 24: Sketch of modifications planned with Pond H

Picture 7: Two individual ponds next to each other

One problem with Pond H is that the farmers have to walk one or two meters into the pond to fetch the water, as the slope is very low. As in Network 4, we intended to dig to a homogenous depth, with the building of stairs and a platform to fetch the water. Resiltation would thus have been prevented.

We have calculated the volume of the ponds when full, the current volume of water used per day and the achievable retention time in the modified configuration (Table 27). A retention time of 3 days can be achieved in both cases.

Table 27: Volumes of water and retention times in Pond Y and Pond H

	Pond Y	Pond H	Unit
BEFORE MODIFICATIONS			
Volume of water when full	11.8	12.3	m3
Volume of water used per day			
Calculated from the water level difference in the pond:	*2.5*	3.2	*m3/day*
Calculated from water applied per bed:	*3.1*	3.0	*m3/day*
AFTER MODIFICATIONS			
Volume of water in the second pond when full	9.0	10.0	m3
Retention time achieved (if vol.used/day = 2.5 m3)	**3.6**		**days**
Retention time achieved (if vol.used/day = 3.1 m3)	**2.9**		**days**
Retention time achieved (if vol.used/day = 3.2 m3)		**3.1**	**days**

For Pond Y, participative process led to wait till the beds around the pond were free of crops, so that the excavated materials could be directly incorporated into the beds. This gives five major advantages:

1. No space is lost because of heaps of materials around the ponds;
2. The materials won't be prone to fall back into the pond;
3. Structuring elements like clay particles will be mixed with sandy surface layer;
4. Bacteria and eggs contained in the sediments will be integrated into the soil, where they will be eliminated through drying or soil activity.
5. Bed level around the pond will be slightly increased, which is, according to Pond Y's farmer, quite advantageous as the area is prone to flooding and water retention during rain periods.

7 RESULTS OF MARCH-JUNE SAMPLING CAMPAIGN

From March to June, new samples were taken in Network 1, Network 4 and Pond Y. Samples were taken in Network 1 on the 1st and 2nd April, in Network 4 on the 25th, 26th, 27th and 3rd April and from 18th to 22nd May and from 1st to 5th June in Pond Y.

7.1 NETWORK 1

7.1.1 Sampling campaign design

Since January, conditions in Network 1 had changed due to the drainage of the main drain. A retention pond was dug before the first pond of the network and, due to dam breaking, the level of water in the network was permanently reduced of about 15 cm. The aim of this new sampling was to see to which extent these changes had an impact on water quality.

Samples were to be taken before the watering period (around 6.30 am) and during the watering period (around 9 am) at the following locations:

- *1 sample in the derivation trench (DP), before the retention pond*
- *1 sample in the first pond of the network (P1) (i.e. after the retention pond)*
- *1 sample in P4-N1 (as in January sampling campaign)*
- *1 sample in P5-N1 (as in January sampling campaign)*

Samples were to be taken for two consecutive days. The days chosen were to be representative, i.e. without rain the day before, and at a time of big watering activity. Observations of the environment had to be made in order to understand any special event that could occur.

Samples were to be analysed for faecal coliform and helminths. DO analyses were to be carried out for the samples before watering on the first day (i.e. on 4 samples).

7.1.2 Samples obtained

Due to problems between farmers, whose consequence has been the departure of most of those working on Mr Mamadou Dabone's land, watering was made almost exclusively during the afternoon. Thus, we decided to sample in the early morning, as planned, and in the afternoon, towards the end of the watering period (around 4 pm). Sampling points remained as planned.

Consequently, 16 samples were taken (4x4, 8 per day).

We asked to analyze DO for all the samples. However, samples taken in the afternoon could not be analyzed because CSIR-WRI lab uses to close short after sampling. Temperature, pH and conductivity were taken for every sample.

At the time of sampling, water colour was dark grey before the retention pond and light grey in P1. No smell was recorded. Only watering cans were used during these two days.

7.1.3 Faecal coliforms

As in January, water quality is improving along the network (Figure 25). We observe that the two days of sampling are quite different in terms of faecal coliform concentrations. Water

quality in the source seems to have degraded overnight, which has an impact on P1 water quality. P4 and P5 are not concerned. Figure 26 shows the distribution of the faecal coliform concentrations results and how they evolve in space and time. Complete data is given in the appendix.

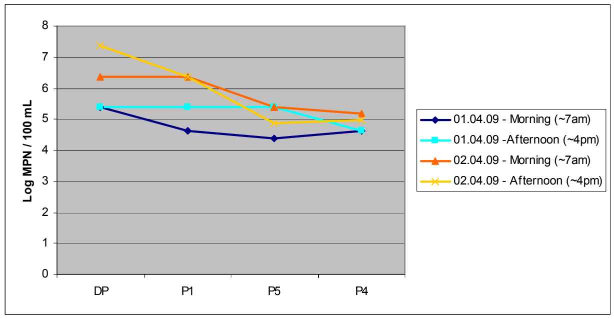


Figure 25: Evolution of faecal coliform concentrations along Network 1

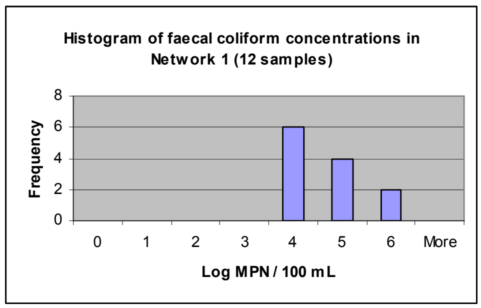


Figure 26: Histogram of faecal coliform concentrations in N1 (without water source)

We compared the concentrations obtained with those in January (Table 28). Data available is put side by side. Sampling before watering was realized in both cases around 6.30 am. In January, samples were taken at the end of the watering session in the morning, around 9 am. In March-April, as farmers were watering in the afternoon, samples were taken around 4 pm. P1 was only sampled in March-April.

Table 28: Comparison of January and March-April results for faecal coliforms in N1

	FAECAL COLIFORMS (logMPN/100mL)			
	January		March-April	
	Average (5 samples)	StDev	Average (2 samples)	StDev
Greywater source /B (6.30 am)	5.7	*1.1*	5.9	*0.7*
Greywater source /A - morning (9 am)				
Greywater source /A - afternoon (4 pm)			6.4	*1.4*
P1-N1 /B (6.30 am)			5.5	*1.2*
P1-N1 /A - morning (9 am)				
P1-N1 /A - afternoon (4 pm)			5.9	*0.7*
P5-N1 /B (6.30 am)	3.7	*0.8*	4.9	*0.7*
P5-N1 /A - morning (9 am)	4.0	*0.7*		
P5-N1 /A - afternoon (4 pm)			5.1	*0.4*
P4-N1 /B (6.30 am)	3.0	*0.4*	4.9	*0.4*
P4-N1 /A - morning (9 am)	3.3	*0.2*		
P4-N1 /A - afternoon (4 pm)			4.8	*0.2*

B = Before irrigation - A = After irrigation - P = Pond - N = Network

For what can be compared, it seems that water quality has degraded in the network, reflecting the changes that occurred in the network, while concentration in the water source is equivalent in both cases.

7.1.4 Helminth eggs

Only three samples, two of which were from the water source, contained one egg. In the rest of the samples, no egg was found, confirming that helminth eggs are not a problem in Network 1.

7.1.5 Dissolved oxygen

The four samples analyzed, from the 1st April in the morning, show that there's no DO in the water source and in P1, and a concentration of only 0.9 mg/L in P4 and P5. This is in the range of those found in January.

7.1.6 pH

pH values are comprised between 6.9 and 7.6 and decrease slightly the further to the water source, which is the contrary to what happens in Network 4. These values are in the range of those found in January.

7.1.7 Conductivity

Conductivity values are comprised between 760 and 1050 µS/cm with a tendency to decrease the further to the water source. Values in P4 and P5 are slightly lower than in January.

7.1.8 Network modifications

Modifications were not realised because of farming activities and impossibility to dry the network. It was decided to wait until the end of the rainy season, thus end of July – August.

A problem has occurred between the main farmer, Mr Mamadou Dabone, and the boys working on his land. Finally, he chased them away, so that a big part of his land was not used anymore.

Mr Dabone then began with maize. The dam was destroyed by a heavy rain. As Mr Dabone is not watering anymore, he didn't repair it and Network 1 was practically dry. Farmers on the eastern side of the network use water from individual ponds to water their crops.

