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Gravity-driven membrane disinfection for household water treatment

Final report: GDMD project 2010-2014

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Photo credit front page: S.Derksen, M.Peter

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1. Introduction

1.1. Gravity-driven membrane technology background

Gravity-driven membrane (GDM) filtration - is a novel technology to disinfect water on household scale. The core element of the GDM filter is a membrane with a pore size of 20-40 nm. Water is filtered through the membrane at a very low pressure (10-150 mbar). No backflushing, cleaning or electricity is necessary to allow sustainable operation without clogging. Water flux stabilizes at 4-10 litres per hour per square meter of membrane (Figure 1, Peter-Varbanets, et al., 2010) and filters can be operated without any maintenance for 5-8 years, even with very turbid water.

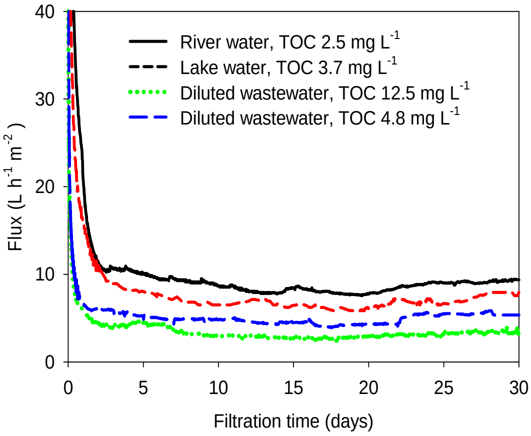


Figure 1 Flux stabilization during filtration of river, lake water and diluted wastewater (Peter-Varbanets et.al, 2010)

The stabilization of flux occurs due to formation of a biofilm on the membrane surface. The biological activity in the biofilm leads to the formation of cavities which combine into channels. As the result, the biofilm becomes porous and allows passage of water. A state of equilibrium is established between the deposition of organic matter and bacterial cells and their degradation, aggregation and sedimentation which leads to the stable flux (Peter-Varbanets, 2011). Higher organisms such as protozoa or worms lead to formation of more open biofilms and can result in a higher stable flux values (Derlon, et al., 2012). However, flux stabilization occurs also if the macroorganisms are not present. In contrast, when all biological activity is inhibited by addition of disinfectants, low temperatures or low dissolved oxygen content, membrane permeability declines steadily throughout the period of operation (Peter-Varbanets, et al., 2011). Figure 2 shows images of the fouled membrane and a biofilm crosssection done by confocal laser scanning microscopy. Pores and aggregation of the biofilm are clearly visible.

Due to biological nature of the processes, stable flux values vary depending on chemical, physical and microbial water quality. As long as biological processes are not inhibited by factors mentioned above, flux stabilization has been observed with all waters tested till now. In general, higher organic content of water alone or in combination with turbidity lead to low stable flux values. Different bacterial composition of the water source might have impact on the level of stable flux values, however, this hypothesis has not been tested yet. In laboratory conditions, lake water (Greifensee, Zürichsee in Switzerland), river water (Rivers Chriesbach (Switzerland), Glatt (Switzerland), Marne(France)), primary effluent of a wastewater treatment plant (up to 20%) mixed with river water have been tested. The results of the field evaluation of GDM filters tested with a variety of water sources in Kenya and Bolivia will be discussed in this report.

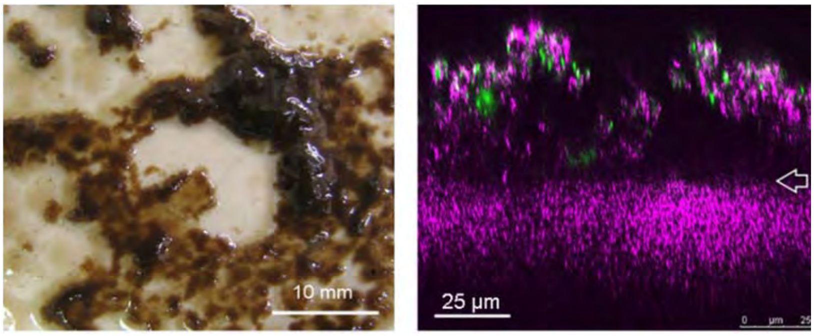


Figure 2 Channels and cavities in the fouling layer pictured by a camera (left) and confocal laser microscope (right) (Peter-Varbnets et al, 2011).

1.2. Potential areas of application of the GDM filtration

The flux values observed during GDM filtration vary between 2 and 10 Liters per hour and square meter of membrane, which is factor 5-25 less than water flux which can be obtained with conventionally operated membrane modules. Thus, GDM systems require higher membrane area to provide the same capacity as conventionally operated modules, which results in higher price of the installation. However, the need for steering and control equipment as well as maintenance requirements are considerably lower compared to conventionally operated membrane modules requiring regular backflushing, periodic chemical cleaning and relatively good raw water quality or pre-treatment. Thus, GDM filtration can be attractive when required capacity is low but provision of reliable operation and maintenance of infrastructure is not feasible due to economic or institutional constrains. These boundary conditions apply to household and community scale drinking water treatment systems in low and middle income countries as well as remote and poorly accessible areas in high-income countries.

For example, a household water filter containing 0.5 m^2 of an ultrafiltration membrane filtering polluted surface water such as a pond or river is able to produce at least 24 L/day of safe water, which is sufficient to cover drinking water needs of a family. One standard membrane module of 35 m^2 operating with similar difficult raw water is able to produce at least 70 L/h or 1680 L/day of safe water and thus supply a school with about 500 children or community with 40 families with safe water for drinking. However, if a town of 10000 people should be served with treated drinking water, other technologies or even conventionally operated membrane filtration most probably will be a more cost effective option.

1.3. GDM project of Eawag: background and objectives

The goal of GDM project started at Eawag in July 2010 was to develop a novel household water treatment system based on the GDM technology. This novel GDM system should be designed considering economic, technical and social conditions in urban and rural communities of the developing world. The focus of the project was on three fields of activities

- the evaluation of the functionality of the system under real conditions in a developing country
- the development of the user-friendly and low-cost design of the filter
- evaluation of the market based approaches for distribution

The project has been structured around three fields of activities. The major activities within these three fields are summarized in the table 1

Table 1 Project overview

	Design	Functionality	Distribution
Phase 1. Preparation	- Evaluation of membrane module configuration - Design of the α-prototype	- Evaluation of the virus removal by GDM filters	- Evaluation of the potential of Carbon market to finance promotion and distribution of the GDM filters
Phase 2. Kenya field study	- Design brief in Kenya	- Field evaluation of the functionality of α-prototype in Kenya	
Phase 3. Optimization	- Design and evaluation of the three prototypes in Switzerland	- Impact of membrane position, air trapping and re-growth on flux and water quality	- Analysis of different distribution models in Kenya and Bolivia using ceramic filters as proxies for GDM filters
Phase 4. Bolivia field study	- Design of the β-prototype “Safir” - Evaluation of the β-prototype “Safir” in Bolivia	- Field evaluation of the functionality of β-prototype “Safir” in Bolivia	- GIS-based multicriteria decision analysis to define areas most suitable for the distribution of GDM filters in Uganda
Phase 5. Finalization	- Final design, optimization and preparation for mass production	- Final analysis of the results	- Finalization of the study in Kenya and Bolivia

In this report, the two chapters Design and Functionality summarize the available information and the results of the project. Some of the activities within the project resulted in independent reports or publications published or in preparation, which will be referenced in corresponding chapters.

2. Design of the GDM filters for household use

2.1. Introduction

The design of the GDM filter consists of two interdependent aspects: the design of the membrane module and the design of the housing.

Membrane module design. In general, there are no membrane modules on the market which are appropriate for the applications in household GDM filters. The required membrane area for the GDM filters is about 0.5 m^2, while commercial membrane modules for drinking and wastewater applications usually have membrane area from about 10 m^2 to 40 m^2. For laboratory scale applications, usually modules of smaller size are used. Therefore, the modules for the evaluation in Switzerland as well as modules used in the field had to be custom made for our request, which results in higher costs of the modules. In general the costs can be lowered for large scale applications, and to estimate this we conducted discussions and negotiations with membrane companies in regard to long term plans and cost development depending on the scale. We have evaluated different membrane module configurations, such as flat sheet modules (Microdyn-Nadir) and hollow fiber modules with inside-out and outside-in flow directions (Norit X-Flow, presently Pentair). For the production of first generation prototypes (α-prototypes) which were evaluated in Kenya, Microdyn-Nadir (Germany) membrane modules were chosen. Custom-made modules by A3 were evaluated during optimization phase, and discussions with Weise Water Systems were held. Microdyn-Nadir custom made modules were also used during filed study in Bolivia. Furthermore, we considered production of our own membrane modules and discussions as well as tests with ultrasonic welding companies were done. Since any company would have to produce the modules specially for the household systems we have evaluated issues of air trapping, drying and transmembrane pressure in laboratory conditions to define position of the outflow of the permeate, as well as position of module inside the housing. The type of the membrane which can be used in the membrane module and its impact on the flux stabilization has been evaluated as well. The results of these evaluations as well as the results of the field evaluation of the membrane modules are summarized in the sections 2 and 3.

Design of the GDM filter housing. The first α-prototype of the GDM filter was design by the Eawag researcher for the field study in Kenya. The functionality of the GDM filter was the major objective of the field study in Kenya and therefore, the design had to be appropriate but not optimal. Due to the extensive studies done by PATH (www.path.org) we were aware of the impact that the design of the housing of a filter can have on its acceptability, use and willingness to pay of the users. Therefore the design of the filter was put into focus besides the technical evaluation activities and the department of Industrial design of Zürich University of Arts as well as private design company Formpol joined the project. ZHdK and Formpol worked with Eawag`s researchers to develop housing most appropriate for the GDM filter. The design brief has been conducted in Kenya to formulate recommendations on the most appropriate design to meet the water management practices, aesthetic tastes, daily handling and cultural values of the target group. The information from the field surveys was used to develop three conceptual models for the 2nd generation filters. The three prototypes have been built and evaluated in the lab. The results of this evaluation, multi-criteria decision analysis workshop with a group of experts and thoughtful analysis of the technical aspects led to the design and production of the β-prototype “Safir”. 11 Safir filters were tested in households in Bolivia. The feedback of the users in Bolivia was used to further optimize the filter and adapt it for the large scale production. The results of this collaborative work between Eawag, ZhDK, Formpol and our Field partners in Kenya - KWAHO and Bolivia -Fundation Sodis, are summarized in the Sections 2.4-2.7.

2.2. Membrane module design

2.2.1. Evaluation of the membrane material and type

During laboratory evaluations which preceded this project we have used Millipore and Microdyn Ultrafiltration membranes made out of Polyethersulfonate (PES) with the molecular cut-off of 100 and 150 kDa. In this study we have evaluated impact of different membrane cut-offs and pore sizes on flux. Although ultrafiltration membranes where chosen from the beginning for their ability to retain viruses, one microfiltration membrane was considered as well, due to higher permeability. Table 2 summarizes properties of some of the membranes used in our experiments and the stable flux values reached during GDM filtration of Chriesbach river water. Table 2 shows that average stable flux values do not differ considerably for different membranes although their initial permeability is different. Only stable flux values for the UP010 are considerably lower compared to the other membranes. This can be explained by the fact that initial water flux through this membrane is lower than the stable flux of the other membranes due to its small cut-off.

Table 2 Membrane properties and stable flux values (Peter-Varbanets et al., in preparation)

Type	Name	Separation layer	Membrane properties		Average initial permeability, $L.h^{-1}.m^{-2}.bar$	Average stale flux during days 10-45, $L.h^{-1}.m^{-2}$
			Cut off, kDa	Pore size, µm		
Microfiltration	MV 020	PVDF	-	0.2	4600	9.7
Ultrafiltration	UP 150	PES	150	0.04	960	9.8
Ultrafiltration	UF 100	PES	100	-	1520	10.1
Ultrafiltration	UH 50	Hydrophilised PES	50	-	760	9.8
Ultrafiltration	UP 010	PES	10	-	110	4.8

* Cut-off or molecular weight cut off refers to the molecular weight of a molecule which is 90% retained by the membrane

** Pore size distribution provides a quantitative description of the range of pore sizes present in a given membrane sample and indicates particle sizes likely to be retained by the membrane

One of the limitations of the application of PES membranes for GDM filtration is their vulnerability to drying. Therefore, in household GDM filters, about 50% of the membrane should always be immersed in water. Due to high humidity in the membrane tank as well as wetting of the entire membrane due to capillary transport of water, partial immersion of the membrane is sufficient to protect it from drying. As an alternative, we have evaluated newly developed PVDF UF membranes with the cut-off of 150 kDa which are resistant to drying. However, the quality of the membranes tested was low due to high number of pin-holes and relative low porosity and the stabilization of flux occurred at lower level. Therefore these membranes were not considered for the further investigations.

2.2.2. Evaluation of the membrane module configuration

Laboratory experiments have been usually conducted using circular membrane holders of 46 mm diameter and the membrane oriented towards water flow. In spite of the fact that all retained particles accumulate on the membrane surface building a biofouling layer, the flux stabilization was observed with this configuration of the membrane. As biofouling layer developing on the membrane surface can become relatively thick, we assumed that flat sheet configuration of the membrane modules with relatively large distances between membrane sheets (7-10 mm) would be better adapted for long term applications.

Flat sheet modules. In Kenya, we tested Microdyn-Nadir flat sheet modules which combine laminated membrane sheets with integrated spacer used in membrane bioreactors of “Biocell” type. The vertical orientation of the membrane sheets in the membrane modules limited sedimentation of particles on the membrane surface and led to better removal of particles detached from the fouling layer. The distance of 7 mm used in the Microdyn modules was necessary to allow free circulation of water during filling of membrane tanks or flushing of sediments.

Another company which produces high quality flat sheet modules is Weise Water Systems. WWS modules are being marketed for use as small MBRs and systems for grey water recycling. The quality of the membrane sealing is high and the modules show good stability, however, the price per 1 m^2 is higher than in case of Microdyn. Martin Systems is another producer which produces modules very similar to the WWS. The price per 1 m^2 is higher than in case of Microdyn-Nadir modules as well.

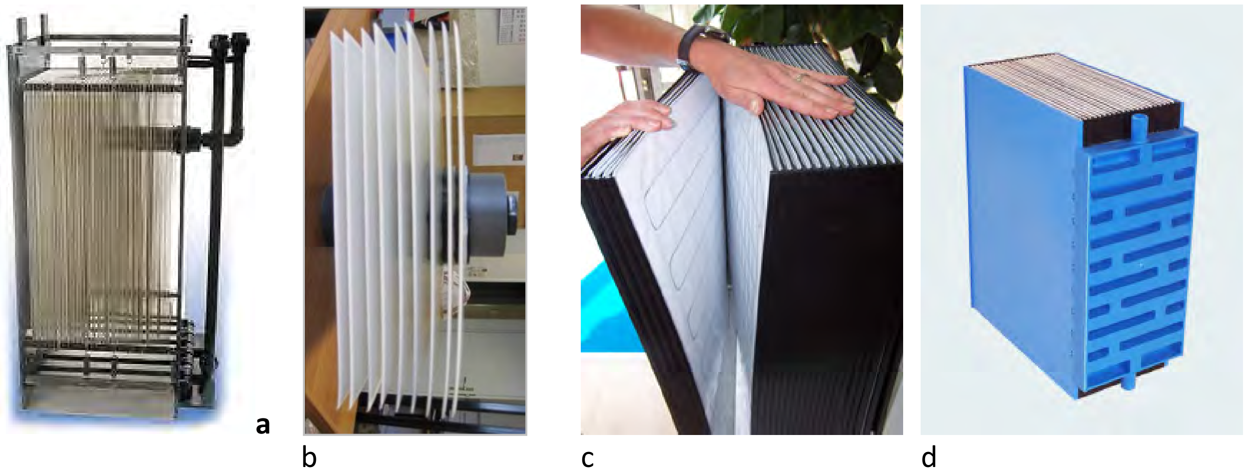


Figure 3 Images of Microdyn-Nadir (a,b) and Weise Water Systems (c,d) membrane modules (source: homepages of the corresponding producers)

Hollow fiber modules

We supposed that flux stabilization cannot be observed in hollow fiber modules due to limited space inside the fiber needed to undisturbed development of the biofouling layer and clogging of the entire fiber. To test this hypothesis we operated 3 laboratory scale hollow fiber membrane modules with “inside-out” configuration of fibers and inside diameter of fiber of 0.8, 1.5 and 3 mm and one “”outside-in” module with 0.8mm inner diameter of the fibers (Figure 4).

In these tests, untreated river water (figure 4) and diluted wastewater (data not shown) were used. Flushing of the fibers with gravity against the flow of the water has been used in case of one river water system to support removal of accumulated particles and prevent clogging of fibers. The stabilization of flux has been observed in all systems during 1-2 month, however, the values of stable flux were lower than in case of flat sheet systems operated at similar conditions and were lower for the fibers of smaller inner diameter. Flushing increased the values of stable flux for 0.8 and 1.5 mm fibers considerably. These results do not put hollow fiber modules out of question for low flux operation, however, long-term tests should be done to evaluate development of flux in time, especially with waters with high TOC and turbidity.

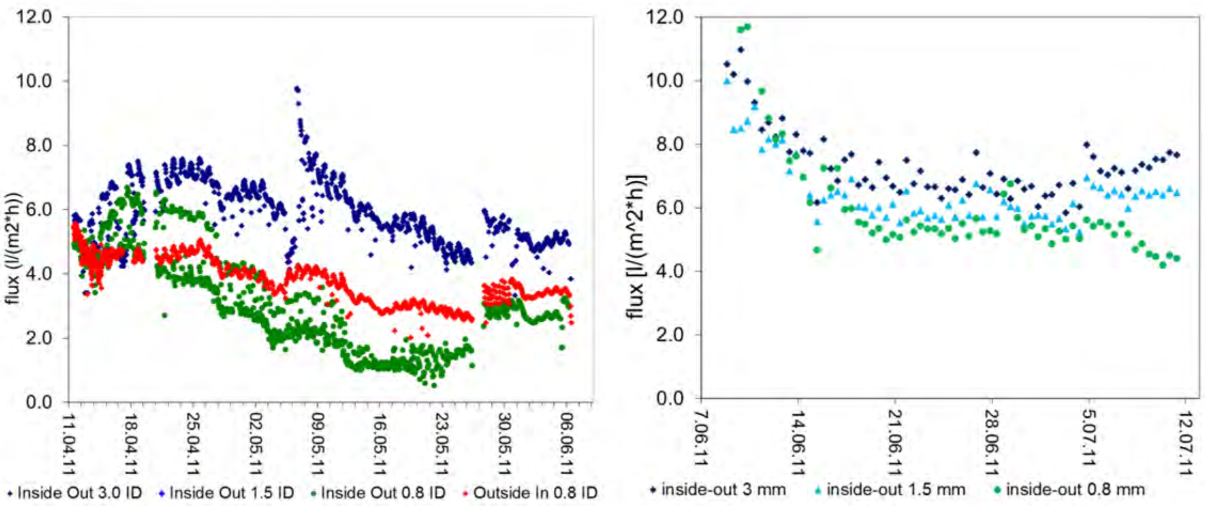


Figure 4 Flux measured in hollow fiber modules during filtration of river water without (a) and with flushing (b) at 22-30 mbar (data not published, D.Stamm)

Summarizing, flat sheet modules of Microdyn-Nadir (Figure 3 b) were chosen for further evaluation in filed study in Kenya due to higher flux values observed during filtration of Chriesbach water as well as more “open” configuration allowing flushing and sedimentation of particles.

2.2.3. Impact of the air trapping and siphon effects in modules on flux

Air can be trapped within the modules as we operate the modules without vacuum on the permeate side and at low pressure. Air trapped within the membrane modules can lead to the reduction of water flux. Experiments were conducted to evaluate what impact air has on flux and how the membrane module configuration can be optimized. Table 3 summarizes the flux values measured at the upper part of the membrane which is exposed to air during standstill periods and the lower part of the membrane which is immersed in water at 29 and 14 mbar hydrostatic pressure. The results show that air trapping leads to the reduction of flux. The reduction of flux is proportionally higher at higher pressure.

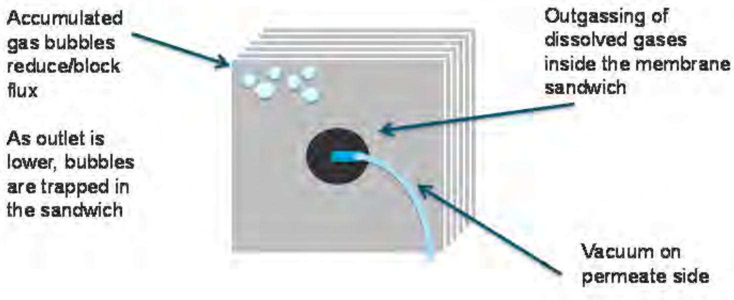
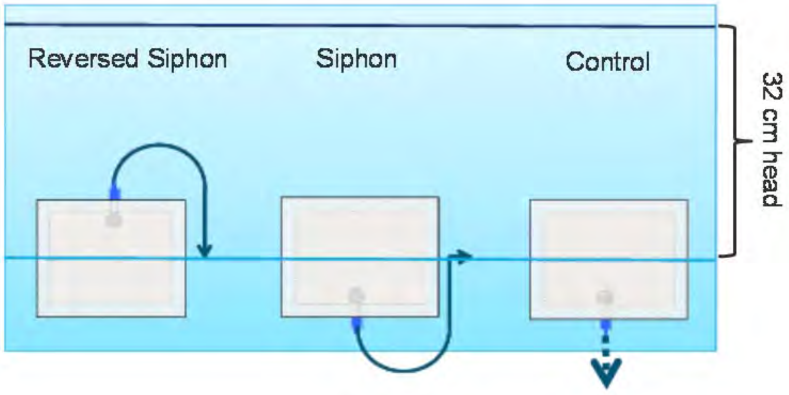


Figure 5 Schematic presentation of the air trapping within the Microdyn module (by S.Derksen)

Another issue is possibility of syphon effect caused by position of the permeate tube. Evaluation of different positions of outlet and siphon summarized on Figure 6 showed that control had the highest flux values, while “reversed siphon” position still showed 60-80% of the flux measured in the control module, the “siphon” position led to flux values of 30-50 % of the initial flux.



Thus, the results show that presence of a siphon between membrane module and permeate collection tank can lead to the reduction of flux and should be avoided.

Figure 6 Position of membrane sheets during testing (by S. Derksen)

Table 3 Water flux through the membrane (by S. Derksen, data not published)

Part of the membrane module measured	Flux at 14 mbar hydrostatic pressure, $L.h^{-1}.m^{-2}$	Flux at 29 mbar hydrostatic pressure, $L.h^{-1}.m^{-2}$
The entire membrane module	7.8	12.9
The part of the membrane exposed to air (upper half) during standstill periods	4.9	6.7
The part of the membrane immersed in water (lower part)	9.6	21.4

2.3. Parameters affecting GDM system design

2.3.1. Impact of the transmembrane pressure on flux

The flux of the clean membrane linearly increases with an increase of pressure (Peter-Varbanets, et al., 2010). However, the stable flux values do not considerably depend on pressure. At pressures over 0.5 bar, stable flux corresponds to less than 2% of the initial flux and is usually neglected (figure 7). This is one of the reasons why GDM filtration was not observed before.

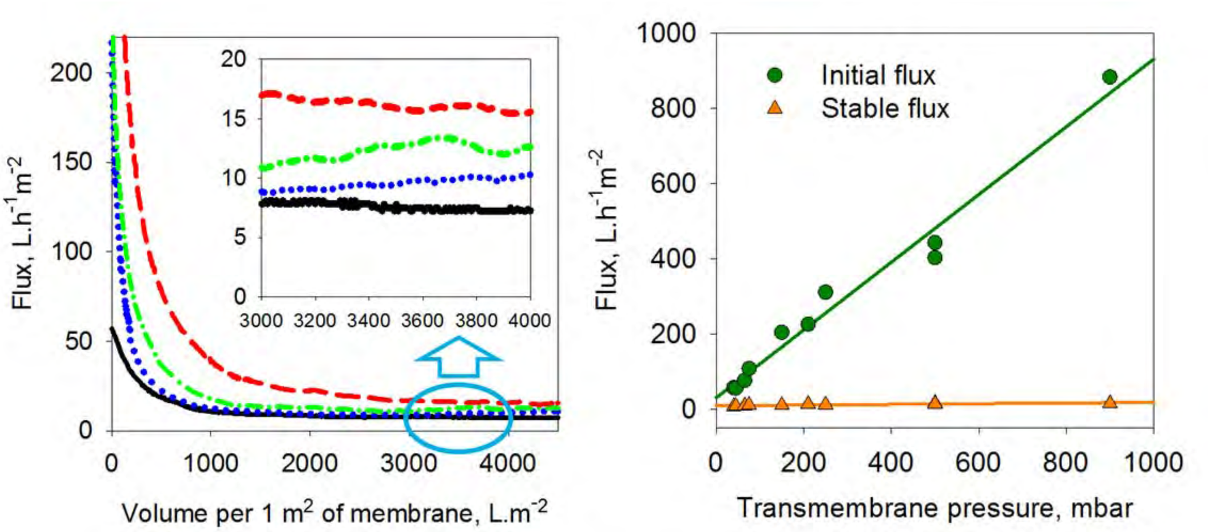


Figure 7 Flux values at different pressures during GDM filtration pressure (a) and average flux depending on pressure for new and fouled membranes (b) (Peter-Varbanets et al., 2010)

Figure 8 shows that increase or decline of pressure during operation leads to a sharp increase or decline of flux (Grau, 2010). However, over some days of operation, the slow decline / increase of flux occurs leading to stabilization of flux at the level similar to one before the change. While there is only a slight increase of flux with an increase of pressure and recovery of flux occurs over some days of operation, there is no need to operate a GDM filter at pressures over 100-200 mbar. As shown later, initial hydrostatic pressure of about 12 cm was sufficient to operate GDM filters in the field.

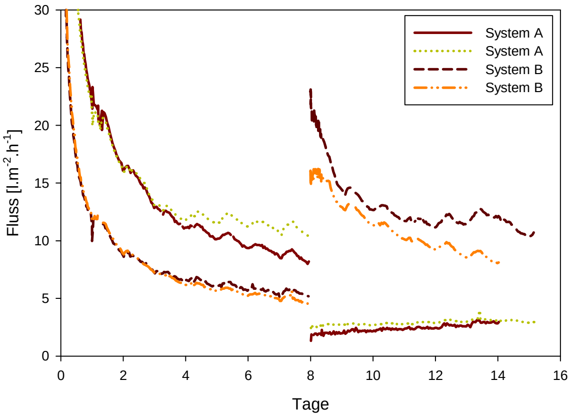


Figure 8 Impact of pressure variation during operation on flux (Grau M., 2010)

2.3.2. Impact of the temperature on flux

Since biological processes control the water flux though membrane, we can expect temperature to have an impact on flux besides increase of flux due to decrease of viscosity with temperature of water. Figure 9 summarizes the results of the laboratory evaluation of the impact of temperature on flux at 15°C, 22°C, 29°C and 36 °C. As expected, the lowest flux values were measured at lowest temperature and the stabilization of flux occured in all cases. However with an increase of temperature from 29 to 36 °C a decline of stable flux values is visible. Correction for the viscosity of water (data not shown) does not lead to the considerable change in the overall pattern of the flux curves. These results indicate that there might be an optimal temperature for operation of GDM systems and neither low nor high temperatures are appropriate for operation of the GDM systems.

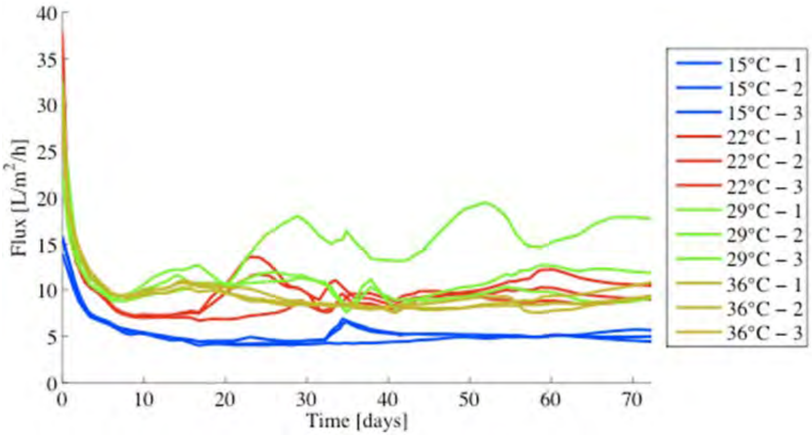


Figure 9 Flux values at different temperatures during filtration of Chriesbach water in laboratory conditions. (Kazior, 2012)

2.4. Design of the α-prototype of the GDM filter for evaluation in Kenya

The GDM filter for the evaluation in Kenya (α-prototype) was developed at Eawag using commercially available plastic boxes out of food-grade polypropylene by Hammarplast (Sweeden) and custom made Microdyn-Nadir membrane with 6 sheets and filtration area of 0.76 m^2. Transparent blue and brown boxes as well as not transparent grey boxes were used as raw water containers, transparent and opaque white boxes were used as clean water tanks. Tap available in Kenya was fixed on the clean water container to collect purified water. Plastic connectors used to direct permeate into clean water tank and fix the membrane to the wall of the container as well as permeate outflow silicon tube were used as well. The filter parts were transported from Switzerland to Kenya and assembled by local workshop in Nairobi. The integrity of all filters was tested by filtering Kaolin and measuring turbidity of water. In case no major problems were detected, water containing high concentration of *Escherichia coli* was filtered through the filters and permeate water quality measured using Nissui Compact fry plates (Japan). When no *E.coli* was detected in the permeate, the filters were loaded on a pick-up and delievered to the households. In case the Kaolin or E.coli tests failed, the place of damage of the filter was detected by bubble test and if possible and closed with double component polyurethane glue provided by Microdyn-Nadir according to their instructions.

Figure 10 GDM filter prototype α-version for the field study in Kenya (photo: S. Derksen, M. Peter)

2.5. Development of the Design Brief for the GDM filter housing

The Design Brief developed by P. Moreton (2011) summarizes general product attributes for the second generation GDM filters and has been formulated using the results of assessment of user preferences and behaviors in Kenya.

2.5.1. User preferences

The user preferences were analyzed in relation to the aesthetics and appearance of the GDM filter. The goal was to define the visual aspects of the filter relevant for local urban and rural population in Kenya. The surveys were conducted among current users of the α-prototype of the GDM filter as well as their neighbors. During the interviews, the respondents were given cards picturing basics and complex shapes, colors and patterns which they could rank, as well as give their comments and explanations during an open discussion. The respondents were questioned about their material preferences and transparency of the filter as well.

The most commonly chosen shapes were the cubic and cylindrical shapes, as they were perceived as the most stable, familiar and not taking too much free space in the household. The middle class users had more clear opinion about the shape of the filter and how it fits their households, while the users in poorer rural areas were more concerned about the storage capacity of the filter. Jar-like oval shapes were ranked low by the users although they were known to them as clay jars used traditionally to store water in some areas in Kenya and were associated with containers for carrying water.

Photograph 1 Users select the colour of the filter (P. Moreton, 2011)

Regardless of the income level or type of settlement, respondents overwhelmingly have chosen blue over other colors. The color blue was perceived as being closely associated with existing water products such as water dispensers and PET-bottles and evoked the feeling of familiarity to users. The yellow color was also identified by a number of poorer users as hygienic. The reason of the choice was the fact that dirt can easier be seen on yellow filter and can easier be cleaned. The yellow jerry cans available on local markets and frequently used to carry water might have been another reason of this choice. However, another household ranked yellow lowest, as it was the color of the tribe they dislike. The color white was disregarded by all respondents as it is impractical to clean. Most respondents prefer solid colors and not the combination of them. Patterns such as African clothes patterns or European style appearances, such as a mixture of transparent plastics were ranked low by the users as well.

2.5.2. User behaviors

Besides information on filter appearance, the design team gathered user feedback on ways to improve the product for daily use. They analyzed the existing water consumption practices, living conditions, environment the users placed the α-prototype of the GDM filter as well as cleaning practices. Two consistent recommendations were an increase of water flow through the tap, and seal the clean water tank to prevent untreated water from accidentally entering the container.

All interviewees has expressed a desire to have a stand supplied with the filter as they claim not own a suitable object on which to place a filter. The GDM filters were placed either in kitchen area in middle class homes, or in living room in the rural areas. In mud huts in the rural areas, the filters were placed close to the main cooking area in the central part of the hut. In the homes in rural areas, water was carried from the source in 20 L jerry cans and stored in larger barrels or tanks in households. The GDM filters were filled using small 3-5L jars or directly from 20 L jerry cans. The questions of water storage were perceived as important, and users generally appreciated the clean water storage tank in the GDM filter. The majority of users cleaned the surface of the filter 1-2 times a week with wet cloth. The inside part of the filter was not cleaned as we instructed the users not to do it and this was well understood.

Photograph 2 GDM filters placed on different objects in low-income households in Kajado area (by P. Moreton)

2.5.3. Design brief

Table 4 summarizes the general attributes of the GDM filter.

Table 4 General product attributes (Moreton P., 2011)

High Importance	
Easy to Use	-The GDM filter must require a low number of operational steps for the user. -The GDM filter must be easily understood through provided paper instruction without the need for outside assistance.
Durable	-The GDM filter must be able to withstand heavy handed treatment, harsh living environments such as contact with dirt and smoke and incur no reduction in performance over time. -Withstand regular cleaning or the ability to function when not cleaned or neglected. -A lifecycle of 5 years is the intended goal before the requirement for intervention and maintenance.
Low Maintenance	-The GDM filter should require minimal maintenance on the side of the user excluding general cleaning of the outside and inside of tanks.
Easy to assemble	-The GDM filter must be easy to assemble by the user with provided instructions and no outside assistance. -Parts of the GDM filter are to assemble in only one correct way.
Accessible to All	-The GDM filter must be accessible to all including children. -The GDM filter should be designed in a fashion that users are confident children can operate it without fear of breakage.
Recontamination	-Education and the design of the GDM filter should reduce the possibility for the recontamination of filtered water. -Providing additional safe water storage for home and outside usage is a method to be explored.
Cleaning	-The GDM filter must be constructed in such a manner that users can clean it independently with materials available to them.
Customisable	-A range of colours and styles should be available to users to reflect the differences in user preference between classes of people.
Portability	The issue of portability refers to the distribution of the filter, the placement of the product in homes and the transportation of filtered water. *Transportation At Distribution* -Components of the GDM filter such as the tanks could be collapsible to reduce the overall dimensions of the product to allow for easier distribution. *Product Placement* -The GDM filter should be portability to allow the user to move it around the house freely and for middle class users who desire to directly fill the membrane tank under the tap. *Filtered Water Transportation* -To encourage users to transport filtered water with them to work and school additional safe water containers could be distributed with the GDM filter.

Using these attributes, for each component of the filter, the technical and design criteria were developed. The boundary conditions, such as price of the filter, possibility of local production, distribution channels and branding were evaluated as well. Table 5 shows the summary of the technical and design criteria used for GDM filter components

Table 5 Technical and design criteria for different components of the GDM filter (Moreton, P., 2011)

	Technical criteria	Design criteria
Tanks	At least two tanks, clean water and raw water storage tanks compose the GDM filter.	Two types of alignments are possible: vertical, where one tank is placed on top of another or horizontal, with two tanks next to each other. The tanks can be separated or are permanently attached to each other
Membrane tank	Size (capacity). Current capacity of 10 L is sufficient. Sludge outlet is needed to flush sediments easily Water level indicator is needed to mark the maximum filling level Overflow indicator is needed if tanks are not attached to each other and overflow can be an issue. Overflow can me expressed as visual mark, buzzer or light. Filling. Spillage should be reduced or avoided. The size of the filling hole could be reduced. Flow rate. Should be stable over time but might be high at the beginning. Affected by intermittent operation	Color: blue Transparency: Neither fully transparent (algie) or fully opaque (water level). The membrane tank can be opaque to hide accumulated dirt, but should still have a water level indicator. Material: plastics
Clean water tank	Size (capacity). Varying storage capacity should be explored.	Color: coherent with the membrane tank Transparency: the clean water tank should be partly transparent to indicate water level and visual appearance of the tank and purified water. Material: plastics
Membrane sheets	0.5 square meter of membrane Protective casing is necessary to avoid damage Save connection to the clean water tank	
Tap	Durable and reliable, users should not have a feeling that children can break it Fast flow rate is needed	
Stand	GDM filter should be self-standing or stand should be available. In poor areas the heights of 450 mm from the floor was considered as optimal.	Supplementary stand available to buy if needed. Such stand could be done locally to save transport costs Fixed or foldable legs could be another option to provide a selfstanding filter

The overall target price of the GDM filter was set at 30 USD. Additional components such as stand can add costs to the target price. The advantages and disadvantages of production in Kenya and outside (e.g. China) were evaluated. The major advantages were considered to be reduced shipping costs, VAT and duty charges, expressed interest of customers to buy locally produced products and generate jobs, lack of confidence into quality of Chinese products. Issues of quality control in Kenya as well as lack or low quality of tools needed for production were considered as major disadvantages of local production. Regarding production in China, another advantage was considered as easier worldwide distribution and established partnerships with producers, while more complex and expensive distribution network was considered as a potential problem. In case of Kenya, some companies were visited which produced locally plastic products. Both injection molding and blow molding was possible in two factories visited (Blowplast and Elgon Kenya Limited). The companies were owned by Indian entrepreneurs with good connections to Indian producers, who would be able to produce molds for plastic production.

Owners of kiosks and small stores in Kajado selling jerry cans and buckets were questioned on the possibility of selling the GDM filters. In general, the store owners were interested in selling the filters. The storage space in most stores was a problem. Only few had enough space for storing the filters in suitable conditions. All kiosk owners purchased and transported their products from Nairobi themselves. For the majority of the stores the GDM filter would be the most expensive commodity on sale. Only some stores were selling large 5000 L water storage containers for about 380 USD. The instalment payments were a common practices in the stores.