7.2 NETWORK 4

7.2.1 Sampling campaign design

Sampling was planned for three consecutive days. Protocol stated to take samples at the following points (Figure 27):

1 sample in the new dam (D1); 1 sample in the old dam (D2); in P1 near the inlet; in P1 at the fetching point; in P2 at the second fetching point; in P3 at the third fetching point; in P5.

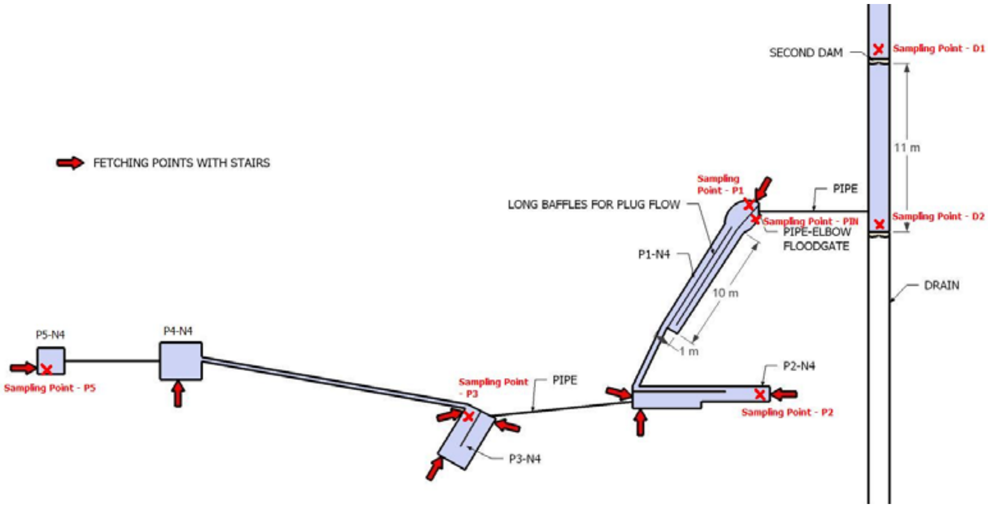


Figure 27: Location of sampling points in Network 4

Samples were to be taken in the early morning before the watering begins, at the end of the watering period (in the watering can or out of the hosepipe), and in the late afternoon (after 4 pm). Besides, one sample of runoff water was to be taken every day during the watering period before the flow reaches pond 2. This was to be done by digging a small hole in the drainage channel lined with a plastic bag. The sample could then be taken in the plastic bag.

Campaign design was justified as follows:

- Samples taken in the new and the old dam show if the construction of the second dam has had any effect on the water quality and if the latter varies between the two retention volumes.
- The sampling campaign is designed to see the variation of water quality throughout the day and the changes during the watering period. Fetching points in use are identified, as well as the use of a watering can or a pumping machine.
- During the first sampling campaign, P1 and 2 have been found to be anaerobic (dissolved oxygen = 0) with a strong H_2S smell. They may now be facultative or even aerobic. Observation of the smell is here particularly important. DO analyses will confirm the diagnostic.
- Samples taken near the inlet and at the first fetching point in pond 1 show if a water quality improvement can be achieved between the two points.
- The farmer in network 4 use to drain the runoff water from the beds to the ponds. This is difficult to avoid, as the topography of the area leads the water towards the ponds. It is thus important to observe this occurrence to may be able to explain episodes of further contamination. Sampling of this runoff water may give a first indication of its real contamination potential and lay a first basis for a pathogen flow study.

7.2.2 Samples obtained

Samples have been taken on the 25th, 26th, 27th March and 3rd April. The seven locations chosen were sampled. Samples were taken before irrigation (B = around 6.30 am) and after irrigation (A = around 10 am). Samples in the afternoon haven't been taken because of lab limitations.

On the 26th March, no watering has taken place, so that samples have only been taken in the early morning. Samples should have been taken all the same in the end of the morning to give control values which could have been compared with the other ones.

The new dam had been opened by the farmer, so that it didn't work as a new retention pond anymore (Picture 8). Hence, comparison between samples in D1 and D2 has to be made with caution.

Picture 8: New dam in Network 4's drain

As wished, flow from the source was cut during the watering period with the pipe-elbow system.

All in all, 50 samples were taken (7x7+1), i.e. 7 for each sampling point and 1 for runoff water. They were analyzed for faecal coliforms, helminth eggs, DO, pH, temperature and conductivity. Accurate observations on the context were made.

During the sampling campaign, only watering cans were used. Main pond in use was P1, and then P2. Very small activity has been recorded from P3 to P5. Smell of H_2S was been observed on the 3rd April in P1 and P2, which is an improvement with the situation before modification. Explanation for the bad smell is a water failure in the area, implying greater concentrations, as shown by the conductivity results. Otherwise P2 and P3 had a light green colour and no smell, whereas P1 had a colour varying from light to dark grey. In P1, water appearance may differ greatly between the inlet and the fetching point (Picture 9).

Picture 9: Difference in water appearance between P1 inlet and fetching point

Watering activity was lower than in January, as only 23 to 43 beds were watered, compared to more than 60 during the previous sampling campaign.

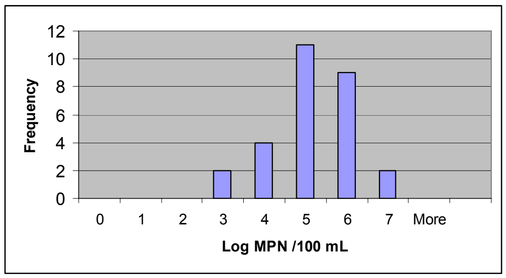
7.2.3 Faecal coliforms

Faecal coliform results are similar to those found in January (Table 29, Figure 28). Complete data is given in the appendix. Concentrations are slightly better in March-April, but it is still not possible to attribute this to our design modifications. Sampling on a longer period would be needed. Unfortunately, we didn't have any value for P1 in January.

Table 29: Comparison of January and March-April results for faecal coliforms in N4

	FAECAL COLIFORMS (logMPN/100mL)			
	January		March-April	
	Average (2 samples)	StDev	Average (3-8 samples)	StDev
Greywater source /B	7.0	*0.5*	6.9	*0.5*
Greywater source /A	7.5	*0.7*	7.1	*0.9*
P2-N4 /B	6.4	*0.3*	6.0	*0.6*
P2-N4 /A	6.3	*0.1*	6.0	*0.6*
P5-N4 /B	4.9	*0.4*	4.3	*0.3*
P5-N4 /A	5.4	*0.0*	4.5	*0.7*

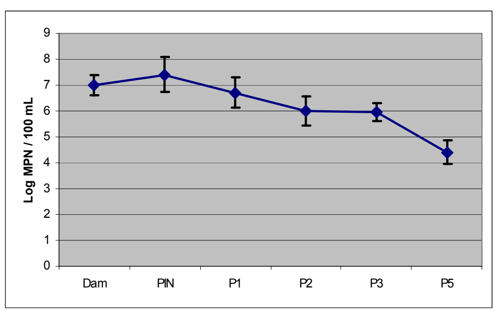
B = Before irrigation - A = After irrigation - P = Pond - N = Network



(28 samples, from P1 to P5)

Figure 28: Histogram of FC concentrations in N4 (without water source and PIN)

Faecal coliform concentration is declining along the network (Figure 29). An average reduction of 3 log units is observed between the first and the last ponds of the network. In this figure, we consider the average of D1 and D2, under the name *Dam* as the second dam has been ineffective.



(mean of 7 samples, taken before and during irrigation; error bars show standard deviation)

Figure 29: Faecal coliform concentration evolution along Network 4 in May-June

We compared in detail the faecal coliform concentrations between ponds, before and after irrigation, and compared the concentrations before and after irrigation for the ponds themselves (Table 30). Negative values in the table mean that faecal coliform concentration is higher downstream than upstream. For example, when D1/B and D2/B are compared, we made the difference between the two (D1/B minus D2/B); as average concentration was higher in D2/B, the result is negative.