2.6. Design and evaluation of the three second generation GDM household filter prototypes

2.6.1. Study set-up

The figure 11 shows the three second generation GDM filter prototypes. These three filters were designed considering the concept of the filter and type of membrane module connection. The position and type of the tap as well as the need for the stand or legs was evaluated independently on the concept of the filter. Following three concepts were evaluated:

- Down-flow filter produced in one part (Figure 11 a)
- Downflow filter produced in two parts which could be easily separated from each other (Figure 11 b)
- Inverted filter produced in one part (Figure 11 c)

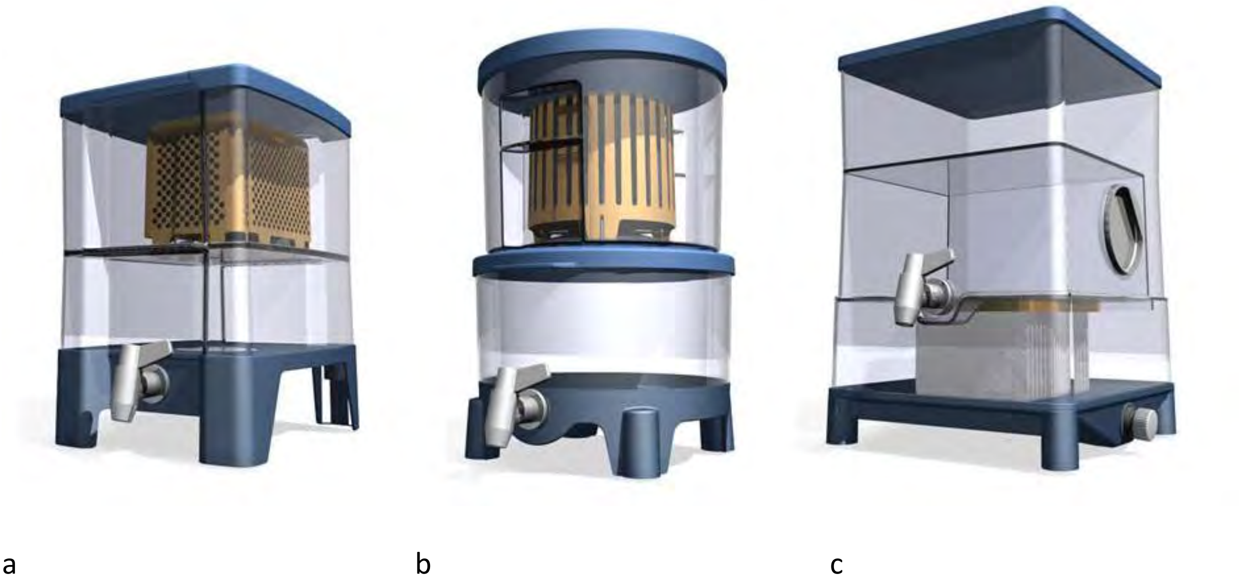


Figure 11 Drawings of the three second generation GDM filters; a - downflow filter in one part, b - downflow filter in two parts, c - inverted filter (by M. Sutter)

The membrane was either fixed in the system or replaceable. The size of the filters was kept similar for all cases. Different design concepts are shown on Figure 11 with short explanation of the major differences. The focus of the evaluation was on technical questions, ease of use and handling. The form of the filter as well as color and other aesthetic design aspects did not have any impact on the evaluation. The filters have been first evaluated in the laboratory and objective information considering each question was collected. After, a multi-criteria decision analysis workshop was held in order to define the most appropriate features of the filter configuration and housing and decide for the next steps.

Evaluation matrix containing 5 major objectives of the evaluation has been developed and is shown in Figure 12. Each criteria used during evaluation of the filter corresponds to a certain objective in the evaluation matrix. Each question was assessed considering all objectives of the evaluation matrix.

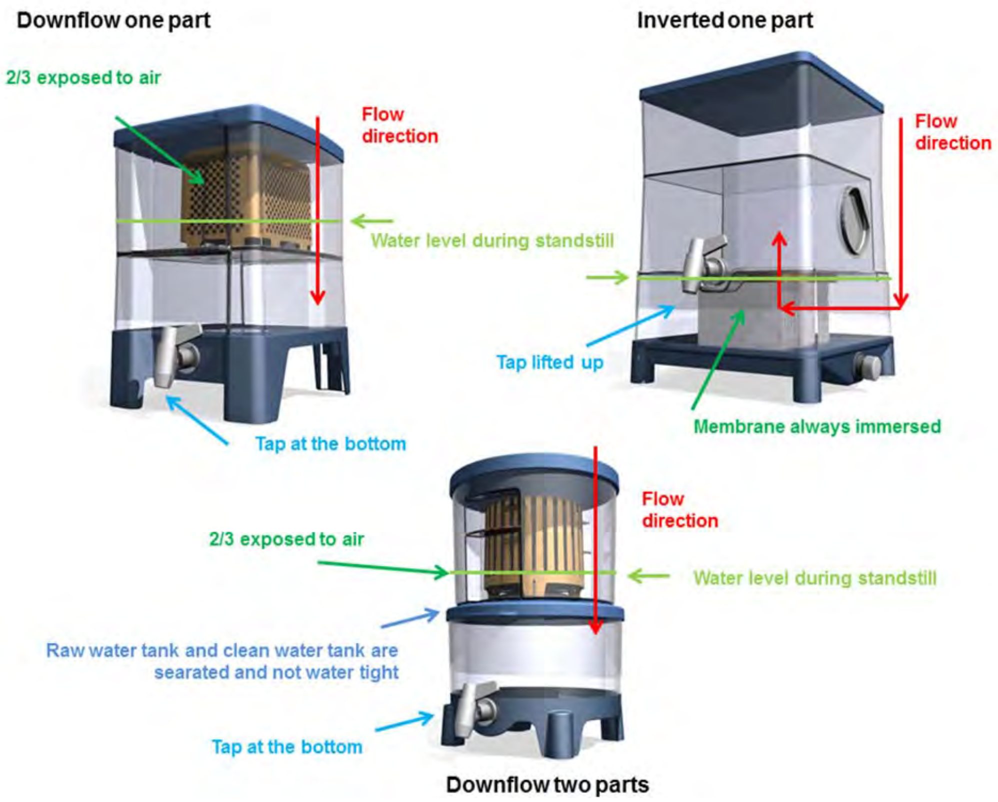


Figure 12 Three prototypes with major differences explained on the drawings (by M.Sutter and M.Peter).

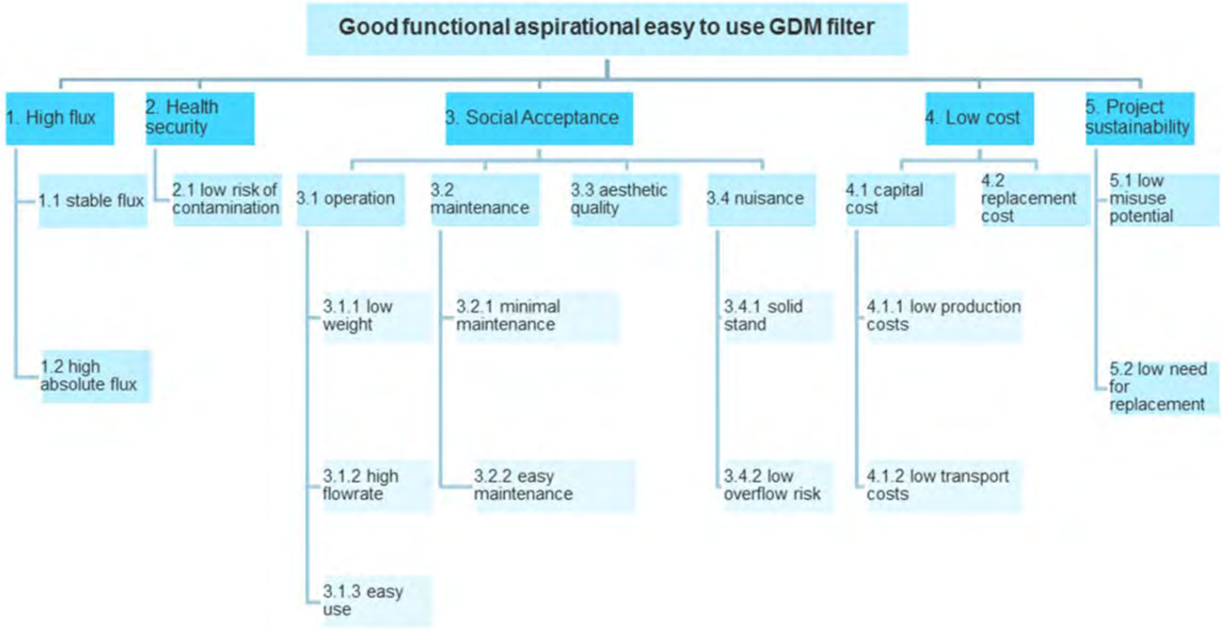


Figure 13 Evaluation matrix of the GDM filter prototypes (by Peter, M, Lohri R., Ulrich, L., Johnston, R.)

2.6.2. Evaluation of the concept of the filter in regard to technical objectives

The concept of the filter had influence on most of the objectives in the evaluation matrix. In order to obtain information on the performace of the prototypes in regard to more technical objectives 1 (high flux) and 2 (health security) experiments were conducted. Following criteria were evaluated during the experiments:

- Stable flux which included ensuring high level of oxygen in the biofilm as well as preventing membrane damage by drying
- High absolute flux which is influenced by high pressure and low membrane area loss during filtration and increase of flux during sloughing of the biofilm.
- Low risk of recontamination which was characterized by position of the tap, access to clean water tank and risk of misuse.

The system set-up was as follows. Primary effluent of wastewater treatment plant at Eawag was added to Chriesbach water and comprised about 5% of the total volume of the water used. Turbidity, COD and total cell count were measured regularly. The COD values varied during the evaluation period due to variations of COD in wastewater and the values between 30 and 79 mg O2/L were measured. The mean value of turbidity was 19 NTU with a variation between 5 and 30 NTU. All three filters were filled once a day till the top during weekdays only and were not operated on weekend. Water flux through filters was measured by Solinst level data loggers. Dissolved oxygen concentrations were controlled in situ by non-invasive optical oxygen sensors (PreSens, Germany) at the top, middle and bottom of the raw water tank containing the membrane . Figure 14 shows the position of the oxygen senosrs in the tanks.

Figure 14 PreSens oxygen spots (red dots) placed in the filters (photo M. Peter and A. Florin)

Filter design parameters

Before the start of the experiment, the basic filter design parameters were measured with nanopure water. The values of the total volume of water in the fitler, volume of filtered water as well as volume of water remaining in the filter during standstill mare summarized in the table 6.

Table 6 Differences in the design of the filters in regard to volume of water during standstill and operation periods

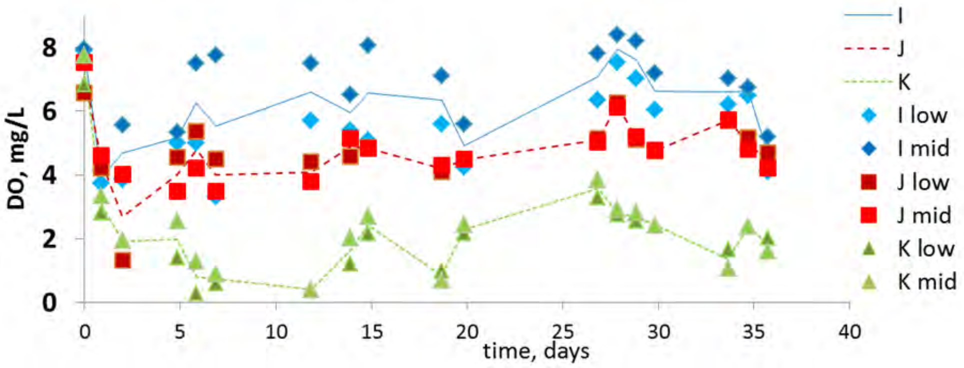
Volumes, L	**I**	**J**	**K**
Total	8.8	9.9	26
Permeate produced in 1 cycle	7	6.7	9.3
Standstill	1.7	3.2	16.8
% of new water in each cycle	80%	68%	36%
% of the membrane immersed during standstill	37.5%	0 %	100%

Table 6 shows that the filters were designed with a large variation in total volume, although the volume of filtered water (permeate) produced during one cycle was in the same range. Thus, the major difference between the inverted and both downflow filters was the volume of water during standstill and the percent of new water needed to be added to fill the filter.

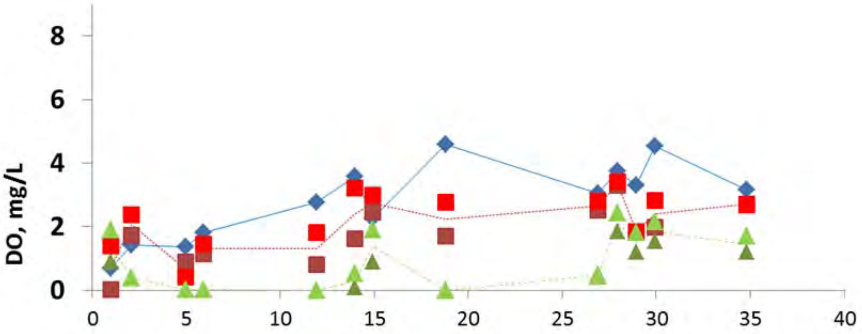
Dissolved oxygen. It was assumed that the inverted filter might rather develop oxygen limiting conditions due to large volume of standstill water. Figure 14 shows evolution of the dissolved oxygen concentrations at different points within the filter measured within first hour of operation, within 1-3 hour of operation and after 15 hours of operation. The results show that DO values in the inverted filter "K" are lower already at the start of filtration and decline to almost 0 during the first 1-3 hours while the downflow filters still show sufficient dissolved oxygen concentrations. After 15 hours of operation and standstill, dissolved oxygen levels decrease in all filters to 0 or almost 0. Thus, at the given conditions all filters experience low DO conditions during standstill period, but increase of volume of standstill water increases the period of exposure of the biofilm in the membrane to the low dissolved oxygen conditions. The design of the filter and the immersion of the membrane into residual water during standstill is the second factor which influences the dissolved oxygen concentrations within the biofilm. While in immersed filter, all membrane surface is always immersed and remains immersed during standstill, the membranes in downflow filters to at least 2/3 of the surface are exposed to the air in the filter during standstill as the filters run partly empty. This leads to increase of concentration of oxygen in the biofilm. Thus, it seems that inverted filter might get problems with low DO values in the biofilm which might lead to clogging as well as taste and odor problems caused by anaerobic processes which can occur during low DO conditions. The reduction of the volume of standstill water by changes in the design and exposure of the part of the membrane surface to air during standstill can reduce the risk of low DO conditions while still keeping the inverted configuration of the filter.

Flow rate. The flowrate through the filter was characterized by the volume collected after 2 hours and 5 hours after filtration. Since the initial water level in the filters, membrane area, exposure of membrane to air etc. were different in the filter, it was difficult to use flux values as an indicator. Figure 16 shows the volumes of water collected after 2 and 5 hours during 50 days of operation. Figure 16 shows that higher volumes of water are filtered by inverted filter during first days of operation due to higher hydrostatic pressure and no loss of membrane area during filtration due to water level drop in the raw water tank than by the downflow filters. However, these effects are reduced already after one week of operation. This is better illustrated on the figure 17 which shows the increase of volume of filtered water in time after the filling of the filter on days 0 (nanopure water) and after 26 days of filtration. After about 2 weeks of operation, the volume of produced water remain similar which indicates that flux stabilization has been reached in all filters in spite of the differences in dissolved oxygen content. High variation of the flux values is observed due to changing raw water quality conditions and high fluctuations in COD and turbidity values.

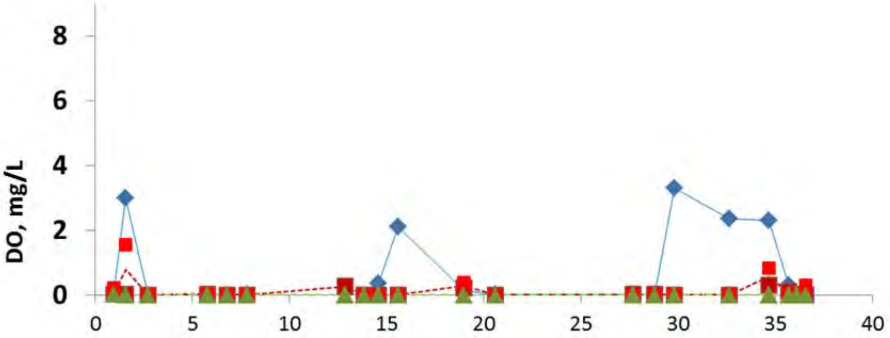
Biofilm Sloughing. Another factor which influences the decline of flux is the sloughing of the biofilm during standstill period. During the field study in Kenya we have noticed that sloughing of the biofilm was different depending on the water quality and if the membrane was immersed in water or not. Therefore the sloughing was investigated in a separate experiment. The system set up was as follows: two separate membrane sheets were fixed on plastic plates to produce two single sheet membrane modules. Both modules filtered Chriesbach river water during 4 hours per day. During standstill period one of the modules was fully submerged in water, while only 1/3 of another one was submerged and the rest exposed to air as shown on the figure 18. Both modules filtered water for 2 month and the daily mean flux values were recorded and the images of the membrane surface taken regularly. Since river water with a TOC content of about 2-3 mg/L was used, no oxygen limiting conditions were experienced during the whole period of operation during standstill period.



A: Values measured during 0-1 hours after the start of filtration

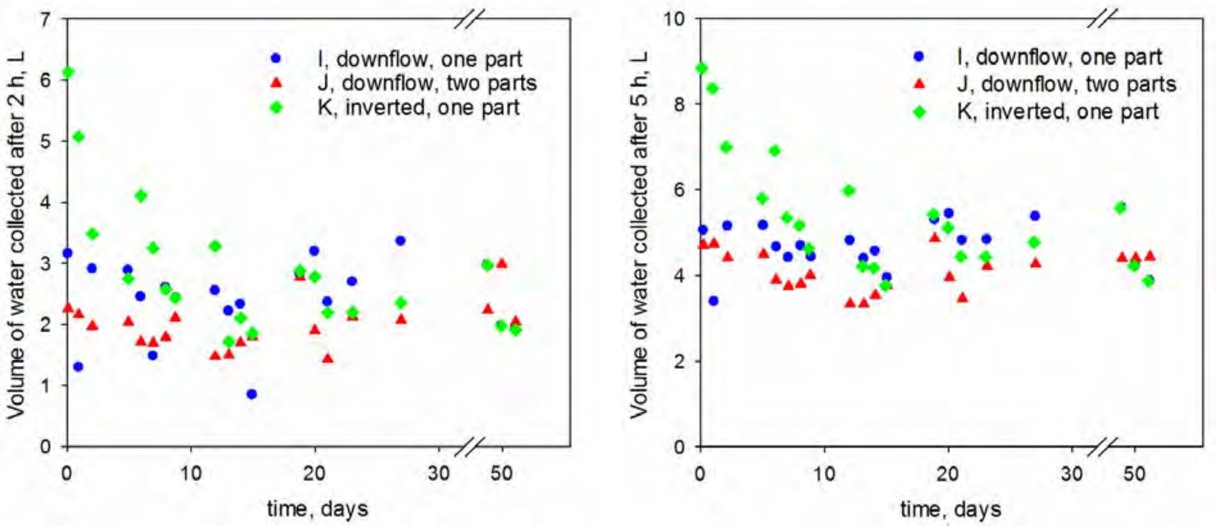


B: Values measured during 1-3 hours after the start of filtration



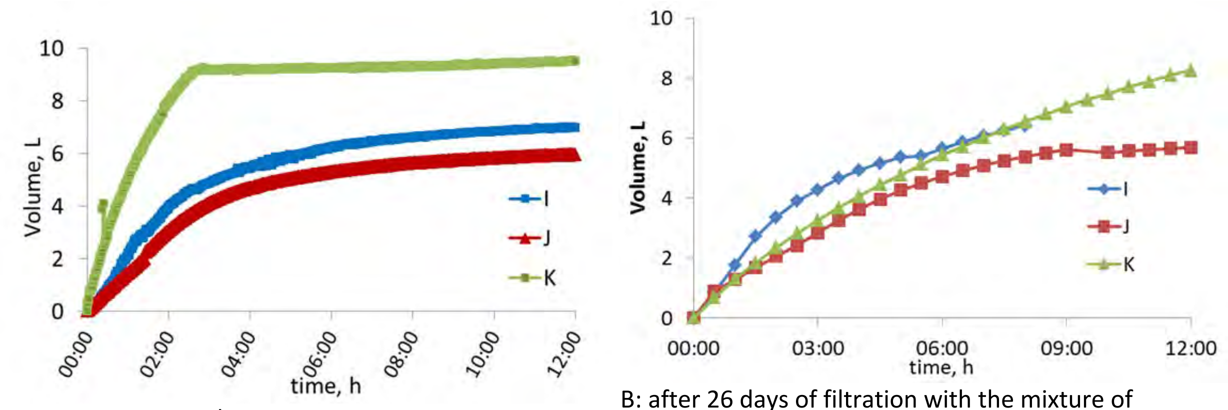
C: Values measured during 15-24 hours after the start of filtration

Figure 15 Dissolved oxygen (DO) concentrations in filter prototypes close to bottom and middle of the membrane modules. A - shows values measured during first 1 hour, B - values measured during 1-3 hour of filtration, C - DO values measured 15-24 hours after the start of filtration. I - stays for downflow filter in one part, J for downflow filter in 2 parts and K for inverted filter.



A: volume collected in 2 hours B: volume collected in 5 hours

Figure 16 Volume of water filtered through the filters after certain period of time A: 2 hours, B: 5 hours



A: nanopure water day 0

B: after 26 days of filtration with the mixture of wastewater and river water and under dissolved oxygen limiting conditions

Figure 17 Volume of filtered water in time produced by downflow one part filter (I), downflow two part fitler (J) and inverted filter (K) on the day 0 with nanopure water (A) and after 26 days of operation (B).

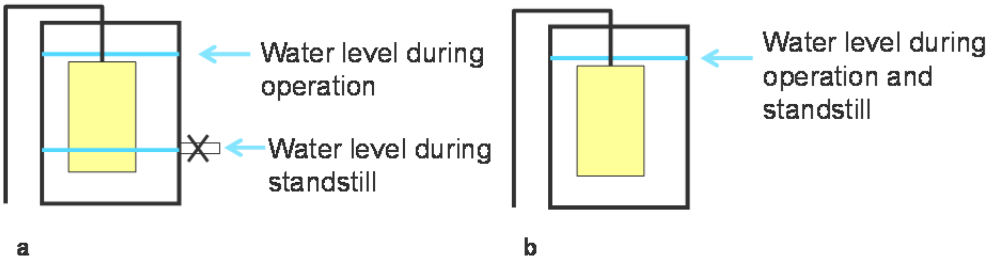


Figure 18 Membrane modules operation during sloughing experiment

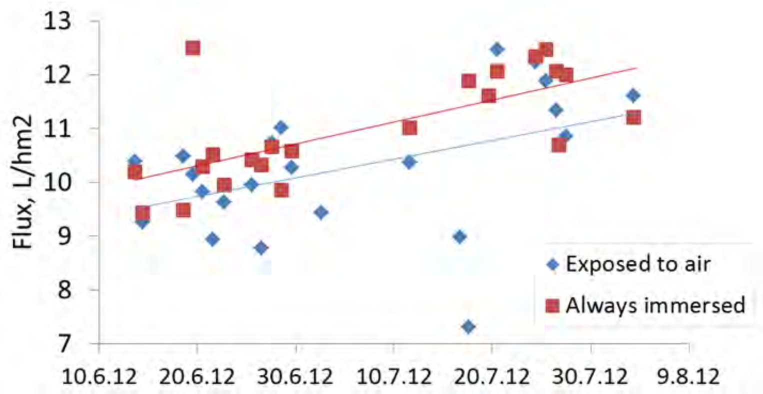


Figure 19 Mean daily flux values during operation of submerged module and module partly exposed to air during standstill period

Figure 19 shows daily mean flux values measured during 4 hours of daily operation during 2 month. The results show that mean flux values vary a lot during operation but in general the flux of the membrane exposed to air is lower than the flux of the membrane always immersed. Pictures of the membrane surface show that sloughing of the biofilm occurred after a standstill period after about 2 weeks of operation on the membrane surface which was always submerged. Sloughing could be also seen on the membrane exposed to air but not to such extent. The images of the biofilms after 3 weeks of operation are shown on the figure 20.

On the image of the membrane exposed to air during standstill (image A of the figure 20) the water level during standstill period can be clearly seen. Some empty spaces are also seen on the surface which was exposed to air, but visually it seems that the membrane surface is more covered with biofilm than in case of the membrane always submerged in water. Therefore, it seems that under given water quality and conditions, submersion of the membrane had a positive effect on the sloughing of the biofilm leading to higher flux values (as illustrated on the Figure 19).

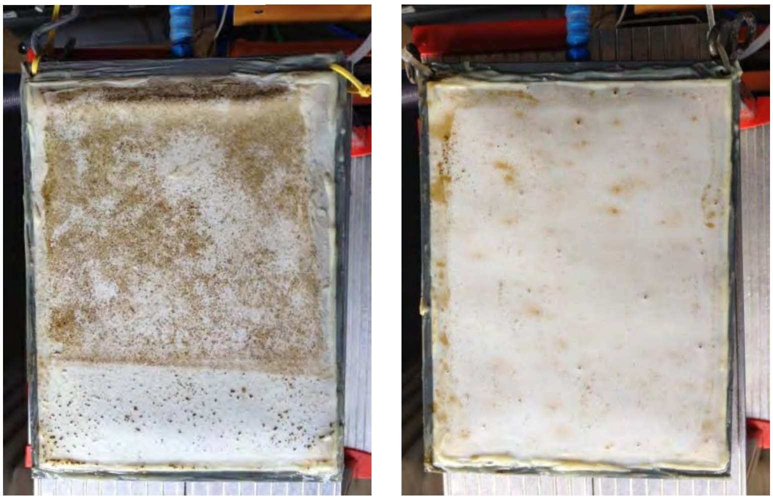

A B

Figure 20 Images of the membrane surface after about 3 weeks of operation after sloughing has occurred. A: membrane exposed to air during standstill period of 20 hours; B: membrane always submerged in water (by M.Peter)

Hygienic security. One of the major design questions discussed and evaluated during the workshop was if cleaning of the pure water tank lead to contamination and should not be easy possible, or does it improve the state of the tank and should be encouraged. There is no clear data on this question and the reactions of the workshop participants were rather based on personal experience and the perception of the hygienic conditions of the target customer group. Nevertheless, one of the issues of re-growth and need of cleaning was evaluated in the lab. Flow cytometry was used to measure total cell count before and after the membrane in order to evaluate the re-growth potential and re-growth trends occurring in the filter during filtration and standstill. Figure 21 shows total cell count measured in raw water and permeate in all three filters for a one representative day. In the raw water tank, slight decline of total cell count is observed after filling the tank and during the first hour of filtration. During the filtration cycle an increase in total cell count is observed for all filters due to rejection of the bacteria by the membrane and accumulation of the bacteria in the raw water

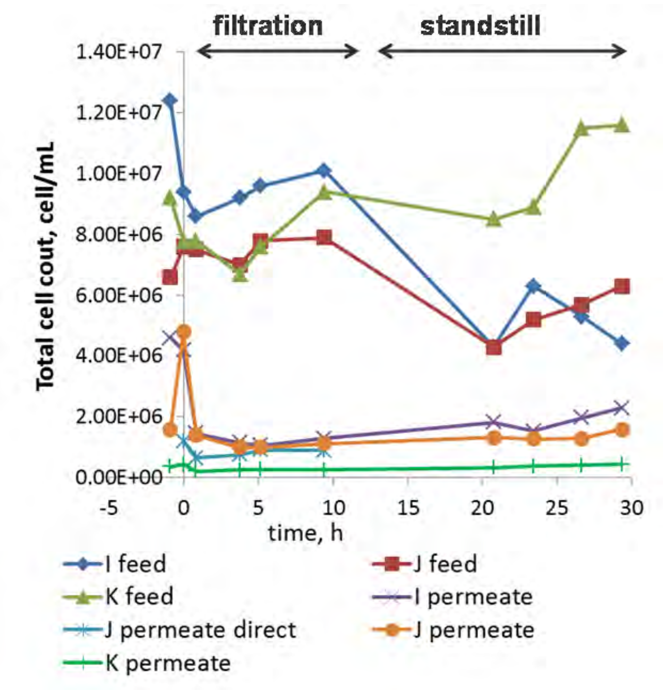


Figure 21 total cell count in raw water (feed), permeate collected at the tap and permeate collected directly after the module (permeate direct) for downflow one part filter (I), downflow two part filter (J) and inverted filter (K).

tank. After the filtration cycle during the standstill period a decline in total cell count in raw water is observed for both downflow filters while an increase is observed in the inverted filter. This can be related to the higher volume of inverted filter, immersion of the membrane and dissolved oxygen limiting conditions, but no clear explanation exists. In case of permeate, a sharp decrease of the cell count is observed within the first minutes of filtration which can be explained by flushing off the bacteria which have grown in the permeate tank during the standstill period. After the first decline, bacteria count remains stable during filtration period and increases during standstill which can be an indication of the microbial re-growth in the filter. The inverted filter shows over 10 times lower counts in permeate compared to the both downflow filters. This could be an indication of higher risk of re-contamination of the downflow filters due to easier access to the clean water tank. Overall, about 2-log removal of bacteria was observed during this experiment for both donwflow filters and about 4-log removal was observed for the inverted filter. Recontamination or low quality of the custom made membrane modules could be a feasible explanation of these values.

Thus, based on the personal experience of the workshop participants and the results of the total cell count evaluations, most participants suggested not to encourage cleaning of the clean water tank by stickers or easy removable containers, but to provide the access to the clean water tank and possibility of cleaning in case of need.

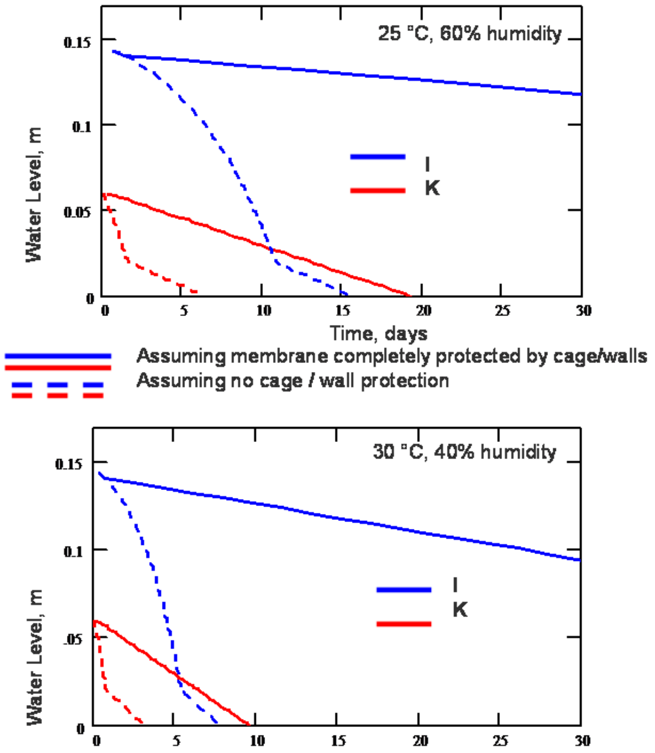


Figure 22 Water level decline due to evaporation under two different conditions. Filter "I" - 1/3 of the membrane is submerged, filter "J" - the membrane is fully exposed to air

Risk of damage of the membrane due to drying. Membranes can be damaged due to complete drying out of the membrane surface and shrinking of the pores. When only part of the membrane is immersed in water and the lid of the tank is closed, no drying is expected as the humidity within the tank is high and does not allow water to leave the membrane pores. We have modelled the decrease of the water level in the both downflow prototypes assuming that in prototype "I" 1/3 of the membrane is submerged in water, while in case of prototype "K" the membrane is fully exposed to the air and only a thin layer of water is present. The difference was also made if the membrane module is protected by cage and walls of the module, or if it is fully exposed. The results of the modelling are summarized in the figure 22 for two different temperature and humidity conditions. Figure shows that assuming no protection of the membrane with the cage, complete drying out of the filter will occur within 3 days for the membrane completely exposed to air during standstill, and about 7 days if 1/3 of the membrane is submerged in water by 30 ^{o}C and 40% humidity. In case the membrane surface is protected by cage and walls, up to 10 days is needed to cause complete drying out of the filter K and over 3 month for the filter I. Therefore, tight lid, protective surfaces around the membrane as well as submersion of at least 1/3 of the membrane in water can reduce the risk of drying out of the membrane considerably.

2.6.3. Evaluation of the concept of the filter in regard to production costs

The size of the filter as well as complexity of the form have an influence on the production and tranposrt costs of the filter. The place of production has also a strong influence on the costs. therefore, some offers were collected to compare the production costs and transport costs including taxes in Kenya and China for different prototypes. The results are summarized in Tables 7 and 8

Table 7 Production costs of the filter parts and molds in Kenya and China

Prototype type	Kenya, Blowplast, US$		China, Schmidt, US$	
	Production costs per filter	Molds	Production costs per filter	Molds
I (downflow one part)	18	-	25.6	51876
J (downflow 2 parts)	20	-	26.9	56880
K (inverted)	23	-	28.9	56952

Table 8 Costs of transport and taxes per filter depending on the place of production and assembly

In Swiss Francs per 1 filter	Housing produced locally, module imported		Housing produced in China, assembly locally		Whole filter produced in China	
	Kenya	Bolivia	Kenya	Bolivia	Kenya	Bolivia
I (downflow one part)	0.42	0.56	2.58	4.18	2.3	3.8
J (downflow 2 parts)	0.42	0.56	1.96	3.11	1.68	2.73
K (inverted)	0.42	0.56	3.36	5.54	3.08	5.16

Tables 7 and 8 show that inverted prototype is more expensive in production than the other two prototypes. The transport of the inverted filter is more expensive as well due to larger size and no possibility to stack its parts. In case of transport costs, it is obvious that local production is cheaper than other scenarios.

2.6.4. Evaluation of the concept of the filter: Workshop results.

12 participants took part in the workshop. Each objective and criteria were discussed and the results of the evaluation presented in the group. After that, using the evaluation matrix, each attribute of the objectives was given a certain weights by each participant and after that for each filter option, scores of 1 to 5 were assigned.
Table 14 summarizes the weighted individual, mean and mode scores for the three options and 12 participants. The table 15 shows the ranking of the filters according to the individually weighted scores.

Table 9 Overview of the individual, mean and mode scores weigthed with individual weights for three options. Option 1 is the downflow filter in one part (I), option 2 is downflow filter in 2 parts (J) and option 3 is the inverted filter (K) (L.Ulrich, R.Lohri).

	Individual Scores			Mean Scores			Mode Scores		
	Option 1	Option 2	Option 3	Option 1	Option 2	Option 3	Option 1	Option 2	Option 3
P1	382	331	346	350	335	339	374	315	332
P2	403	412	345	375	362	316	398	361	299
P3	385	385	275	381	366	307	400	380	299
P4	356	411	386	361	340	344	385	323	337
P5	337	322	401	338	327	369	333	312	354
P6	407	390	339	365	325	344	411	284	333
P7	334	350	277	358	343	332	380	334	323
P8	345	309	362	364	340	348	379	324	350
P9	315	305	317	363	359	315	385	375	304
P10	377	237	414	342	305	377	389	250	365
P11	365	360	223	376	355	328	406	345	313
P12	315	314	349	355	340	333	380	303	317
Mean	360.1	343.8	336.2	360.6	341.3	337.6	385.0	325.5	327.2
StDev	31.6	51.3	55.7	13.1	17.6	20.8	20.1	37.4	21.9
Median	360.5	340.5	345.5	361.7	339.9	335.9	385.0	323.5	327.5
Mode	315.0	#NV	#NV	#NV	#NV	#NV	385.0	#NV	299.0
TOTAL	4321.0	4126.0	4034.0	4327.2	4095.3	4051.1	4620.0	3906.0	3926.0

Tables 9 and 10 show that option 1 downflow filter in 1 part received in total highest weighted scores compared to the two other prototypes. The weighted scores assigned to the options 2 and 3 were similar and there was difficult to see a clear preference of the participants. Also the values of the standard deviation show that opinions were different in regard of the option 2 and 3 while the standard deviation for the option 1 is smaller. Ranking of the filter shows considerable difference in the personal opinions of the individual participants. While individual ranks strongly vary and rank counts does not show a consistent picture, the ranks identified based on the individually weighted mean and mode scores show that option 1 was clearly ranked as prefereed option while options 2 and 3 were almost equally ranked as second and third preferred options.
The results show clearly that option 1 is the most preferred option for the most participants. The analysis of the matrix table and individual weights showed that the attributes:

- stable flux due to sufficient oxygen concentrations in biofilm
- low risk of membrane drying
- optimal access to the clean water tank
- low production costs

received highest weights. Easy maintenance, aesthetic quality as well as low transport costs were considered important as well. These factors were further strongly considered during development of the next generation prototype and further evaluated in the field study in Bolivia.

Table 10 Overview of the individual, mean and mode ranks weigthed with individual weights for three options. Option 1 is the downflow filter in one part (I), option 2 is downflow filter in 2 parts (J) and option 3 is the inverted filter (K). (L.Ulrich, R.Lohri)

	Individual Scores			Mean Scores			Mode Scores		
	Option 1	Option 2	Option 3	Option 1	Option 2	Option 3	Option 1	Option 2	Option 3
P1	1	3	2	1	3	2	1	3	2
P2	2	1	3	1	2	3	1	2	3
P3	1.5	1.5	3	1	2	3	1	2	3
P4	3	1	2	1	3	2	1	3	2
P5	2	3	1	2	3	1	2	3	1
P6	1	2	3	1	3	2	1	3	2
P7	2	1	3	1	2	3	1	2	3
P8	2	3	1	1	3	2	1	3	2
P9	2	3	1	1	2	3	1	2	3
P10	2	3	1	2	3	1	1	3	2
P11	1	2	3	1	2	3	1	2	3
P12	2	3	1	1	2	3	1	3	2
TOTAL	1	2	3	1	2	3	1	3	2
Counts Rank 1	3	3	5	10	0	2	11	0	1
Counts Rank 2	7	2	2	2	6	4	1	5	6
Counts Rank 3	1	6	5	0	6	6	0	7	5

2.6.5. Choice between a tap or a flexible tube to collect treated water

Tap is the only part in the filter which has moving parts and thus can be the weakest part in the system. One of the idea proposed by our designers was to develop and use a silicon tube which is self-sealing. The main idea is that a number of tubes is provided together with each filter and can be easier replaced than tap (tap require screwing, while tube can be pulled over a tube, if material is flexible). The length of the tube can also vary depending on the needs. However, the development and testing of it is needed to verify the usability and lifetime of it. This question was not discussed during the workshop due to lack of time but within the group we decided to produce a first prototype of a tube and evaluate it.