Table 30: Faecal coliform concentration comparisons in N4 (spatial and temporal)

Sampling points compared	AVERAGE FAECAL COLIFORM CONCENTRATION DIFFERENCE (logMPN/100mL) *(4 samples)*	*StDev (logMPN/100mL)*
D1/B and D2/B	-0.28	*0.68*
D2/B and PIN/B	-0.66	*0.56*
PIN/B and P1/B	0.62	*0.58*
P1/B and P2/B	1.15	*0.94*
P2/B and P3/B	0.12	*0.75*
P3/B and P5/B	1.53	*0.72*
TOTAL: PIN/B and P5/B	**3.41**	***0.76***
TOTAL MODIFIED PART: PIN/B and P3/B	**1.88**	***1.02***
	(3 samples)	
D1/A and D2/A	-0.45	*1.66*
D2/A and PIN/A	0.34	*1.53*
PIN/A and P1/A	0.82	*0.50*
P1/A and P2/A	0.13	*0.41*
P2/A and P3/A	-0.06	*0.50*
P3/A and P5/A	1.56	*0.77*
TOTAL: PIN/A and P5/A	**2.44**	***0.69***
TOTAL MODIFIED PART: PIN/A and P3/A	**0.89**	***0.19***
	(3 samples)	
D1/B and D1/A	0.03	*0.45*
D2/B and D2/A	-0.05	*0.94*
PIN/B and PIN/A	0.76	*1.22*
P1/B and P1/A	0.97	*0.30*
P2/B and P2/A	-0.39	*0.85*
P3/B and P3/A	-0.20	*0.53*
P5/B and P5/A	-0.35	*0.98*

Faecal coliform decay along the modified part of the network (from PIN to P3) ranges between 1 and 3 logMPN/100mL before irrigation *(mean: 1.88, stdev: 1.02)*. Decay is lower after irrigation *(mean: 0.89, stdev: 0.19)*, partly because water quality improved in PIN. Faecal coliform concentrations vary between 6 and 7 logMPN/100mL in P1. On the contrary, they are always around 6 logMPN/100mL in P2 and P3. P5 concentrations are around 4.5 logMPN/100mL, which means a reduction of 1.5 log from P3. This can be due to the fact that P5 is the furthest to the source and, as P4 and P5 were not much used during the sampling campaign, they have a much longer retention time.

There's no significant difference between P2 and P3 in terms of faecal coliform concentration. Differences between P1 and P2 are more variable. This reflects the management practices: P1 and P2 were the two ponds in use during the sampling campaign. Hence, water flows from the one to the other.

There are no significant differences in concentration between before and after irrigation (for samples from P1 to P5: *mean: 0.01 logMPN/100mL, stdev: 0.85*), which tends to confirm what was found in the previous campaigns. However, we observe that concentration in P1-fetching point seems to improve significantly after irrigation, with a difference of about 1 logMPN/100mL. In regard to the small number of samples, we can make hypotheses to explain this. During the sampling period, this fetching point has been the most used. When water is withdrawn from it, water comes from PIN direction, but also from P2 direction. As we closed the pipe from the source with the pipe-elbow system, no water was flowing from the source anymore, which prevented further contamination (water quality remained stable in D2 (D2/B – D2/A: *mean: -0.05, stdev: 0.94*)). Thus, most water was flowing from P2-direction and, as the latter water had a better quality, its flow towards the fetching point may explain the improvement of quality after the watering period. Difference in faecal coliform concentration between D2 and P1 passed from a mean value of -0.04 logMPN/100mL *(stdev: 0.58)* before irrigation to a mean value 1.16 *(stdev: 1.31)* after irrigation. These results give a positive argument for the use of pipe-elbow system coupled with a long retention trench to separate the water source form the network during the watering period.

When we focus on the pipe-elbow system impact, we see that mean difference between D2 and PIN faecal coliform concentration before irrigation was -0.66 logMPN/100mL *(stdev:*

0.56), which means that water quality was better in the former. After irrigation, the mean value goes up to 0.34 logMPN/100mL *(stdev: 1.53)*, representing a relative improvement of about 1 log. This can be attributed to the pipe-elbow system. Indeed, as water was withdrawn in the network, water would have otherwise surely flown from the source to PIN, equalizing water qualities.

The extension of P1 with the long baffles, leading to a 20 m distance between the inlet and the first fetching point seems to have a positive effect (Picture 9). Reduction in faecal coliform concentration has a mean value of 0.62 logMPN/100mL *(stdev: 0.58)* before irrigation, and 0.82 *(stdev: 0.50)* after irrigation. Consequently, we see that the retention trench account for a quite stable permanent improvement, whereas pipe-elbow system account for before/after irrigation improvement.

We observe that the greatest faecal coliform concentration before irrigation is found in PIN, and shifts to D2 after irrigation, except for Day1. Explanations for this may be settling in PIN, as well as variation in source contamination. For example, we can assume that at the time when most washing activities take place, bacterial quality is better. Thus, differences between PIN and the source are highly dependent on the time when water flows between the two. These results should be confirmed with further sampling, as three samples are not sufficient to make definitive conclusions. Especially, water quality on the 3rd April before irrigation was particularly bad in PIN (8.66 logMPN/100mL, which can be considered as an extreme value).

We observe as well that differences between D1 and D2 are highly variable, and may be positive or negative. This is due to the fact that D1 dam was opened by the farmer. This could even have created a channelling effect (short-circuiting) (Figure 30), which makes results very sensitive to the sampling point location (in the wastewater flow or in a hydraulic dead zone). It could also be explained by a variation in inflow contamination.

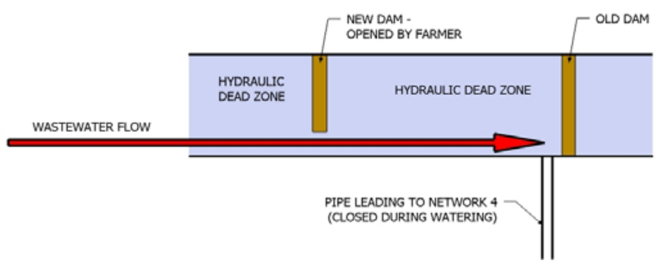


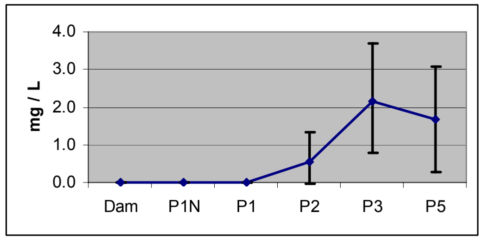
Figure 30: Explanation scenario for wastewater flow in Network 4's drain

7.2.4 Helminth eggs

Out of the 50 water samples that were analyzed, only 3 contained helminth eggs (twice one egg and once 3 eggs). Only one egg was found in the network itself. Helminth eggs are definitely not a problem in Network 4.

7.2.5 Dissolved oxygen

Dissolved oxygen concentrations are still very low (Figure 31). However, it is better than in January, as some dissolved oxygen may sometimes be found in P2, which was not the case before. This is a sign that biological activity now takes place in this pond, even if still low.



(mean of 7 samples, taken before and during irrigation; error bars show standard deviation)

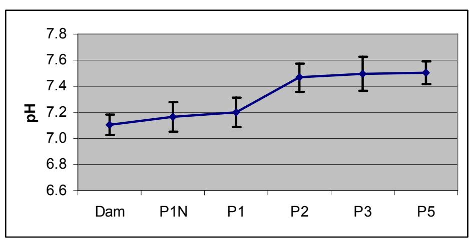
Figure 31: Dissolved oxygen concentration evolution in Network 4

DO concentration increases in P2 to P5 during the morning, up to 4 mg/L in P3 and P5 at 10 am. Concentrations in P2 may reach 1.5 mg/L at the same time.

In further sampling campaigns, we recommend collecting data in the afternoon, to see how high concentrations can become during peak photosynthetic activity and to see if this can account for some faecal coliform removal.

7.2.6 pH

pH increases slightly along the network (Figure 32) and values are quite similar from day to day. It is similar to what as been found in January.



(mean of 7 samples, taken before and during irrigation; error bars show standard deviation)

Figure 32: pH evolution in Network 4

Focusing on the each sampling point, we observe that pH increases in the course of morning. At about 10 am, it reaches more than 7.5 in P2, value that remains almost constant till P5. Alike dissolved oxygen, it would be interesting to have values in the afternoon during the peak photosynthetic activity. pH is an important parameter for faecal coliform removal. pH higher than 9.3 are known to have much effect on faecal coliform removal in waste stabilization ponds (Curtis *et al.* 1992a).

7.2.7 Conductivity

The three first days, conductivity remains quite stable, around 900 µS/cm. (for comparison, conductivity of tap water is around 190-200 µS/cm). The situation is different on the 3rd of April, where conductivity reaches about 1500 µS/cm in the drain, and decreases progressively along the network to reach the concentrations found previously in P3 and P5. This is explained by the change of water quality coming from the source (tap water was cut in the area on that day) and correlates to the strong smell observed. This shows how water from the source progressively enters the network, and to which extent furthest ponds can remain untouched under certain conditions, especially when water is not withdrawn from them.