2.6.6. Need of a stand

The filter can be distributed without stand and every household is responsible for organizing a table, stool or box to place the filter. Two other options include providing stand as a part of the filter, or providing it as additional feature of the filter, which can be purchased separately. The stand can be made of plastic or can be produced locally e.g. using aluminium or metal pipes available locally as legs and creating sockets on the bottom of the filter were they can be fixed. The major question discussed during the workshop was if the stand should be integrated in the filter, provided separately or not provided at all. Following criteria were used

- Filter stability and risk of damage of the filter due to falling in case of unstable floor or object used to place the filter on. Also in some households a suitable object such as stool or box can be not available.
- Risk of recontamination. The distance from the floor of the house to the filter tap is important to provide access to filter also to children but to avoid animals touching the tap.
- Costs. If stand is produced not locally by plastics manufactures, the costs of the filter has to include costs for production and transport of the stand, and will result in higher costs of the product. Availability of stand for additional price may result that people who needed it most will decide not to buy it to safe the money.

During the workshop it was concluded that the stand should be considered during the development of the next generation prototypes.

2.7. Safir filter design

2.7.1. Safir design criteira

The Safir filter (Figure 23) was designed by Formpol and Eawag using the results of the workshop and experiences collected during field study in Kenya and laboratory evaluation of the three prototypes in Switzerland. The following criteria where considered and implemented during the design phase:

- The filter cannot overflow
- The clean water tank is tightly closed and protected from intrusion of raw water to it even during misuse of the filter.
- The membrane is placed in the raw water tank and protected from access by users
- Clean water tank cannot be easily opened and cannot be easily accessed by users. However, it can still be opened in case of need, for example to replace the tap
- The accumulated sediments can easily be removed by shaking the filter and discharging accumulated water
- The remaining water during standstill is minimized to reduce taste and odor problems but the volume is still sufficient to avoid drying of the membranes
- Membrane can be replaced if necessary
- The filter is compact and stable
- The spilling of water during filling is reduced
- The filter can be easily lifted and carried.
- Low cost in production (minimize number and size of parts)
- Can be produced by injection molding process

Figure 23 Sketch of the safir filter (M. Bräm, F.Müller)

2.7.2. Safir filter description

The design of the filter has been described in detail in the report (Derksen S. and Graf V., 2013) and is summarized in this section. The safir filter consists of four plastic parts, two membrane module attachments (from now on called “V”) and a removable, metallic stand. The clean water tank (CWT) is the large, exterior tank with an approximate volume of 30L. It is 40cm high, 25cm x 31.5cm at the bottom and 29cm x 39cm ant the top. The internal tank is the raw water tank (DWT), has a volume of 14.5l and clicks tightly into the CWT at the top rim. This connection is purposely very hard to open, but can be opened by a single person with some effort. A spill protector is permanently fixed on top of the DWT in order to protect the membrane from being damaged. A honey comb – like plastic grid is part of the protector, through which water is filled into the tank and its shape protects water from spilling water back, out of the tank. A top lid is supplied to close the filter completely, protecting the filter from dirt and minimizes evaporation from the membrane tank. Two manual modifications are done to the filter body after it is delivered from the prototype company. With the current design, removing the spill-protector is effortlessly possible. Therefore the spill-protector is almost irremovably attached to the membrane tank with six screws. Furthermore the attachment of the V-shaped membrane holders is reinforced by clamping in plastics blocks.

An ultrafiltration membrane (150 kDa cutoff, ca. 20nm pore size) module with 3 sheets and a total surface area of 0.35m^2 is installed in the raw water tank of the filter. To attach the module to the filter, two grey end caps are screwed to the module, attaching the “V” to the module and connecting the permeate side to a short silicon tube (16 mm outer diameter, wall thickness ca. 1.5-2mm) which is connected to the outlet of the DWT, directing filtered water into the CWT.

Instructions on how to use and maintain the filter are printed on stickers and pasted onto the surface of the CWT and the spill protector. Sticker “USE” is placed next to the honey comb and “CLEANING” instructions are on the left side of the CWT. Two decorative stickers with contact information are above the tap and on the right side of the CWT.

Figure 24 stickers with the logo, contact information and the cleaning recommendations (M.Bräm., F.Müller)

2.7.3. Design evaluation in Bolivia. Field study set up

The goal of the field study was to involve users in the filter`s design optimization process and test its functionality. Handling and design were evaluated through structured interviews, discussions, workshops and video recorded observations. The evaluation of the Safir filter prototype was done in comparison to the locally available ceramic candle filter. The ceramic filter was included in the study in order to give participants a possibility to imagine how functions and design of the filter can be different and be able to compare different features of the filters, such as handles, form, lid, etc. The ceramic filters were locally assembled by Sodis foundation in Cochabamba, Bolivia. The ceramic filter candles (Stefani S.A., Brasilia) had a pore size of 0.5-1 µm, were coated with colloidal silver and filled with grabular activated carbon. The locally available plastic buckets were used as raw and clean water containers (volume of 15 litres and 18 litres accordingly). Figure 25 shows drawings of the Safir and ceramic filters and the major sampling points.

Two field sites were selected: Encanto Pampa, a peri-urban community in highlands with a warm semi-arid climate and San Benito, a rural community in low-lands with a tropical climate. 11 families could participate in every site. The table illustrates the list of criteria for the choice of the families and sites. These criteria were discussed with the local authorities, which recommended certain families for the participation in the study. The families were visited and a short interview conducted in order to confirm the choice and obtain and agreement of the family members.

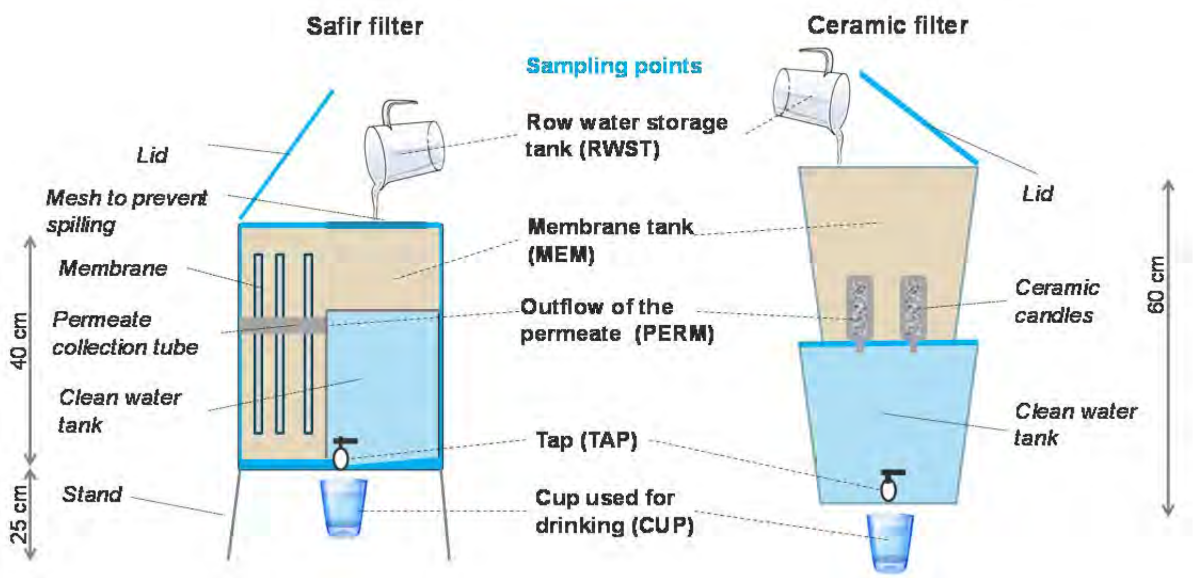


Figure 25 Drawing of the Safir and cermic candle filters with major sampling points (Derksen S., and Graf V., 2013)

Table 11- Field site characteristics and criteria for choosing the families within the field site (Derksen S., and Graf V., 2013)

Criteria	**Group 1 Encanto Pampa(11 families)**	**Group 2 San Benito (11 families)**
Area	Peri-urban	Rural
Economic income level	middle	low
Hygienic conditions in the households	intermediate	low
Water source	Microbially contaminated, untreated, slightly turbid water	Microbially contaminated, turbid, untreated surface/shallow well water
Family size	4 to 8 family members	
Education level	Maximize variety within the group	
Profession	Maximize variety within the group	
Housing	Maximize variety within the group	
Availability	Participant needs to be at home during the day	
Motivation	Participant needs to be motivated to contribute to the study	
Water Treatment	Families do not treat their water	
Body size	Maximize participants variety in body size	

In San Benito, the families received first ceramic filters which were replaced with the Safir filters after at least one month. In Encanto Pampa, the families had to evaluate the Safir filter first und could use ceramic filters afterwards. The measurements of the microbial water quality as well as interviews and video-recorded exercises were done during 6 monitoring visits per field site as schematically shown in Figure 26. Each visit was conducted according to a separate protocol specially developed for the visit.

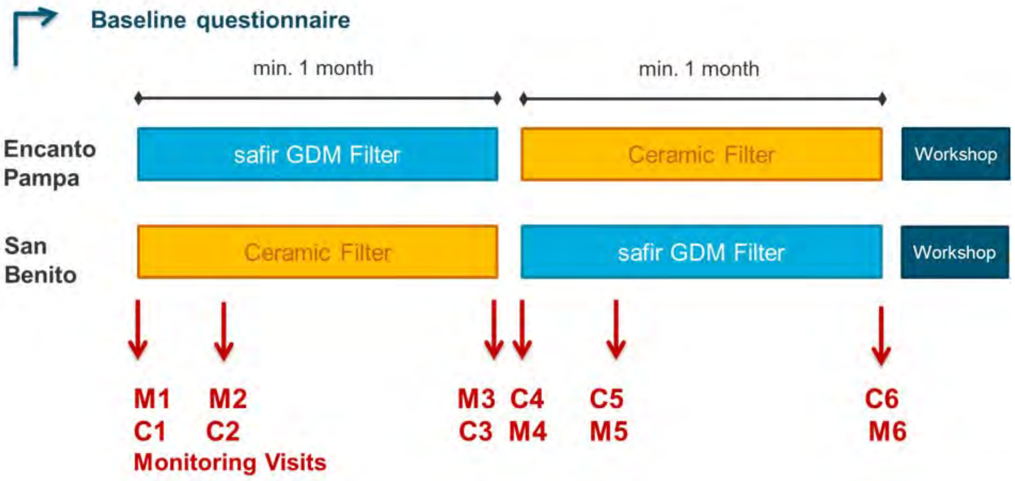


Figure 26 Setup of the field study for the two field sites Encanto Pampa (Peri-urban area of Cochabamba) and San Benito (rural area in the Chapare region). Monitoring visits of the safir GDM filter are abbreviated with M* and visits of the ceramic filter with C* (Derksen S., and Graf V., 2013)

The visits of the safir filter are abbreviated with M1-6, the visits of the ceramic filter with C1-6. Table 12 summarizes the topics and exercises which were addressed during the visits:

Table 12 Content of excersizes, observations and interveiws during the monitoring visits (Derksen S., and Graf V., 2013)

Visit	Exercise	Observation	Interview
M1, C1, M4, C4	Assembling and use only with written instructions on the filter	Handling aspects, misunderstandings, correct use and problems during assembling and first use	First impression and ease of use
M2, M5	Discharge of sediments and surface cleaning	Handling, correct cleaning and discharge of sediments	Clearness of the instructions, perception of lux and everyday use
C2, C5	Cleaning of the filter and ceramic candles	Handling, difficulties during cleaning, use of instructions	Easiness of the cleaning and instruction, everyday use, flux
M3, M6	Cleaning of the clean water tank	Difficutlies in opening the tank, risk of contamination during cleaning, use of insructions	Potential for improvement in general and improvement of instruction, handling and cleaning of the clean water tank, water quality perception
C3, C6	Disassembling and reassembling of the tap	Ability to exchange tap without instructions	Ease of use in general, water quality perception, improvement potential, preference of the filter type

The water level in each water filter was recorded and logged using Solinst level loggers. These data were used to calculate flowrate, water flux and frequency of use of the filters using a script developed in a software Stata. All data were presented and questions discussed at a workshop with participants of the study at each location.

At the end of the evaluation, a final workshop was conducted in each study area. The goal of the workshops was to share the microbial and physical testing results, find solutions for any problems which came out of the study and give the participants an opportunity to raise any concerns about the product in a group discussion. All family members as well as the interested neighbors were invited.
The following topics were addressed during the workshop as plenary discussion or during group activities:

- Non-transparency of the insert and the filter: does this bother people, do they want to see how the filter works, can they find out that the filter is broken, are they curious to open the filter?
- Instructions: do people understand pictograms picturing waiting time, risk of drying, need of shaking
- Perception of adequateness of the filter for different socio-economic conditions: does the filter fit in your kitchen or another type of kitchen?
- Alternative vocabulary used to name pictures on the instructions, since some of the words used by the monitoring group were not well accepted by the users
- Heights of the stand and table on which the filter is placed: participants could select the most appropriate table and stand from available material and discuss if the heights is sufficient and acceptable in regard to access by children, animals, ease of filling water, etc.
- Spill-protection and honey-comb structure of the spill protection: ease of cleaning as well as possibility of removing it and thus gaining access to the membrane

In San Benito, willingness-to-pay for a safir filter was measured, using a modification of the Becker-DeGroot-Marschak (BDM) auction. All variations of BDM auction have in common that participants have to bid for an aspired object, according to their own financial resources. Normally a price for this object is drawn randomly. If the participants' price is above the drawn price he or she is able to buy the product. If not he or she cannot buy anything and gets nothing at all. (Horowitz, 2006)
In our case a price hidden in an envelope was used as suggested by Luoto et al. (2012). Participants were able to buy their safir filter at their bid, if their bid lied above the price hidden inside an. The hidden price was set to zero by the research team, because there was no intention to sell the filters, but users did not know this.
In the study, it was promised in advance, that the ceramic filter stays with each family as sign of tribute for participation. It was mentioned that Safir filters would be taken back. Thus, the possibility of buying safir was offered, if the bit proposed by participant was above the hidden price. If it was below, he would stay with a ceramic filter anyways. Participants were also able to state that they want to stay with the ceramic filter instead and not take

Figure 27 Introduction of the Safir filter in San Benito (photo S. Derksen)

part in the auction. Hence, their bid actually represented the additional value of the safir over the ceramic filter. The retail price of the ceramic filter of 220 BOB (ca. 30 CHF in 2013) was mentioned in all households during the visits. In preparation of the workshop, participants were asked to discuss their financial resources and willingness to pay with their partner to achieve more reliable and realistic bids.

2.7.4. Design evaluation in Bolivia. Results

Everyday handling and use. The main question of the study was to find out if the Safir filter prototype satisfy user expectations in terms of handling. The results of the evaluation are summarized in the table 13

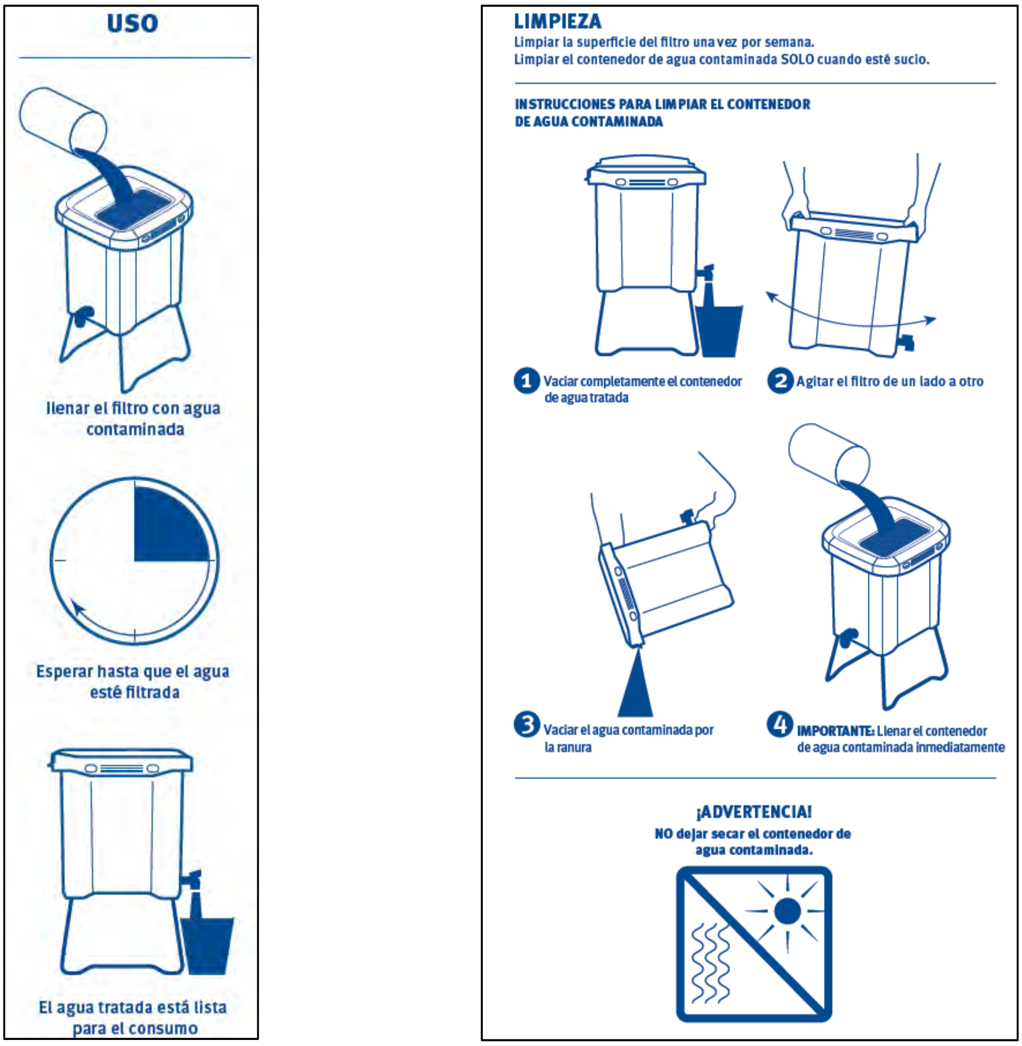


Figure 28 Instructions (M.Bräm, Derksen S., and Graf V., 2013)

Table 14 Summary of the results of the evaluation of everyday handling (Derksen S., and Graf V., 2013)

Factor	Results
Target group	Women and children are responsible for filling and cleaning the filter. Therefore handling needs to be adequate for these groups.
Spill protection	The spill protection performs fine. The area with the honeycomb mesh should be increased to reduce spilling further. The users were able to remove the spill protection mesh and therefore could gain access to the membrane, therefore a modification of the closing mechanism is needed to prevent access of users to the membrane.
Handles	Handles were well accepted and used independently on the body size of the user. The handles are mainly used during cleaning. Large rim on the long side of the filter was sometimes used instead of handles which led to shaking filter in the wrong direction. Therefore, the rim on the long side should be smaller and slimmer to avoid misuse of the rim as handles and save packing volume.
Lid	Lid has to be tighter and be more ergonomic to increase the use.
Tap	The tap was well appreciated due to high flow and easy regulation. However, the quality of tap was low: the material is too soft, the thread is too short, and with the current wall thickness a good fixation of the tap was not possible. Thus, many taps broke during the study. The change of the tap was not a problem for the majority of users.
Stand	Opinion about the stand were very different. Some thought that the stand is not necessary, others appreciated it. At the end, majority of the users used the stand, therefore we would advise to keep it in the next version but redesign it. The major issues concern the form and the heights. The heights of 18.5 cm on average was recommended by workshop participants. The form should be changed as well to avoid using the stand incorrectly. The current design also showed to be very stable against tilting front or back, but very unstable in regard to tilting to the sides.
Weights	Weights was perceived to be too high during the cleaning and should be reduced if possible.
Transparency	Vast majority of users would prefer transparent material and volume scale. However, transparency can lead to the growth of algae. Therefore, a window with a scale would be the most acceptable solution, although it might make production more complex.
Instructions (Figure29)	The USE sticker on the top of the filter was overlooked and should be positioned somewhere else and the clock was never recognized as a clock or as an indication to wait. Furthermore, the filter was often not fill completely and this should be indicated on the instruction. The WARNING pictogram should be improved as well, as it was misinterpreted as to not leave filter on the sun, and not as it was meant: do not leave filter EMPTY (on the sun).

Regular cleaning. Raw water tank and the membrane. The raw water tank should be cleaned regularly to avoid accumulation of sediments and change in taste and odor. The cleaning includes shaking of the membrane module and discharging of the sediments. The membrane should never be cleaned to avoid its damage and therefore is protected from the users with a mesh also used to prevent spilling and avoid large contaminants such as leaves or stones to enter the water filter. Table 15 summaries the results of the evaluation of ease of cleaning and handling during cleaning.

Table 15 Results of the evaluation of regular cleaning of the raw water tank (Derksen S., and Graf V., 2013)

Factor	Results
Efficiency of cleaning	Instructions need to be improved and the handles redesigned as mentioned in Table 14 to increase the impact of cleaning. If done correctly, sediments could be removed efficiently from the filter.
Sediment slit	The slit was not always recognized by the users immediately but might have been detected with the time. The better indication on the instructions could help finding it. Another option would be relocate it in the corner, as people intuitively tend to tilt the filter to the corner to empty it. The position of the slit should be adjusted with the position of the handles to avoid wet hands.
Access to tanks	The membrane tank should be better locked to avoid access of the users to the tank leading to the potential damage of the membrane. Measures should be also taken to promote refilling of the filter after cleaning, such as better indication of the minimal water level as well as warning sign on the instructions.
Instructions	Add: never open the membrane tank or you would destroy the filter. The shaking step should be shown more clear, as shown in the figures 29 and 30.

Figure 29 suggested pictogram to indicate the shaking of the filter (Derksen S., and Graf V., 2013)

Figure 30 used pictogram on the filter (Derksen S., and Graf V., 2013)

Cleaning clean water tank. The clean water tank is not supposed to be cleaned regularly, therefore the access to this tank should not be obvious and prevent people from cleaning it regularly. The reason of limited cleaning is the risk of contamination of the filter during the cleaning procedure due to low hygienic conditions and lack of supplies such as soap and disinfection solution. However, there should still be a possibility of access to the clean water tank to allow replacement of the tap or cleaning when it is really necessary. The results of the evaluation of the easiness of access to the clean water tank and related risks is summarized in the table 17.

Table 16 Results of the evaluation of cleaning of the clean water tank (Derksen S., and Graf V., 2013)

Factors	Results
Effectiveness and risk of contamination	There is the risk that dirty water would be collected and used for other purposes and not disposed. Therefore, this has to be highlighted clearly and also mentioned during the introduction of the filter. Another issues is lack of using the soap for cleaning the filter or cleaning the hands before touching the clean water tank surface. Therefore, the clean water tank should not be easy to open and cleaned only if really necessary, as the risk of contamination during cleaning is too high. For the users in San Benito the opening mechanisms for the clean water tank was rather complicated and would keep them from opening it. In case of Encanto Pampa most users had no difficulties in opening the tanks.
Instrucitons	In general, the short version of the instructions is recommended, as the amount of information on the long version is too overwhelming for most of the users. Some of the steps in instructions, such as closing mechanism were not understood and should be modified. Lamination of the instruction sheet is advised also in the future.
Replacing the tap in the clean water tank	The replacement of the tap was straightforward once users know how to open the clean water tank. The idea of buying a tap in the town was not always obvious to the users in San Benito.

Aspirational factors. Aspirational factors are important on one hand for acquisition of a filter and on the other hand for placing it in an accessible, prominent spot to support regular use. Table 18 summarizes the main outcomes of the evaluation of aspirational factors.

Perceived value of the filter

All users would recommend the safir filters to their family, friends or neighbors, some already did so. The willingness to pay was evaluated by BDM auction as described above and the results of the seven families out of eleven are presented in table 19. The four remaining families did not take part in action for various reasons. For the seven families, the willingness to pay lies between 200 and 1000 BOB (circa 29 – 145 USD in 2013), in average 650 BOB (94 USD). Monthly payable rates are 100 – 250 BOB (14.5 – 36 USD), in average 161 BOB (23 USD).

Table 17 Results of the evaluation of aspirational aspects of the filter (Derksen S., and Graf V., 2013)

Factor	Results
Visual perception of the design	The filter was perceived as beautiful and nicer that the ceramic filter. The color and form should not be changed. In general, the positive perception was related to the impression that the filter fits well into the house. These results were observed in both regions.
Transparency of the material	Slightly more transparent material could be recommended for the clean water tank and stickers. The membrane tank can stay as it is. This would allow recognition of the water level and prevent sediments being discernible.
Size	The size was perceived as optimal
Stand	In terms of stability and size, the stand was discussed intensively, but not in terms of its material or design.
Vocabulary	The language used on the instructions and during the introduction of the filter was not always understandable to users, especially in San Benito and therefore should be simplified and adapted to local conditions.

Table 18 Results of the BDM auction in San Bentio. Willingness-to-pay for a safir instead of a ceramic filter in San Benito. 700 Boliviano (BOB) ~ 100 USD (Derksen S., and Graf V., 2013)

ID	Ceramic filter	safir	Willingness-to-pay in BOB	At a stroke	In rates	Comment
1	-	-	-	-	-	Authority was informed
2	x	-	-	-	-	Unable to consult partner
3	-	-	-	-	-	Information not available
4	-	X	1000	-	x	166.6 BOB each month
5	-	X	800	-	x	200 BOB each month
6	-	X	450	-	x	150 BOB each month
7	-	X	600	-	x	100 BOB each month
8	-	X	200	x	-	Pays at a stroke
9	-	X	-	-	-	Answer unreadable
10	-	X	1000	-	x	250 BOB each month
11	-	X	500	-	x	100 BOB each month

As mentioned before, the BDM auction displays the difference in value between safir and ceramic filter. Theoretically, 220 BOB need to be added to the values shown in table 19 to display the real willingness-to-pay. We did not expect the willingness to pay to be so high and raise serious discussions between the participants. The answers, even if willingness-to-pay is exaggerated, can be seen as a proof of high importance of the safir filter for experienced users. This is also confirmed by the high recommendation rate of 95%.

2.7.5. Summary of the evaluation of the Safir filter design

In general, the design was considered adequate and appropriate for the households and the families perceived the Safir as nice and easy to use. Major criticism of the filter concerned its lid and the stand`s heights. The tap was perceived as good due to regulation and high flow, but was not enough robust. The handles were perceived as easy to use and comfort, but could be also smaller in order to save the weights and the packing volume of the filter. None of the users opened the membrane tank during use, but they could do so if asked. Therefore, the recommendation was to invent a better mechanism to protect the membrane from possible damage. In general, users managed to do maintenance handling only using this instructions and, sometimes, help of their family members. About half of the participants understood the concept of shaking the filter for cleaning purposes, however, some of them shook it in the wrong direction which affected the cleaning efficiency. The improvement of instructions and relocating the position of handles can improve this. Also the slit on the side of the filter was located with time and users used it to discharge the sediments. The majority perceived the filter as heavy during cleaning, but not unbearably so.

The results of the evaluation were communicated to the designer team and implemented, resulting in the last version of the Safir Prototype.

3. Functionality and operation

3.1. Introduction

Functionality of the GDM filter has been tested in the laboratory conditions as well as during field studies in Kenya and Bolivia. The focus of all evaluations was on water flux and flow-rate through the filter, filter use frequency as well as microbial water quality and efficacy in reducing indicator bacteria.

Laboratory investigations. The impact of water quality parameters and transmembrane pressure on flux has been studied before and therefore was not investigated during this project. The focus of laboratory investigations was on ability of membranes to retain MS2 bacteriophages used as proxies for viruses during GDM filtration. During this study river water was filtered through different microfiltration and ultrafiltration membranes and MS2 bacteriophages were spiked into raw water at different days of filtration and measured in permeate. The results showed the ability of the membrane to retain the bacteriophages as well as the impact of the biofouling layer formed on top of the membrane on the final permeate water quality.

Field studies. As mentioned in the section 1.3, two field studies were conducted. The focus of the evaluation of 24 prototypes in Kenya during May 2011-October 2012 was on the long term functionality of the filter under real conditions in remote rural households. During this study, the frequency of use, flux as well as retention of indicator organisms *Escherichia coli* and other coliforms at different points within the filter were evaluated. The physical and chemical water quality parameters such as turbidity, dissolved oxygen, pH, conductivity and total iron were measured as well. In case of the design study in Bolivia during May-August 2013, only the short term changes could be evaluated as the duration of the interactions of the users with the filters was limited to 1-2 month. However, the flux, microbial water quality as well as frequency of use were measured as well.

3.2. Removal of bacteria and viruses by GDM filters in laboratory conditions

In general UF membranes are physical barrieirs and should provide complete removal of pathogens larger than the pore size. The microdyn membranes used during the field studies and Millipore membranes used in the laboratory investigations have a cut-off of 150 and 100 kDa and therefore a complete removal of bacteria and most viruses should be expected. In the laboratory conditions we used flow cytometry to investigate the removal of bacteria (figure 31). The results showed that all bacteria have been removed during the membrane filtration.

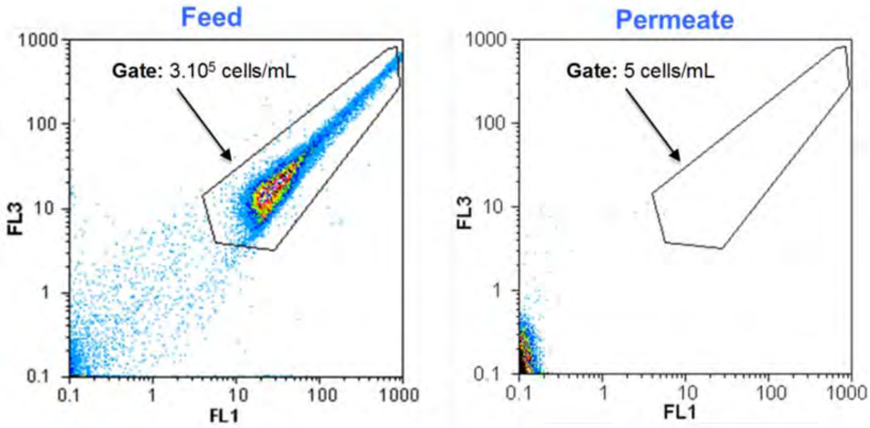


Figure 31 Flow cytometry dot plots of the feed spiked with fluorescently labeled B. diminuta, and the permeate (Peter-Varbanets, et al., 2010)

To control removal of viruses, bacteriophage MS2 (about 20 nm radius) has been filtered through the membrane at various stages of biofilm development and detected on the feed and permeate side by plating method. Although the removal of the MS2 phage was low by the new membrane (about 1-log removal has been observed), the log-removal values improved already after 2 days of filtration of Chriesbach river water through UF membranes and did not change considerably for the MF membranes (figure 32). The log-removal values measured for UF membranes after 2 days of filtration varied between 3.2 and 5.9 -log removal and did not depend on the pore size of the UF membrane. We assume that reversible and irreversible fouling reduces the effective pore size of the membrane and therefore increases the log-reduction of phages (Peter-Varbanets, et al., in preparation).

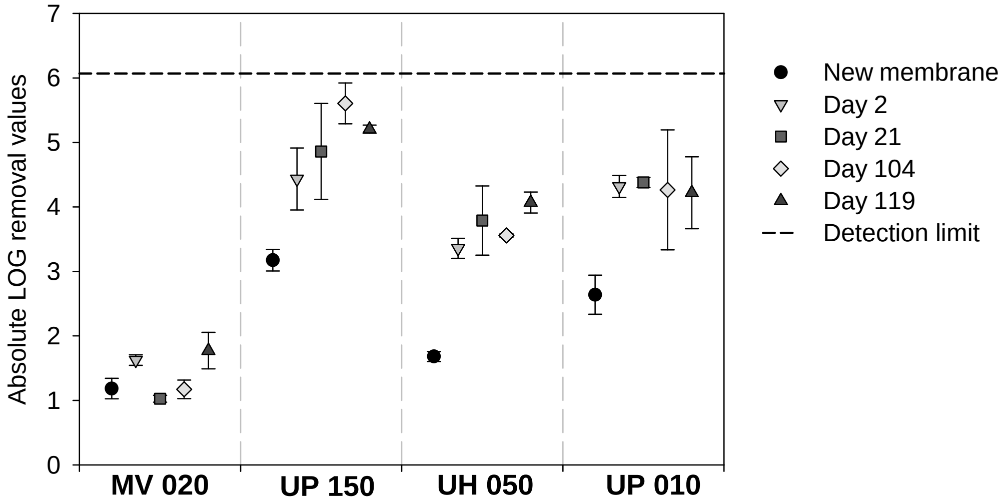


Figure 32 Log-reduction values for MS2 phages filtered through 4 types of membranes after 0, 2, 21, 104 119 days of filtration of river water. Bars show standard deviation values, n=6 for samples measured on days 0, 2, 21 and n=4 for samples measured on days 104 and 119. (Peter-Varbanets et al., in preparation)

3.3. Field evaluation of the α-prototypes in Kenya

3.3.1. Field study set-up

The long term functionality in regard to water quality and flow rate as well as user feedback was evaluated during the field study in Kenya with 24 filter prototypes. The selection has been done based on the quality and type of raw water, the willingness of the people to participate in the study, the question if people were consuming raw water instead, the type of raw water source and the accessibility for monitoring. Four field sits were chosen:

- Oloosuyian, Kajiado County
- Esokota, Kajiado County
- Thika, Kiambu County
- Nairobi

All participating families had recently received a hygiene promotion through other projects. Table 19 summarizes the type of water sources used in each field site and the number of filters distributed.

The raw water sources were aggregated into five clusters, which were used later during data analysis:
Pond: surface runoff water collected in a manmade pond protected by a natural fence.
River: Thika river water collected directly from the riverbank or pumped to the household.
Dug wells: protected and unprotected shallow wells about 20-30 m deep.
Borehole: Machine-drilled borehole (reportedly 70 m deep) with an electricity powered pump
Tap: occasionally chlorinated water supplied during about 4 days per week through a distribution network by the Nairobi City Water and Sewerage Company.
After distribution, the filters were monitored every month for 13 months and a last monitoring was conducted after a five-month gap, i.e at 18 months.

Table 19 Overview of the field sites and water sources used in the study (Derksen S., et al., in preparation)

Location	Water Source	Hygienic Conditions	Number of filters distributed
Oloosuyian	Pond, borehole	poor	9
Esokota	Dug wells, borehole	poor	6
Thika	River, dug well	inadequate	5
Nairobi	Tap water	good	4

User perception and behavior were systematically recorded using a questionnaire during the monitoring visits. For verification of filter use and flowrate, pressure meter dataloggers (Solinst Canada Ltd., Canada) were used for monitoring of water level and temperature. In order to evaluate microbial removal efficiency of the filters, E.Coli and other coliforms (total coliforms not including E.Coli) were measured using EC compact dry plates (CDP) (Nissui Pharmaceutical Co., Ltd., Japan) according to the HyServe protocol (Hyserve 2012) . Turbidity was measured with a turbidity tube (5 - 2000 NTU) in the first 4 months and with an optical turbidity meter (0 - 1000 NTU +/- 2% (Wagtech, UK)) thenceforth.

Dissolved oxygen (DO, luminescent dissolved oxygen probe, 0 - 20 mg/l +/- 1%), pH (0 - 14 +/- 0.002) and electric conductivity (4-pin graphite electrode, 0.01 µS/cm - 400 mS/cm +/- 0.05%) were measured with a multi-meter (HACH 40d, USA). Free iron in groundwater sources and free residual chlorine in tap water were monitored as well.

3.3.2. Filter use

After one and a half years of operation, 96% of the filters were functioning and none have failed due to technical reasons. Filter use declined somewhat in the days following the distribution but then remained stable throughout the year. The number of family members consuming filtered water varied from 3 to 21 people. On average, people drank about 4 liters of filtered water per week per person. The volume of water filtered was the lowest in Nairobi where most people spent their day outside of home and the highest (up to 15 liters per person per week) in rural areas. In all cases, the filters where not used to their full capacity of at least 20 liters per day with very turbid water.