Conductivity is lower than in January, period at which the average was around 1500 µS/cm in the whole network. This can only be explained by variation in source water conductivity or input of rain water.

7.2.8 Runoff water

Only one sample of runoff water was taken, near P2. Faecal coliform concentration is 7.63 logMPN/100mL, which is much higher than the values found in P2 itself. No helminth egg was found. Runoff water should be further studied to see if it can really impact water quality in the network.

7.2.9 Network management

For Network 4, we had planned to dams in the drain and a closure of the water flow from the source during the watering period. At the time of writing, both measures are not working.

In both case, the farmer said it prevented sufficient water to flow into the network. For the new dam, he surely could have waited longer before opening it, and water would have flown as before. Only the readily available water, practically part of the network water volume if the pipe is open, was reduced by this measure (Figure 22). If this is really a problem, it would mean that the water volume is not sufficient in the network. As said above, the way he opened the dam on one side may have adverse effect on water quality, as it may induce a channelling effect. Finally, after one week, both dams were washed away by a heavy rain.

As for the pipe-elbow system, the farmer said that most water was coming in the drain in the morning, during washing period. Flow is lower in the afternoon and in the evening and is not sufficient to refill the network. This is the reason why he renounced closing the pipe in the morning.

7.3 INDIVIDUAL PONDS

7.3.1 Sampling campaign design

The hypothesis we made was that each pond will have sufficient water for about three days watering and should be use alternatively, i.e. one pond will be used during three days, while the other is let untouched, and when the water of the former is finished, it is filled again but let untouched for three days, while the latter will be used. Thus, the water of each pond will have a *three-day retention time*.

The farmer should change pond when the water height in the pond in use gets to about 40 cm. Otherwise, resiltation may occur, cancelling the positive effect of retention.

Before sampling, we waited for two weeks after the modifications to allow time for the ponds to achieve a new biological and chemical stable state.

Sampling was carried out the following way:

- *Pond in use:* 1 sample taken in the pond before the watering period and 1 sample taken in a watering can at the end of the watering period.
- *Pond in rest:* 1 sample taken in the pond before the watering period and one sample taken in the pond at the end of the watering period.
- 1 sample out of the *hosepipe* when each pond was filled.

The two ponds had to be sampled like this successively, i.e. during one cycle for each.

Following observations were made: runoff in the ponds after rain or watering of neighbouring beds; changes in colour; odour (H_2S); algae blooms (green layer on water surface); rain episodes; number of beds watered; use of watering cans or pumping machine for watering.

We justify our design with the following arguments:

- Sampling before the watering period shows how the water quality varies from day to day. We can assumed that, at that time, the ponds have been let untouched for at least 12 hours. The quality found thus reflects the natural phenomena, avoiding human nuisance such as resiltation
- Sampling at the end of the watering period shows if the farmer's practice affects the quality of water, either because of resiltation, or because of runoff from the neighbouring beds.
- Samples are also taken in the pond in rest at the end of the watering period as a control. If there's no runoff, it can be expected that the quality of water at the end of the watering period is at least as good as before.
- Rain episodes can affect significantly the quality of water.
- The colour of water is a good indicator of resiltation occurrence.
- Runoff of water from the neighbouring beds can bring pathogen present in the soil or in manure, thus contaminating the pond further.

7.3.2 Samples obtained

43 samples were taken, corresponding to 1.5 cycles (rest-use-rest for PY1 and use-rest-use for PY2). Among those, 3 samples of stream water were taken. PY1 is the newly dug pond whereas PY2 is the "old" one.

The samples have been taken in two distinctive weeks (from 18th to 22nd May and from 1st to 5th June), which means that the cycles are not successive. This should be corrected in the following sampling campaigns, as it limits results interpretation.

Continuation of the sampling campaign was stopped because of rain.

7.3.3 Faecal coliforms

Number of cycles observed is not sufficient to draw general conclusions. However, results available show a potential of 1.5 log units removal in two days and a FC concentrations of about 4 log units when ponds are in use (Figure 33 and Figure 34). This is quite promising.

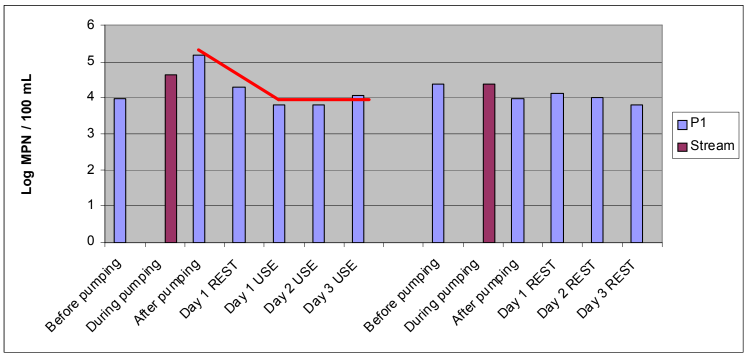


Figure 33: Faecal coliform concentrations in PY1 with alternation of use and rest periods

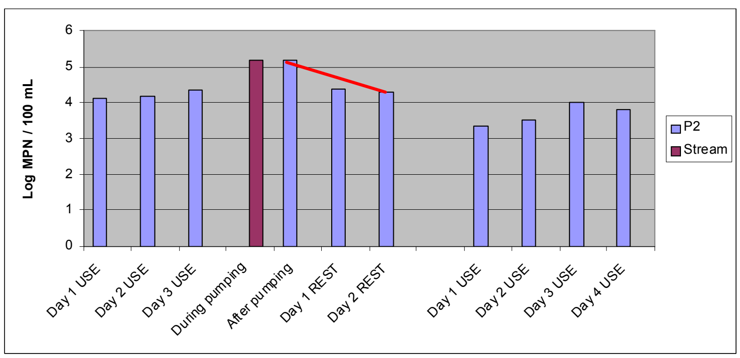


Figure 34: Faecal coliform concentrations in PY2 with alternation of use and rest periods

7.3.4 Helminth eggs

Only 5 samples contained 1 egg, and it was not assessed if these eggs were viable or not. Again, helminth eggs are not a concern in this case.

It has to be mentioned that no egg was found in the stream water samples.

7.3.5 Signs of contamination through manure

On the 3rd and the 4th June, an increase in faecal coliform concentration of about 1 log unit took place between the two morning samplings (6.50 am and 10.05 am on 3rd June and 6.40 am and 8.00 am on the 4th June). A slight increase in pH has been observed at the same time (Figure 35). Our observations show that on the 3rd June, poultry manure was applied on beds close to the ponds between the two samplings. On the 4th June, the same thing happened with

ammonia fertiliser. It is one of the first times that such a recontamination event is recorded. The impact of such events and the ways to avoid them have to be investigated.

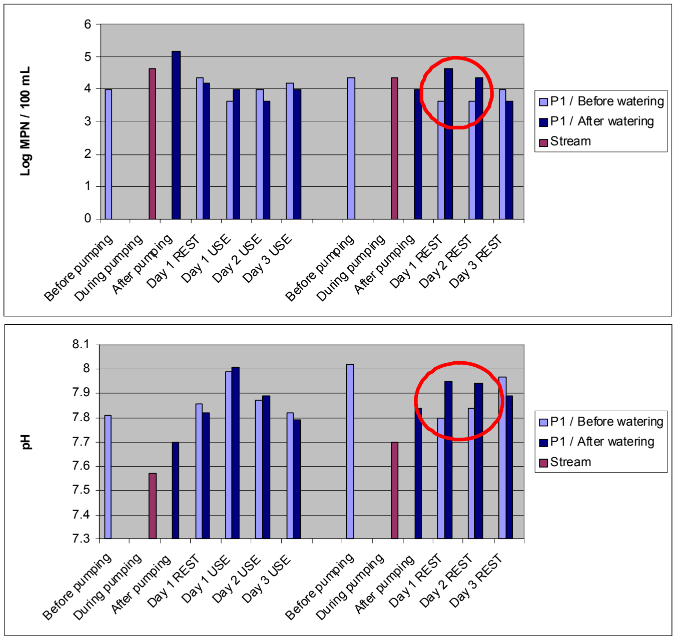


Figure 35: Increase in faecal coliform concentrations and pH in water after manure and fertilizer application on surrounding beds

8 LOGISTICS FOR CONSTRUCTION STEP

8.1 MATERIALS

After the initial discussions with farmers, materials have been searched and bought in the centre of Accra, with the help of the agriculture extension worker attached to the farmer group - Sowah (Ministry of Agriculture - MofA). An afternoon has been devoted to look at the available materials and their price: wood, plastic sheets, metal sheets, pipes, elbow. The different types of wood have been looked at in the Timber Market and the other items in specialized shops around.