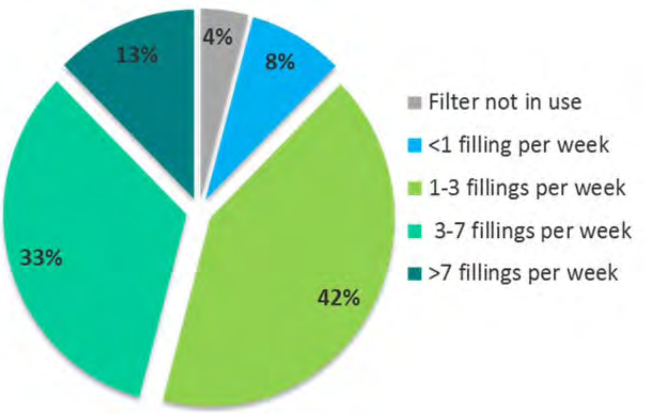
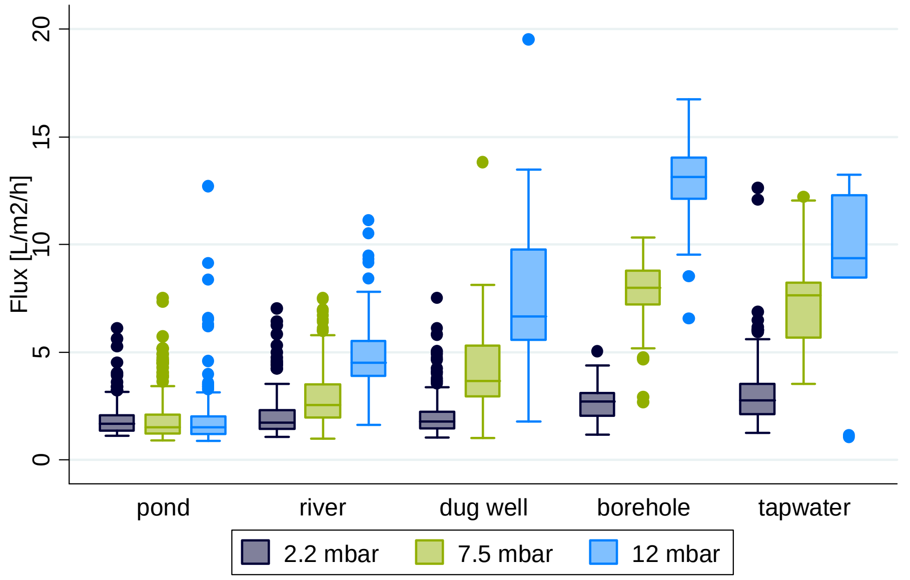


Figure 33 Filter use frequency (by M.Peter and S. Derksen)

3.3.3. Impact of water source on flux

All filters produced sufficient volume of water. The filters fed with highly polluted and turbid water from surface sources such as ponds and rivers were still able to produce at least 20 liters of purified water per day, while filters used to treat ground water or water from piped network could produce up to 90 liters of water per day. The water flux was calculated at three different levels, representing the flux shortly after filling (12 mbar), at intermediate level (7.5 mbar) and at the end of filtration cycle (2.2 mbar). The flux values varied from 2 to 19 liter per hour and square meter of membrane depending on water source and water level in the filter. After initial decrease, no systematic decrease of flux was observed over time and none of the filters clogged. Most variation in flux over time can be observed in filters being fed with changing feed water. Thus, the sustainable operation of the filters without any chemical cleaning was achieved. The figure 34 shows that the impact of transmembrane pressure is much stronger for tap, borehole and dug well water, still detectible for river water and almost not identifiable for pond water.



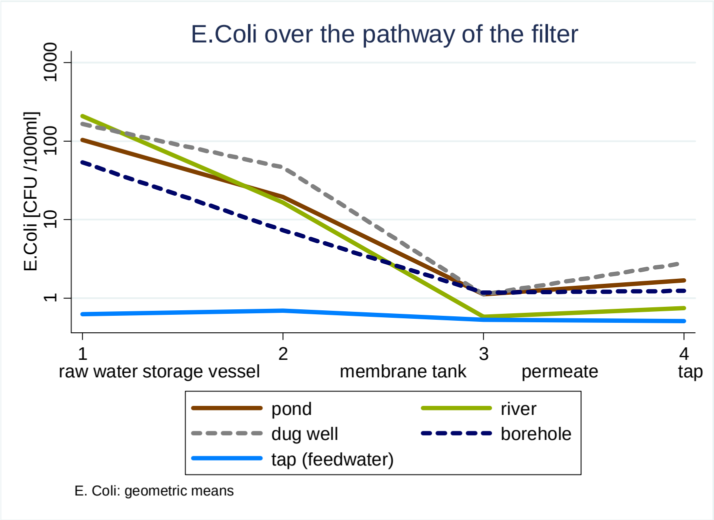
n: pond* 224/268/265 river 383/271/102 dug well 456/192/56 borehole 158/47/14 tapwater 256/52/9

*pond or borehole, depending on season

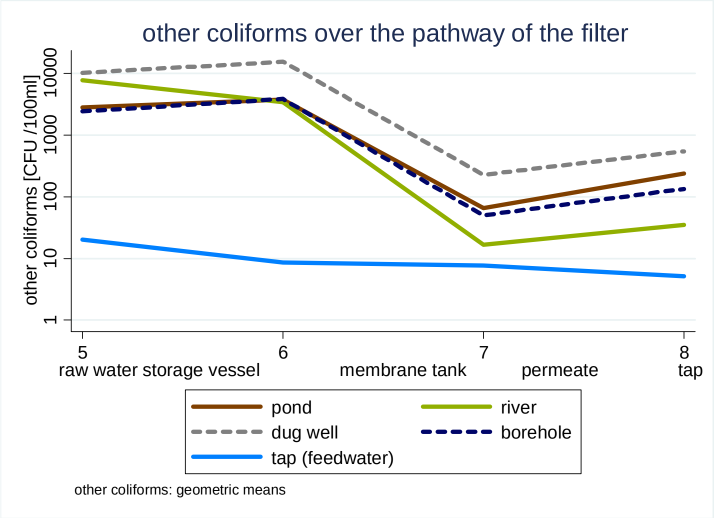
Figure 34 Measured flux in [L/m2/h] at three different pressure levels 12, 7.5 and 2.2 mbar representing an almost full, medium and almost empty filter, respectively. Values calculated as boxplots for each class of water sources. Household using pond water and occasionally changing to borehole water in the dry season are classified as pond water users. (Derksen S., et al., in preparation)

3.3.4. Microbial water quality

Microbial water quality changes were measured at different points within the filter: in raw water storage tank, membrane tank before fitlration, at the outflow of the permeate after filtration and at the tap of the filter. Figure 35 shows E.coli counts at different sampling points within the filter. The reduction of e.coli counts can be observed already after raw water tank for all water types except of tap water. After passing the membrane, concentration of E.coli decreases to 0 CFU/100 ml for tap and river water. For dug wells, pond and borehole water an increase on average to 1 CFU/100 ml is observed. In 75% of all samples taken from the permeate tube, no E.Coli are detected in 100 ml. An increase in E.coli counts can be observed at the tap of the filter for all types of water except of tap water.



a



b

Figure 35 *E.Coli* (a) and other coliforms (b) along the pathway of the water through the filter, by water source. Geometric means, zero values replaced by 0.5 CFU/100 ml. (Derksen S., et al., in preparation)

Other coliforms are more often detected in the permeate tube than E.coli and only 15% of the samples show zero count values. As in case of E.coli counts, an increase of other coliform count is observed in water taken from the tap of the filter compared to the permeate.

The performance of the whole device is represented by the log-removal values (LRV) between storage tank and tap which range from 0.08 to 2.46 for E.Coli and from 0.51 to 2.45 for other coliforms (see table 20) The low LRV values are mostly observed due to the low concentration of the E.Coli and other coliforms in the raw water. The highest LRV is achieved with the highest E.Coli concentration in the feed water (17600 CFU/100 ml) and is 4.55. Other coliforms reach the upper detection limit in the storage vessel and thus the highest LRV is 4.78 which is the maximum detectable log reduction. Table 20 also shows that LRV values between storage vessel and tap are lower than LRW values between storage vessel and permeate collection tube. This indicates post contamination of the water at the tap or at the clean water storage tank.

Table 20 Log removal values (LRV) between the storage vessel and permeate collection tube and storage vessel and tap for the different water sources (Derksen S., et al., in preparation)

Source	LRV *E.Coli*		LRV *other coliforms*	
	Storage to permeate	**Storage to tap**	**Storage to permeate**	**Storage to tap**
pond	2.01	1.85	1.77	1.38
river	2.55	2.46	2.68	2.45
dug well	2.22	1.80	1.69	1.30
borehole	1.61	1.62	1.76	1.43
tapwater	0.06	0.08	0.30	0.51
Geometrical mean value	**1.73**	**1.60**	**1.67**	**1.43**

These results confirm that GDM filter shows good microbial removal efficiency also in the field. However, an increase of E.coli and other Coliforms in the tap shows that questions of recontamination and regrowth are of importance. The design of the filter and possibility of raw water to penetrate in the clean water tank during severe overflow of the filter was identified as a major reason of the contamination observed in some cases. It was considered during development of the new filter design.

3.3.5. Microbial regrowth

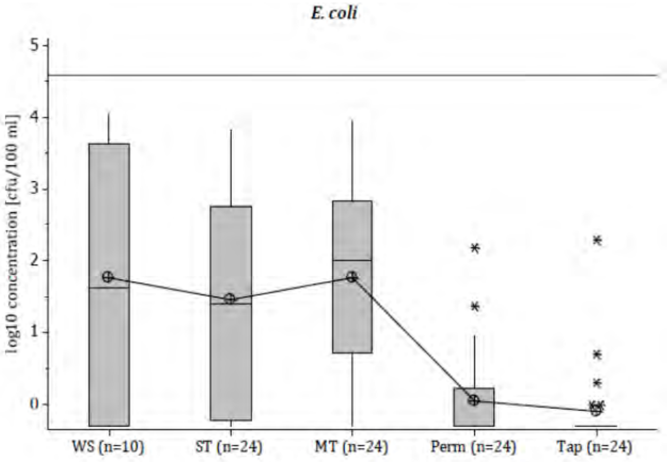


Figure 36 E.coli counts in 6 filters monitored frequently during 2 month of operation. WS - water source; ST - storage tank; MT - -membrane tank; Perm - permeate tube; Tap - filter tap (Perron S., 2012)

Figure 35b shows that other coliforms were detected in relatively large numbers in the permeate while *E.coli* was mostly retained by the filters. This difference in removal efficiency of the filter shows that not only recontamination, but also microbial re-growth of non-pathogenic bacteria on the clean side can be an issue. Therefore, microbial regrowth in the filters was investigated separately in more detail. Besides the standard *E.coli* and other coliforms measurements, also total viable count and ATP were measured during 2 month in 6 filters. Figure 36 shows that as discussed above, the *E.coli* counts are reduced by the membrane by about 2 LOG and the LRV values strongly depend on the *E.coli* concentration in the raw water. This shows that membrane is in general efficient in removing *E.coli*. Since E.coli usually do not grow in the open environment under standard conditions, and the integrity of the memrbanes was tested before, E.coli detected in 21% of the samples could be explained by the recontamination of the clean water tank and permeate tube. As discussed above, the situation is different for other coliforms and higher LRV values (mean of 2.5 Log reduction) are observed for other coliforms due to higher concentrations of the other coliforms in raw water. Nevertheless, in 23 out of 24 samples other coliforms were detected on the permeate side. We assume that both, regrowth and recontamination could have played a role. In case of total viable count (figure 37), values close or higher than the detection limit were measured for almost all of the samples in raw water and membrane tanks. Only very slight decline in total viable count is observed after the membrane. Since good e.coli removal values indicate that the membrane integrity has not be compromised, we assume that such low removal values are caused by microbial regrowth within the filter. ATP measurements shown on figure 39 indicate that there is biological activity within the filters and thus confirm re-growth hypothesis.

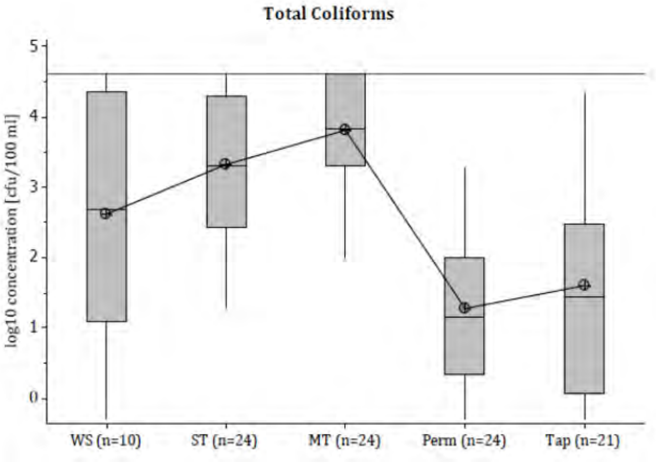


Figure 37 Other coliforms counts in 6 filters monitored frequently during 2 month of operation. WS - water source; ST - storage tank; MT - -membrane tank; Perm - permeate tube; Tap - filter tap (Perron S., 2012)

In general, re-growth of bacteria can be expected after any filtration process: bacteria present in raw water are mostly rejected by the membrane (or ceramic filter) during filtration while nutrients pass freely through the membrane due to small size of the molecules. In case filtered water is not biologically stable (assimilible organic carbon values exceed 10 microgram/liter), regrowth of the bacteria will occur. Thus, the major question is whether bacteria re-growing in the clean water tank can cause any health risk. Assuming that no pathogenic microorganisms are present in the clean water tank because recontamination, only regrowth of nonpathogenic natural bacteria can be expected. Thus, regrown bacteria would not cause any health risk. However, this question should be investigated in more detail as it is relevant for any filtration method and there is not yet much information available on the question whether pathogenic microorganisms can grow in open environments or not in the absence of competition.

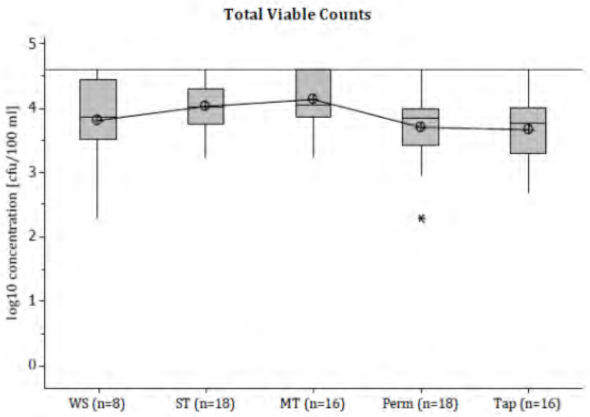


Figure 38 Total viable counts in 6 filters monitored frequently during 2 month of operation. WS - water source; ST - storage tank; MT - -membrane tank; Perm - permeate tube; Tap - filter tap (Perron S., 2012)

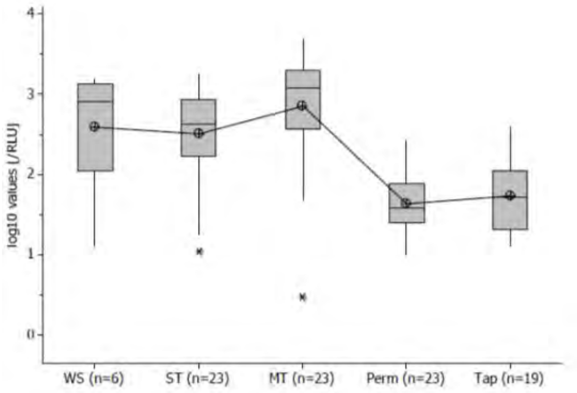


Figure 39 ATP values measured in 6 filters monitored frequently during 2 month of operation. WS - water source; ST - storage tank; MT - -membrane tank; Perm - permeate tube; Tap - filter tap (Perron S., 2012)

3.3.6. Other parameters

Turbidity, conductivity ferrous and ferric iron as well as oxygen content were measured. The membrane recued turbidity considerably and the values of less than 2 NTU in 95% were observed. Electric conductivity was not affected by the membrane filtration considerably. Values of up to 1.1 mg/l for ferrous iron were detected in membrane tanks of the filters filled with water from dug wells. Only 2 % of the samples taken at the tap of those filters showed concentrations of ferrous iron higher than 0.3 mg/L. Oxygen slightly reduced from 6 mg/l on average in the storage vessel to 5 mg/l on average in the membrane and was lowest in filters filled with dug well water. Anaerobic conditions were not observed in any of the filters during regular use, about 17% of the samples of the membrane tank could be considered hypoxic (< 2 mgO2/L). Figure 40 shows that dissolved oxygen changes through the pathway of the filter for 6 filter representing different water qualities during 2 month of data collection (Perron S., 2012).

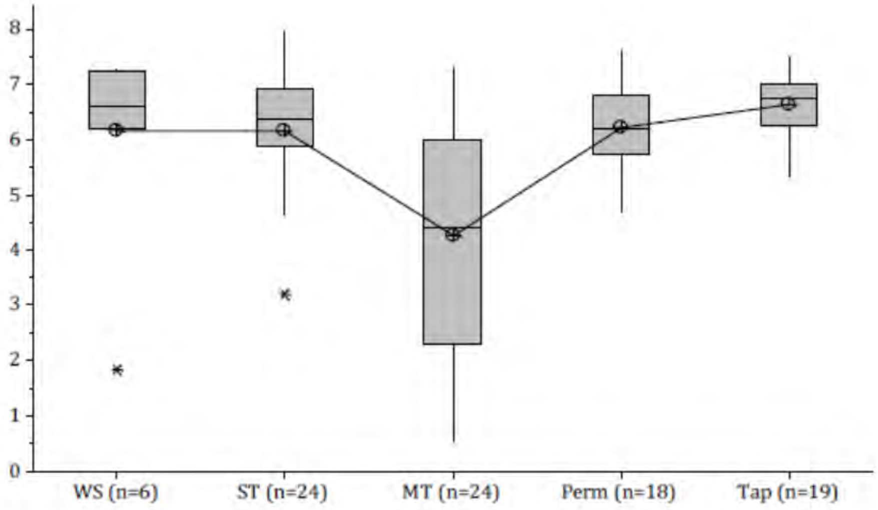


Figure 40 Dissolved oxygen values through the pathway of the filter. WS - water source, ST - storage tank, MT - -membrane tank, Perm - permeate, Tap - filter tap (Perron S., 2012).

3.3.7. Sloughing of the biofilm and cleaning of the filter

During experiments in the lab and in Kenya we have observed that fouling layer detaches (sloughs of) during long standstill periods. Shaking of the membrane module or flushing intensifies detachment if done after standstill period, but is inefficient if done without it. The areas affected by sloughing seem to be larger in case of aerobic waters with high organic content. In case of anaerobic conditions, long term exposure of membrane surface to air, or when inorganic precipitates such as iron or manganese oxides cover the membrane surface, sloughing of the biofouling layer does not occur or affects only small area of the membrane surface.

Figure 41 Pictures of the membranes showing sloughing of the biofilm after 3-6 month of operation (Photos: M.Peter, S.Derksen)

Chemical cleaning has been used on old modules operated in GDM systems for months to recover permeability. Treatment with NaOH and HCl in the pH range allowed by producer (pH 2-12) or cleaning with HOCl (up to 100 mg/L) were efficient and recovered up to 70-80 % of initial permeability of the membrane module. HOCH treatment over short periods of time can be used if needed to recover permeability and remove biofilms from the membrane surface after long term operation.

3.3.8. Follow up visit of Thika after 3.5 years

The households in Thika were visited without a notice after 3.5 years after the start of the study (about 2 years after last monitoring visit) and three households out of 5 were at home during the visit. Two filters out of three visited were in use. The third filter was not in use since about 1 month due to the breakdown of the tap. The family said that they plan to buy a new tap and replace the tap as soon as they visit the next town.