A second afternoon has been devoted to buy the materials. To take it back to IWMI, a pick-up has been necessary.

Most materials needed were for the construction of baffles. For such a project, materials should be low-cost, but last long. Consequently, we have chosen the following according to the ratio quality-price:

- *Redwood*, more expensive than white wood, but that is supposed to last longer in water.
- *Light corrugated plastic sheets*, which has a good size to make baffles.

Redwood and plastic sheets have both been used for the same purpose, the baffles, as a test. If light corrugated sheets are half the price of redwood on the price/surface aspect (Table 31), they both present advantages and disadvantages. Redwood is heavy but strong, whereas plastic sheets are light but weaker. Besides, a plastic sheet is 90 cm wide, whereas redwood planks are 30 cm wide. This means that three planks are needed to cover the full-height of a baffle, which can lead to gaps between planks, whereas only one plastic sheet can make it. Thus, only the latter is impermeable. Last issue is how long these materials last, but this will be observed on the long run.

Material	Price (GHC*)	Dimension	Price/surface (GHC/m2)
Redwood	16	12ft x 1ft = 3.7 x 0.3 m2	14.5
Wakia wood	8.5	12ft x 1ft = 3.7 x 0.3 m2	7.7
Transparent plastic sheet (corrugated - thick)	35	4 ft x 8 ft = 1.2 x 2.4 m2	12.2
Transparent sheet (corrugated - light)	15	3 ft x 8 ft = 0.9 x 2.4 m2	7

** 1 GHC = about 0.85 USD at that time; the rate is subject to quick change*

Table 31: Comparison of material price to make baffles

In our case, we have used plastic sheets for plug flow retention pond baffles, as they are in total 20 m long, and wood for shorter baffles. However, it could be the other way round. Very often, it depends on the water depth.

Other materials bought are nails, wood poles, PVC pipe, pipe elbow and cement. We have also bought tools for us to make the baffles (saw, hammer), for the diggers (shovels, peaks) and for the farmers to make the stairs (trowel, head pan). Tools and pipes have been bought in Nima Market and cement in Plant Pool area. Redwood planks have been sharpened with machines directly in Timber Market.

Sand and gravel are not to be bought on the market. It is difficult to get small quantities. Normally, a truck should be ordered, which means a volume of about $5m^3$. In our case, as we don't need particular sand to put in sand bags, farmers have holed some near the stream, which doesn't cost anything. If concrete slabs are to be made, they can be made on site by a mason, provided we bring the materials. Then, he will make slabs according to the dimensions we want, with a frame.

Details and prices are found in appendix.

8.2 WORKERS

Farmers use to hire workers for various tasks: digging ponds, helping for watering and bed maintenance. Thus, hiring workers is already a common practice for them. The practice is only limited by the budget that farmers have.

Different workers and "helpers" have been hired in the course of the project. One worker has been hired to dig the ponds in Network 4 (see also "Handling money and workers", §9.5.1). He himself hired a boy to help him. In such a case, the boy works under his responsibility, and he shares the agreed sum of money as he wants. For the baffles, we have begun making them ourselves, but have then hired the help of a carpenter to saw the planks and make the wood and plastic baffles. This has been a precious help, especially for the advice he provided (way to nail plastic sheets on wood poles without breaking the plastic). The farmer's boy has proposed himself for various help (carrying the baffles, installing them, adding nails where needed, fill sand bags, install the dam).

In Network 1, we have taken the opportunity of the big dredging machine being on-site to dig the retention pond between the source and the network. The dredging machine was there to dredge the nearby stream and the drain. We have found out that this was much cheaper and much quicker than hiring workers. We also pay it to rebuild the derivation trench it had destroyed, which has been an important benefit for Network 1 farmers. They have been grateful for that.

To dig Pond Y, two workers have been hired.

Money is always an issue with workers. They always want more, and ask for some everyday. At the beginning of day, some "chop-money" should be given, for them to buy food and drinks. In the evening, money equivalent to what they have done should be case. In all case, the work should never be completely paid before it is finished! There's like a tacit rule saying that if work is completely paid, it means it is finished. Then, any further work will have to be paid extra. Besides, workers will always ask for more money, arguing that work is harder or bigger than previewed. One has to be strong and balance how far they are right.

As for the boys' help, there's no agreed price, but some "chop-money" is always appreciated.

8.3 PRACTICAL CONSIDERATIONS

Four main difficulties have arisen whilst doing the work:

- Removal of the sediments
- Clayey nature of the soil
- Difficulty to plant the baffles
- Difficulty to nail plastic sheets against wooden poles

Sediments at the bottom of ponds consist of a very liquid black mud (Picture 10). It has to be removed prior to digging. It is quite a long and tedious job.

Picture 10: Removal of sediments prior to digging in P3-N4

The clayey nature of the soil makes it hard and long to dig. When workers see how the soil is, they will ask for more money. As a matter of fact, there's a big difference between digging in a sandy soil and in a clayey soil. This also prevents the farmer to dig very deep, as it is very energy and time consuming.

Hardness of soil has made it very difficult to plant the baffles, even when the wooden poles had been well sharpened. We had to plant the baffles deep enough for them not to fall, but not too deep for the planting not to be a too big problem. It should be noticed that when we hit on a pole holding planks, there is a risk that the baffles breaks, especially with plastic sheets. That's why poles have to be hit little by little and homogeneously. Finally, we dug holes where we wanted to put the poles and filled them afterwards.

Another issue when planting the baffles is that it is very difficult to have a ground which is really flat. Consequently, we had to dig a small trench in the soil to put the baffles in, to avoid gaps under it.

Great care had to be taken to nail the plastic sheets against the wooden poles, and above all, when planting them in the ground. Indeed, they break very easily. As the carpenter suggested, plastic baffles can be made stronger by gripping the plastic sheets between the pole and another piece of wood and nail on it. Then, pressure on the plastic sheet is homogenous on the full height, which makes it much stronger.

8.4 BUDGET

The price of each design modification component has been recorded (Table 32). Cost of each material, tool and work per unit is given in appendix, as well as the accounting for the months of January and February.

Table 32: Price of design modification components

	GHC	Remarks
Digging of ponds		
Modification of 1 pond	30 - 60	*Remove sediment + dig ~30 cm clayey soil*
Dig a new pond	~100	*In a clayey soil; pond dimensions: 4 x 3 x 1 m3*
Pond dug by a dredging machine	~30	*Machine already on-site*
Baffles		
Baffles for plug flow retention ponds		*Length of baffles: 20 m; height of baffles: 0.9 m*
8 plastic sheets + 18 wooden poles + nails	139	
Short baffles (length 4 m, height ≥ 40 cm)		*For water level of 40 cm or less*
1 plastic sheets + 5 wooden poles + nails	21	
2 wooden planks + 4 wooden poles + nails	35	
Short baffles (length 4 m, 45 cm ≤ height ≤ 50cm)		*For water level between 40 and 50 cm*
2 plastic sheets + 5 wooden poles + nails	36	
2 wooden planks + 4 wooden poles + nails	35	
Short baffles (length 4 m, height ≥ 50cm)		*For water level between 50 and 70 cm*
2 plastic sheets + 5 wooden poles + nails	36	
3 wooden planks + 4 wooden poles + nails	50	
Stairs		
4 blocks + 1/2 cement bag	7	
Pipe-elbow floodgate system		
1 half PVC pipe + 1 PVC elbow	6.7	
Dam with sand bags		
15 bags + sand	1.5	

** 1 GHC = about 0.85 USD at that time; the rate is subject to quick change*

9 PARTICIPATORY PROCESS

As said above, a lot of time has been spent on the field with the farmers. It has allowed us seeing which constraints farmers have to face, but also which problems we have to face when trying to improve water quality in an urban farming area. It has also allowed us integrating farmers' suggestions into our design and to build up a confidence relationship.

Many informal discussions have been hold with each of the farmers and a meeting with Network 1 farmers has been organized in the end of one afternoon to explain how we intended to modify the network.

9.1 COMMUNICATION WITH THE FARMERS

Farmers have different backgrounds, but most of them are not very familiar with English or French. In Network 1, most farmers are from southern Burkina Faso (Garango and Tenkoudougou region) and speak to each other in Bissa. With the younger ones, discussion can be hold in French. The older people, who have been in Accra for up to 25 years, discussion should be hold in Twi. As for Network 4, Twi is the communication language.

Time has to be taken for them to gain confidence in the intervention and to make sure they really understand what is being carried on. Even three or four explanations may not be enough. In the course of the process, one has always to reassure that everything is understood.

9.2 COOPERATIVENESS OF THE FARMERS

Farmers have been quite cooperative, though it is very difficult to plan any activity with them, as they all have different activities, prone to a lot of unforeseen events.

In Network 1, speaking French has turned out to be a good asset to get into a closer relationship with the younger farm workers. The key person in the network is Mamadou "Baba" Daboné, the old man, who was the first farmer in the area in 1982, and who started digging the whole network. Almost half of the land watered from the network belongs to him or to one member of his family. He gave some parts of his land to his son Mohammed and to other young people from Burkina Faso, like Matthias, Zaccharia and Abdullay. His brother Issaka works on the neighbouring piece of land. One has to go and talk with him before beginning any activity on his land. He showed himself very cooperative as soon as he saw that we intended concrete action. He told us he was tired of people coming all year long without bringing any change.

Mamadou Daboné allowed us to dig the retention pond near his land. His boys always helped us, to take samples, but also to install the baffles.

In Network 4, situation is quite different, as we mainly have only one person to speak to, Kwame. He is very dynamic and cooperative. He did agree to all the modifications proposed and helped us to put them in place. However, he lets somehow aside the young farmer (Selassie) working at the end of his network, such that we thought at first he was working for him. In fact, he's independent and has to be integrated fully as well in the participative process. The mistake has been discovered when we made modifications on Pond 3, that both farmers use, and where Selassie also had a role to play.

Situation has not been such easy with individual ponds. We had thought first to collaborate with Blackie, the representative of Roman Ridge farmers. But each time we wanted to begin sampling, he had just filled his pond without calling us as agreed. Finally, it was too late, so that we turned to the farmer at Pond Y, who has been cooperative on the whole process. As

for the farmer at Pond H, we have been able to sample without problem, even if he's difficult to reach as he also works elsewhere. However, when modification step came, the problem arose that he was sharing the land with his brother, who didn't let us dig a second pond close to the existing one. Finally, we couldn't modify this pond.

9.3 INTEGRATING FARMERS' CONSTRAINTS

9.3.1 Permanent need of water

It is difficult to close or dry ponds and trenches for more than one day, as farmers need significant amount of water, sometimes more than the volume of the system itself for one single day. Moreover, it is not possible to deepen ponds significantly if water is still inside. Normally, farmers restore their ponds at the end of the rainy season (July/August), when corn has been harvested and vegetables still not planted. This appears to be the best time to help them dig the ponds deeper. What is more, choosing this period allows spreading the extracted materials all over the beds, before them to be prepared. Otherwise, disposal of extracted materials may be a problem, as bringing them outside the field may be very hard and expensive work.

It means also that if several dams are placed in a drain (upstream action), the quantity of water readily available in the last dam (i.e. where the water is derived from) and in the network should be sufficient to cover the daily need of the farmer. The problem happened in Network 4, where, on a day of intense watering, readily available water had been used, and the drain flow rate was not sufficient to fill the dam and the network again quickly enough. The farmer, Kwame, has then decided to open the second dam we had built, thus returning to the previous situation.

Same problem may arise when trying to close the entry of water from the source during the watering period. Before doing this, we must make sure that the volume of water in the network is sufficient. Then, we must also make sure that the quantity of water readily available in the dam plus the incoming flow in the drain is sufficient to fill the network again before the following watering period.

9.3.2 Variability of water needs and watering schedule

The quantity of water needed and the time for watering depend on the type of crops and their stage of development. For example, seedlings will need reduced amount of water in the evening, as they are quite sensitive. In all case, they will have to be watered with watering cans. On the contrary, mature cabbages demand a lot of water, and farmers frequently use pumping machines to meet this demand. These are aspects that have to be taken into account when planning water management in a farming area.

Besides, farmers are often not only farmers. They have different jobs during the day, like gardeners or security men, and work on their farm in the early morning or late afternoon. Sometimes, they may also have different farming plots in different sides of the city. This affects their watering schedule as well.

9.3.3 Difficulty to dig deep ponds

Digging ponds is hard work. Farmers usually hire external worker to dig the ponds for them. This work is long, hard and quite expensive, so that farmers usually stop to the minimal depth allowing them to fetch water easily (i.e. around 40 cm). It is only when space is very short or for individual ponds that they dig sometimes deeper.

Work is made even harder in Roman Ridge as the soil is clayey, thus quite hard to dig in. Workers know it as they ask for more money when they see the nature of the soil.

This means that, in the perspective that the farmers should reproduce alone what we propose, it is unlikely that they will dig to the recommended depth in such conditions. The effort is too big for the expected benefit.

9.3.4 Energy needed to carry water

Carrying two watering cans of 15 liters each is a big effort, especially when it is repeated dozens of times in a few hours. That's why farmers always search for the shortest way to fetch water. This has to be taken into account when planning the fetching points. In fact, all the existing fetching points should be kept and the design should adapt with it. They are already an optimization made out of farmers' habit.

9.3.5 Lack of space

Many farmers don't have a large farming area, so that every square meter counts for them, especially when they are lent a few beds to earn a minimal living, as it is the case for a few young people in Network 1. Moreover, soils in the area are poor. They are sandy on surface and vegetables never grow big. Design modifications of ponds and trenches should consequently not involve further land uptake.

9.3.6 Lack of land tenure

Our study confirms that lack of land tenure is a major constraint towards improvement of on-farm water quality (Faruqui *et al.* 2004; Mubvami and Mushamba 2006). As farmers don't have any legal status, they can potentially be chased out anytime. Consequently, they are very careful not to hurt the government, neighbours and owners of the land. Especially, they don't want to build solid infrastructures, as owners may see it as a *de facto* appropriation of the land and fear to lose the grab over it. This is particularly true in Roman Ridge, where the land, though officially possession of the railway company is still owned by Ga people, the natives of Accra. Indeed, it appears that this land had been sold to the railway company, but Ga people never got paid, so that they feel they still own the land. Ga people are not well organized anymore; they are not under a single authority, so that independent groups frequently come to the farms to claim for some vegetables and control that the farmers haven't built anything. That's the reason why farmers don't agree to put any concrete, or to dig too big ponds.

9.3.7 Nuisance affecting neighbourhood

The dams that the farmers build on the drains create areas of stagnant water, prompt to become mosquito breeding areas. Conflicts may then arise between the farmers and the neighbours. It is the case in Roman Ridge. This parameter should also been taken into account when planning water treatment upstream in drains. For example in Network 4, the number of dams that can be placed in the drain is limited to two, as an informal settlement is present 80 meters upstream of the farming site.

Sometimes, stagnant water may also release unpleasant smell, especially when it turns to anaerobic conditions, as observed in Network 4.

9.3.8 Lack of financial resources

Farmers and their families live on a shoestring. Their money is hardly sufficient to send their children to school and they often have to face two jobs to live. Thus, every expense is counted.

A good example for water management on the farms is the use of pumping machine. They will use it only when they have to, because fuel has a significant cost. This means that we cannot propose a solution where they would have to often use a pumping machine.

We have proposed the use of baffles to improve water quality. This has to be tried, as the impact can be good and may give good indications for the design of future networks. However, it is unlikely that individual farmers will invest in construction or roofing materials to put into water.

9.3.9 Flooding

Major part of Roman Ridge farming area is prone to flooding during the rainy season, from May to August. When ponds and trenches are immersed in running water, it is clear that they will suffer from important input of earth and sand. In the end of the rainy season, farmers have to restore them. This is also a reason why they don't dig the ponds too big or too deep: they would have to repeat the effort every year. For us, it also means that putting in place a more important infrastructure would mean protecting it against flooding.

It has been discussed to build two or three dams in the drains as upstream treatment action. During heavy rains, dams are destroyed by the current. In a way, it is good as drains have to be able to evacuate excess water and are already often underdimensioned. However, it also means that no solid infrastructure can be built in such drains, unless it is planned with the government and build in a way that it doesn't block the flow of water during heavy rains but guarantee enough water to the farmers in normal times.

9.4 INPUTS OF THE FARMERS IN THE DESIGN

On top of the constraints described above, which influence indirectly our design, the farmers have also participated directly with some practical suggestions.

This has particularly been the case with the modifications of the fetching points. They have proposed the use of blocks from demolished buildings instead of concrete slabs to make the stairs, which is much cheaper and much stronger. Then, they required the use of a little bit of cement to bind the stairs together, to prevent them from sliding on the clayey mud after a while and to make them much more sustainable. They have also proposed, for the ponds where a homogenous digging would be difficult, to dig the pond deeper around the fetching point, which would reduce the effort but have an effect on resiltation.

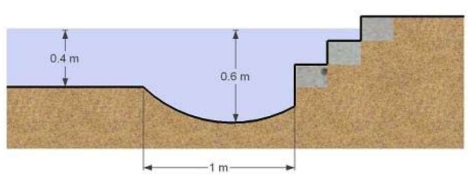


Figure 36: Fetching point with non-homogenous depth

The meeting with the farmers in Network 1 has allowed determining how to synchronize best the modifications with their farming practices. They told us that they use to restore the

trenches and ponds after the rainy season, and that they can then incorporate the excavated materials into their beds.

9.5 Role and responsibilities of the farmers

9.5.1 Handling money and workers

At first, we wanted the farmers to take the responsibility to deal with workers and to make the price. We wanted the farmers to choose the workers, which could bring some revenue to some relatives or friends, or even to their young workers. We tried it with the modifications in Network 4. We realized very quickly that this had put the farmer in a delicate position. On one side, we were helping him and, acting this way, wanted him to manage fair prices with the people he would employ. On the other side, the workers, in this case, the brother of the farmer, saw that he was working for a project and has always been asking for more money. The farmer didn’t dare to say anything to the worker, so that we ended up treating directly with him. This problem has also risked spoiling the relationship we were entertaining with the farmer.

When we asked farmer at Pond Y to choose a worker, he proposed a friend, who gave a huge price for the work to do. The farmer was not in the position to say openly that it was too much. Then, we agreed with him that it we would deal with the workers directly, which was a relief for him.

The price should be made according to soil quality. In our case, the soil is very clayey and thus hard to handle with; when estimating the price of a work, experience has shown that one has to differentiate well between sandy and clayey soils. The price will be negotiated for the work and is independent of the number of people. Once a worker has been found, he can decide if he wants to take one or two more people to help him. He will then receive the whole money and give what he wants to the other workers.

Another question can arise when the boys of a farmer come and help. In such a case, we have given one Cedi at times, but not always, for it to remain a sign of gratefulness and not a habit.

Our conclusion is that farmers may propose workers, but that money problems are to be dealt directly with the workers themselves. Then, the farmers are responsible to supervise the workers so that they do what we have agreed to do, as far as digging is concerned.

9.5.2 Participation to the work

In order that the farmers appropriate the intervention themselves, they should participate as much as they can. As said, they often don’t dig the ponds themselves, but hire workers. One can’t ask them to dig themselves. But when it comes to improve the fetching points, they should find the blocks and build the stairs themselves. The project brings only the cement and, if necessary, the tools. Then, the farmer can do it as he wants and is proud of what he has done. Sometimes, when other people or his own boys help for the work, it may seem awkward to give some money to the others and not to him. However, this should be considered as normal as he will be the one benefiting from the project.

Sometimes, farmers lack appropriate tools for digging and construction work. We have bought shovels, peaks and trowels for them to be able to work properly. This investment has been welcomed, and has allowed building the stairs quickly and tidily. *Such an initiative should be renewed when farmers restore their ponds and trenches.* This way, they will be encouraged to dig deeper, which will benefit everybody. They will do the work themselves, which may even prevent from hiring workers. We think that lending tools is a small investment, but, in this context, lent at the right moment, is a very important step in the participative process.

10 FOLLOW-UP STEPS

10.1 MOST RELEVANT RESULTS

Up to now, the project has brought the following main results:

- There is a natural faecal coliform removal of about 2 log units from the wastewater source and the last pond of the investigated network.
- Helminths are not a problem in our context. Most of the time, no egg is found. Contamination cases only show 1 or 2 eggs per liter.
- Nutrient levels are very low.
- Constraints for design modifications are described.
- Practical experience for building and managing workers has been gathered.
- On the field, farmers have seen concrete action.

10.2 FURTHER SAMPLING

We wrote a protocol for a further sampling campaign which should have taken place between the months of June and July, with the aims to strengthen the results obtained to this point and deepen the understanding of pathogen flows in our systems. These samplings are now in stand-by because of the rainy season and ending of watering activities.

We give this protocol in the appendix as a hint to what should be done next.

11 PERSPECTIVES

11.1 UNDERSTANDING EVOLUTION OF WATER QUALITY

- Assess runoff water impact on water quality: three runoff samples were taken in Network 4 and show faecal coliform concentrations as high as in the water source. It indicates that this is a serious issue.
- Assess pathogen flows in an urban farming system: this can be done by measuring pathogen concentrations in the soil, in the manure and in the runoff water. Samples of soil and manure may be taken in N1, N4 and around Pond Y on beds from which irrigation runoff water may go into the pond. Runoff samples can be taken the same way as we did already as a test in Network 4. These analyses could prove that the main source of contamination may not be wastewater and that one should not only focus on treating the latter.
- Assess the impact of plug flow retention pond: this can be done by taking samples just before and just after the pond, several times during the day.
- Understand the factors determining the stabilized faecal coliform concentration value in individual ponds (see §5.3.2).
- Determine where helminth eggs sedimentation takes place. Samples of sediments may be taken in the dams (in N1 and N4), in the first pond of the network, and, in case of Network 1, in the trench in between. Thus, we can determine if and where helminth sedimentation takes place.
- Follow water quality through the whole day: this may give a hint about the time needed for the source water to have an impact on the quality of water in the network from the first watering in the morning, and also the time needed for concentrations to go down again. It may also explain some removal phenomena, with measures of DO, pH, COD to test the algae activity. To be comprehensive, water samples may be taken about every two hours.
- Understand the impact of using a pumping machine instead of watering cans on water quality and adapt the design to this difference of management. Flow rate of a pumping machine should also be assessed. This study can be done via a sampling campaign in Network 4. However, it seems it can't be done before end of May, as the farmer is now growing salads, which are to sensible for use of pumping machine.
- Estimate maximum quantities of water withdrawn from Network 4.
- Understand under which circumstances a floodgate system between the source and the network is advisable. This has to do with readily available water, capacity of the network to refill and social patterns of the network. Is the water quality better when the network refills quickly when we open the floodgate after the watering period or when we let the system continuously open to let the water come little by little?
- Peak pathogen concentrations in the source: impact on a network; conditions where there's an impact. Water quality in the dam varies over the day. It depends on the water arriving in the drain. This varies greatly, in quantity and quality. One can expect that the biggest inputs take place in the morning and in the evening. The volume of water retained behind a dam in a drain acts like a buffer. It is important that the outlet toward the farming area be as far as possible to the wastewater inlet. This prevents peak contaminations due to special events no to affect too severely water quality in the network. However, the way that water quality in the network is affected by the one in the dam also depends to the time when water is withdrawn from the network. If water is withdrawn during a peak contamination in the dam, a

peak contamination will also occur in the network, at least in the first ponds. Consequently, it is important to increase the buffer potential lying before the first fetching point.

- Place recipients at the bottom of the ponds we modified to follow sediment accumulation.

11.2 PARTICIPATIVE PROCESS

- Keep contact with farmers in Network 1 and lend tools for digging at the time they need (restoration of the ponds and trenches after the rainy season)
- Make a calendar of farming activities (e.g. when are they growing vegetables, or maize, or periods without crops?) Such calendar would permit to plan modifications at the most appropriate times. It's difficult to determine a calendar with the farmers. Best option is to observe what's happening on the field through the year.

11.3 FURTHER SUGGESTIONS

- Important parameters should be added in further research. Effect of *macrophytes* and *biofilm* has been shown to be important for water purification (Polprasert and Agarwalla 1994; Polprasert and Agarwalla 1995; Kone 2002a; Kone 2002b). Macrophytes increase biofilm surface areas and organic load elimination (Kone 2002b) but also prevent visible light to penetrate the water and hence lower beneficial action of algae. It should be investigated where and when they should be used in ponds-trenches networks and individual ponds. *Protozoa* may also be important (Barcina *et al.* 1997; Chabaud *et al.* 2006).
- *Use of Daphnia to remove faecal coliforms and feed fish?* Use of Daphnia micro invertebrate in wastewater treatment and food production is currently being investigated. Our project presents very good conditions to test it. First of all, it would be good to see if Daphnia species are already present in our water.
- *Fish and frogs as mosquito control?* Mosquito breeding can be a problem in retention ponds, especially if they are close to human settlements. Making a review of techniques to avoid such breeding, for example, by weeding or not, or allowing the presence of fish and frogs. Presence of biologist Dr. Patrick Baker in IWMI may be a help, as he's interested in amphibians in the ponds. If guidelines are to be written, it would be good to integrate this aspect in one chapter.
- *Use of faecal sludge to improve soil structure*: on Roman Ridge main farming area (Network 1, individual ponds), soils are very sandy in surface and crop doesn't grow well. Farmers complain about it. It could be a good opportunity to test faecal sludge application with them.

12 OVERALL CHALLENGES AND LESSONS LEARNT

In such a project, most challenges and lessons learnt are social (see chapter 9). Farmers have constraints which in turn constrain the techniques that can be applied and the way they can be applied.

As soon as we saw that traditional low-cost wastewater treatment schemes were not adapted to local constraints, we tried to developed original solutions. For example, we realized that it was very difficult to install ponds in series (facultative, maturation ponds) because the space available was not sufficient and, as gravity is used, the water level would become too low compared to ground level. We also realized that helminth eggs are not always an issue. In our case, concentrations are very low and don't deserve specific removal infrastructure like sand filters.

Some of the modifications proposed still haven't been successful, which means there's margin for improvement. For example, in Network 4, the second dam we had planned had been partially removed after a few days, to be entirely destroyed a few days later during a heavy rain. The floodgate system still has to be refined, to know under which conditions it can be used and to make sure that it results in a water quality improvement. Besides, no plunging and immersed baffles have been placed up to now. Their usefulness is still to be demonstrated in our context. What is more, we doubt that farmers would invest in baffles.

Conditions are always changing, which asks for a great adaptability on the field. It is difficult to plan sampling, as desired conditions may not be present and farmers can quickly change their mind. On some days, watering may not take place. Watering hours often change. Farmers would fill individual ponds earlier than expected. Or, major events like dredging of the main drain can affect seriously the study area. Recently, a conflict between the older farmer and his boys has led to big changes in Network 1 or, as farmer in Network 4 grows salad, assessing of pumping machine impact on water quality has to wait for at least one month. Same for sampling in Pond Y, delayed because the market was not good for selling his salads.

For construction and digging activities, we have realized that we are dependent on farming schedule, which itself is variable. This is one of the biggest lessons learnt: to be efficient, we have to help at the more convenient time for the farmer. Otherwise, input may only serve scientific purposes.

Communication with farmers may also be improved. Some farmers are tired of not seeing concrete action and some feel let aside from the process. Sometimes, big meetings with all the farmers may not be enough to make them understand and integrate everything's that would be done. Moreover, time of meeting often exclude important farmers, as some of them are only present in the early morning or late evening. Informal explanation in smaller groups, at the beginning or at the end of the day would be complementary to big formal meetings and involve the farmers better. A few farmers have also shared the desire to receive more information. In all case, they shouldn't be underestimated.

On the analysis aspect, laboratory capacity is a limiting factor. Much more samples would sometimes be needed to get a clear and definitive idea of a situation. Now that we have seen that helminth is not an issue in Roman Ridge, we may focus only on faecal coliforms. As helminth eggs analysis is very time-consuming, this could allow taking much more faecal coliform samples.

All in all, the big challenge is to get scientific results with an environment which is not a controlled one, but trying to understand deeper all the influencing factor, environmental, social, or economic will surely lead to a much more integrated way to manage urban agriculture issues.

13 IMPLICATION FOR INTEGRATED URBAN WATER MANAGEMENT

At this stage of the research, it seems that WHO multiple-barrier approach is quite appropriate as first results show that it is difficult to treat the water to harmless levels of pathogens only with small design changes. Space available for ponds construction is limited on the farms and upstream action is quite constrained in our study area by the facts that only temporal dams can be built and, in case of Network 1, the configuration of the drains don’t allow building several dams. In the long term, and in a perspective of Integrated Urban Water Management (IUWM), the best solution seems to adapt the drains for agricultural purposes. Of course, this can only be made in partnership with the government. A system of floodgate installed in the drains themselves should allow creating retention ponds during the dry season and letting the water flow freely during the rainy season. From the right beginning, drains should be made much wider upstream from farming areas to be able to store large volumes of water.

Experience also shows how heavy the lack of land tenure weighs on the impossibility for the farmers to build permanent installations. IUWM would mean that areas are given precise purposes and that everything is made to serve these purposes. A farming area should gain the status of farming area, which would allow the realization, by the farmers and by the government, of infrastructures aimed at farming areas. Adequate water quality can’t be only achieved with ponds that can’t be dug deep and big and where efforts are periodically destroyed by the rain.

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APPENDIX

Appendix 1: Complete faecal coliform results for March-April sampling campaign in Networks 1 and 4

Complete data for faecal coliform analysis in Network 4

	25.03.2009	26.03.2009	27.03.2009	03.04.2009	AVERAGE	STDEV
D1/B	7.18	6.38	7.18	6.38	**6.78**	***0.46***
D2/B	6.85	6.38	7.38	7.63	**7.06**	***0.56***
PIN/B	6.97	7.63	7.63	8.66	**7.72**	***0.70***
P1/B	7.18	6.97	6.63	7.63	**7.10**	***0.42***
P2/B	5.63	6.85	5.97	5.38	**5.96**	***0.64***
P3/B	5.97	5.63	6.38	5.38	**5.84**	***0.43***
P5/B	4.38	4.63	3.85	4.38	**4.31**	***0.33***
R (Runoff)	7.63					
D1/A	7.38		6.63	6.63	**6.88**	***0.43***
D2/A	5.97		8.38	7.66	**7.34**	***1.24***
PIN/A	7.38		6.97	6.63	**6.99**	***0.37***
P1/A	6.18		5.97	6.38	**6.17**	***0.21***
P2/A	6.38		5.38	6.38	**6.05**	***0.58***
P3/A	6.38		5.97	5.97	**6.11**	***0.24***
P5/A	4.38		5.30	3.97	**4.55**	***0.68***

B = Before irrigation - A = After irrigation - P = Pond - PIN = Pond Inlet - D = Dam

Complete data for faecal coliform analysis in Network 1

	01.04.2009	02.04.2009	AVERAGE	STDEV
DP/B	5.38	6.38	**5.88**	***0.71***
P1/B	4.63	6.38	**5.51**	***1.24***
P4/B	4.63	5.18	**4.90**	***0.38***
P5/B	4.38	5.38	**4.88**	***0.71***
DP/A	5.38	7.38	**6.38**	***1.41***
P1/A	5.38	6.38	**5.88**	***0.71***
P4/A	4.63	4.97	**4.80**	***0.24***
P5/A	5.38	4.88	**5.13**	***0.36***

Appendix 2: Cost per unit of materials, tools and works

COST PER UNIT	
Materials	**GHC***
1 transparent corrugated plastic sheet (light)	15
1 redwood board	15
Machine work for 1 redwood board	1.5
1 wooden pole	1
1 long wooden pole (1.3 m)	1.5
1 packet of roofing nails	8
1 pound nails	1
1 PVC pipe (3", ~4 m long)	10
1 PVC pipe elbow	1.7
Glue	2
1 bags of cement	10
1 block from demolished building	0.5
Sand for sand bags (taken near the stream)	0
1 bag (to make sand bag) - bought in food shop	0.1
Tools	
1 shovel	4.5
1 hammer	8
1 saw	5
1 trowel	2.5
1 metal head pan	8
Digging	
Modification of 1 pond (remove sediment + dig ~30cm)	30 - 60
Dig a new pond (in a clayey soil)	~100
1 pond dug by a dredging machine (already on-site)	30
Sporadic help	
Boy	1
Transport of material in the market (per person)	2
Others	
Pair rubber hand gloves	3.5
Pumping machine	350
Fuel for the pumping machine per cubic meter of water	~0.2
Polytank (3000 L)	504
Polytank (5000 L)	750
Polytank (10000L)	1280

** 1 GHC = about 0.85 USD at that time; the rate is subject to quick change*