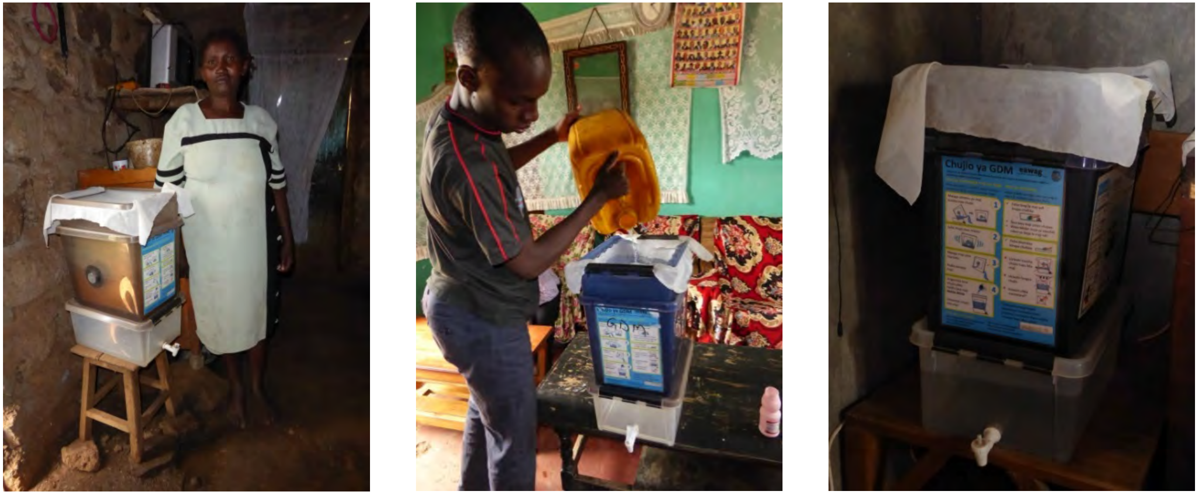


Figure 42 GDM filters in use in Thika 2 years after the end of the study (3.5 years in total) (Photo: R.Meierhofer)

3.4. Field evaluation of the Safir filter functionality in Bolivia

The field evaluation of the functionality was conducted during the whole duration of the field study for both ceramic and Safir filter in comparison and the results are summarized in the report by Derksen and Graf, (2013). Although the scope of this study was on user acceptance and use preferences regarding the design of the filter, functionality of the filter was evaluated as well. Following parameters were monitored during the field study:

- Filter use frequency and volume of filtered water
- Microbial water quality changes at different sampling points within the filter
- Chemical and Physical water quality parameters
- Water flux and flowrate through the filter

The characteristics of the raw water sources in San Benito and Encanto Pampa are listed in Table 21. The shallow wells in San Benito are more contaminated in terms of microbial parameters and iron content, they show lower dissolved oxygen values and a low pH, which is typical for tropical and old and therefore acidic soils. Electrical conductivity is slightly higher in Encanto Pampa, but both values are fairly low and do not pose any difficulty for water treatment or consumption. Total and dissolved organic carbon values are higher in Encanto Pampa than in San Benito.

Table 21 Characteristics of raw water sources. *geometrical mean values (Derksen and Graf, 2013)

	Encanto Pampa	San Benito
E.Coli [CFU/100ml]	56.5*	138.2*
O_2 [mg/l]	7.41	1.97
Electrical Conductivity [µS/cm]	194.3	51.7
pH [-]	7.7	5.5
Turbidity [NTU]	1.98	20.22
Total iron [mg/l]	0.04	1.19
Free iron [mg/l]	0.01	0.75
DOC [mg C/L]	3.79	1.85
TOC [mg C/L]	4.08	1.79

3.4.1. Filter use

Figure 43 shows that the safir filter was used more frequently in San Benito whereas in Encanto Pampa, families used the ceramic filter more often. The volume of water filtered per day is comparable in San Benoto, whereas in Encanto Pampa, Ceramic filters filtered more water.

One explanation for the strong increase in use of the filter in Encanto Pampa could be a misunderstanding of the filter instructions in the first place. One of the instruction stickers warns from drying out of the filter. The low water level in the ceramic filter was often misinterpreted as drying and therefore some families filled the filters all the time to keep the candles immersed all the time. After the people got instructed that drying of the filter would not occur if lid is closed and even only a very thin level of water present, they changed the behavior and filtered as much water as they needed.

On average, the safir filters were filled 6.08 times per week while ceramic filters were only used 5.2 times per week. Nevertheless, the volume of water filtered per day is the same for both filters if both areas are considered. Consequently, the volume filled into the filter per use is lower (3.6L/fill) for the safir filter than for the ceramic filter (3.9L/fill).

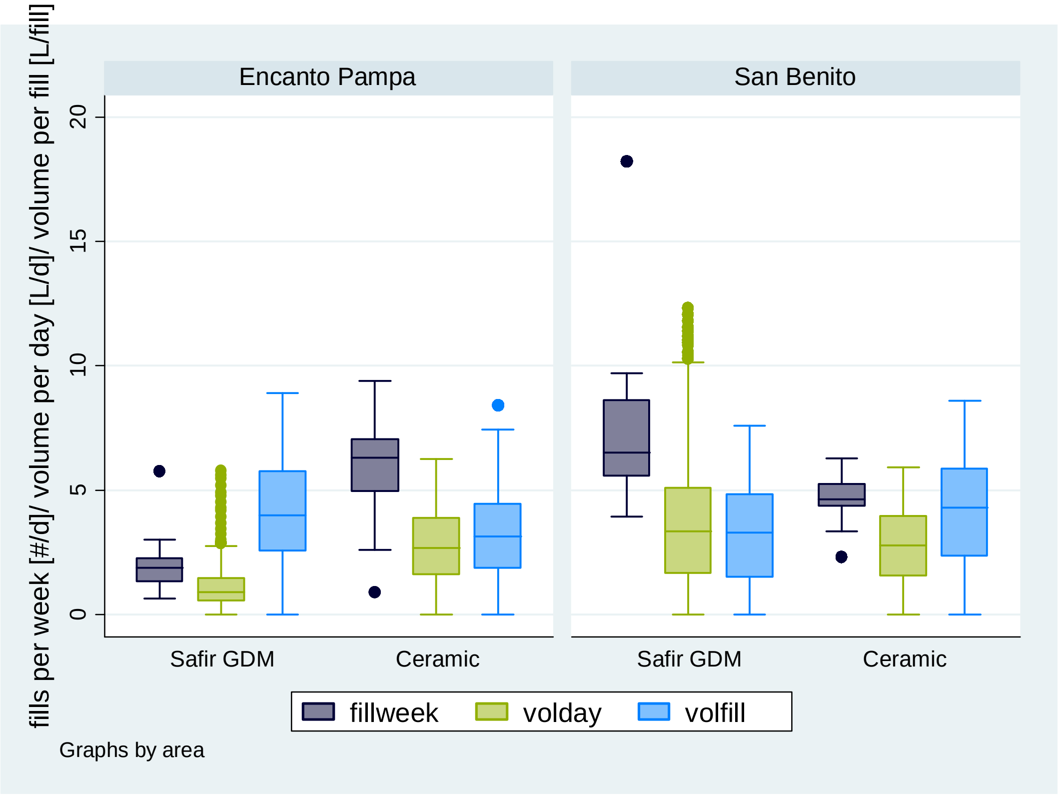


Figure 43 Frequency of use (filling), volume filtered per day and mean volume per filling for both filters in each study area (Derksen and Graf, 2013)

3.4.2. Flux and flow rate

Water flux of the new membrane was measured before use and was 5.7L/m2/h on average of three measurements on one membrane module at a head of 14 cm which results in a permeability of 400L/m2/h/bar. Figure 44 shows the flux measured in the Safir filter at a transmembrane pressure of 5, 10 and 12 cm respectively during the duration of the study with level data loggers. Similar flux value range can be observed in both areas. In case of Encanto pumpa, flux increases with the water level in the filter, while in case of San Benito, no flux difference was observed at water levels of 10 and 12 cm. This behavior is similar with the data obtained in Kenya with raw water of high turbidity and organic matter content. The clustering of the values to the weeks measurements illustrated on figure 45 showed no considerable changes between different weeks. A slight decline is observed for San Benito during the last two weeks of operation. For the ceramic filter, flow rates were calculated at water pressures of 5, 10, 12, 15 and 20cm respectively. An increase of flow with water pressure can be observed in both field sites, but values are generally higher in Encanto Pampa, especially at higher water levels (Figure 46). The clustering of the results by week or month shows clearly a decrease in flow rate in San Benito, and more or less stable values in Encanto Pampa. This decrease in flow rate in San Benito was also noted by the end users and some of the filters were clogged after a month. In these filters algae growth on the ceramic candle itself could be observed. In Encanto Pampa the flow rate remained stable, and clogging was not observed due to low turbidity values.

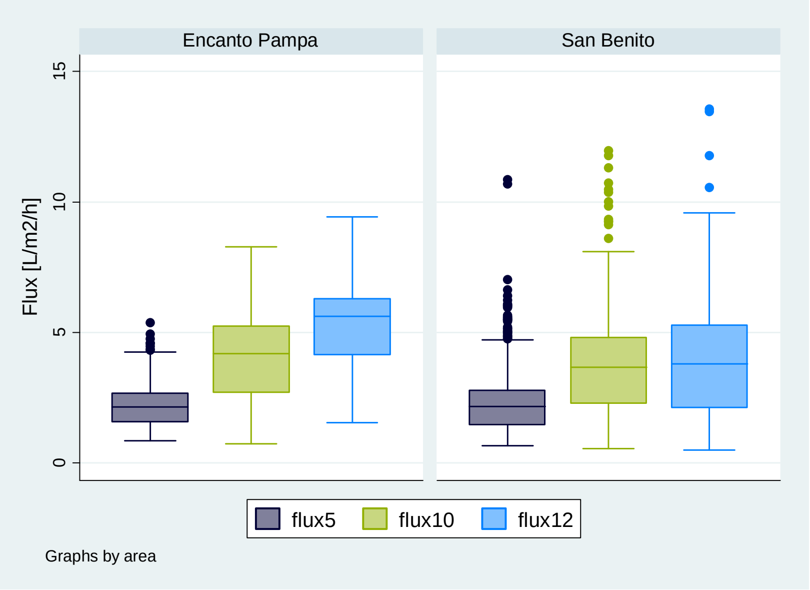


Figure 44 Fluxes measured in the Safir filter at a transmembrane pressure of 5, 10 and 12 cm water column respectively(Derksen and Graf, 2013)

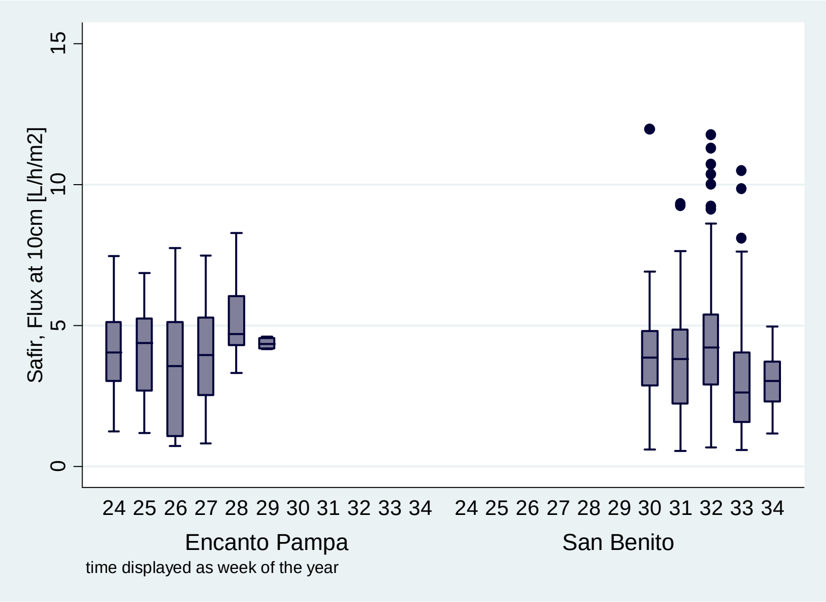


Figure 45 Safir: development of flux over time, clustered in weeks(Derksen and Graf, 2013)

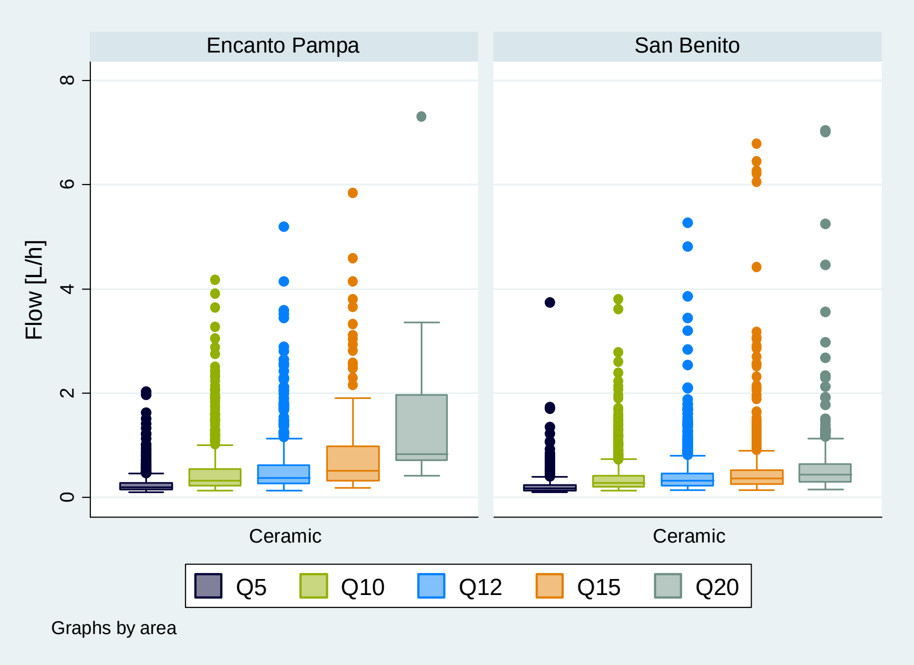


Figure 46 Ceramic filter: flow rates measured in both field sites at 5, 10, 12, 15 and 20cm water pressure(Derksen and Graf, 2013)

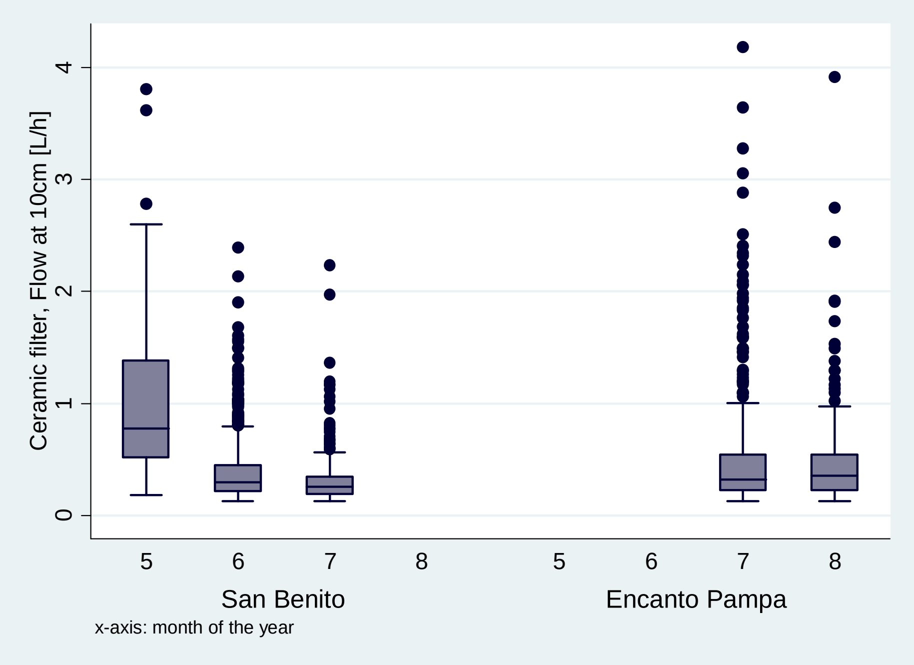


Figure 47 Ceramic filter: development of flow rate over time, clustered in months (Derksen and Graf, 2013)

In order to compare the filtration velocity of the two filters, flow rates at the same water have been plotted on the same figure 48. In the direct comparison of flow rates of equal pressure, the Safir filter always outperforms the ceramic filter.

Summarizing, both ceramic filter and Safir performed well in both areas and could produce sufficient amount of water in sufficient time and flow rate. In case of Encanto Pampa, no considerable difference was observed. However, in case of San Benito decline of flow rate of ceramic filters down to complete clogging were observed and the filters had to be cleaned often. The Safir filters did not clog and the flowrates remained stable in San Benito independent on water quality.

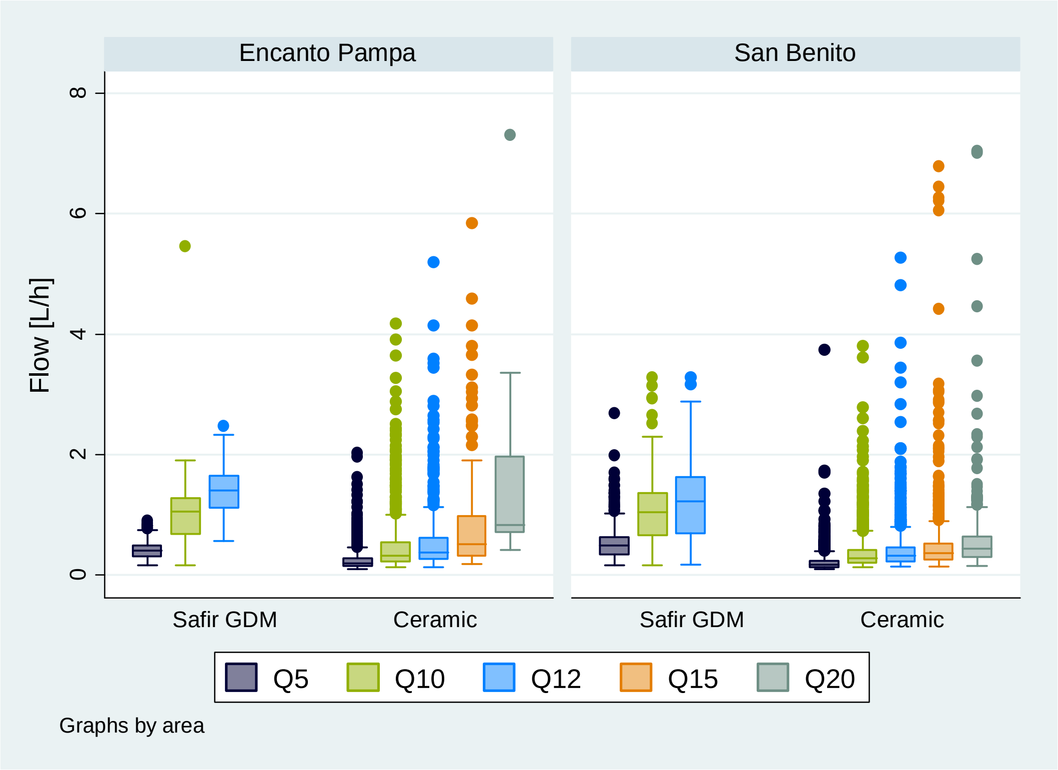


Figure 48 Comparison of flow rates of safir and ceramic filter at 5, 10, 12, 15 and 20cm water pressure. (Derksen and Graf, 2013)

3.4.3. Microbial water quality

The integrity of the safir filters were controlled by enterococci bacteria and log-removal values of about LOG 4 were measured in all filters. *Escherichia coli* counts at different sampling points were measured for Safir and ceramic filters. Figures 49 and 50 show the *E.coli* counts for the two filters depending on the area. In Encanto pampa, the level of microbial contamination was in general lower than in San Benito. Both ceramic and safir filters showed complete removal of *e.coli* after after the membrane. In general, almost no cases of recontamination at the tap were observed in Encanto Pampa. Reconamination at the cup was observed more often in this area, however only in few cases, e.coli counts exceeding 1 CFU/100 ml were measured. Figure 50 shows that in case of San Benito, higher level re-contamination was observed. Although in San Benito, the average counts in raw water were similar to Encanto Pamap during evaluation of Safir filter and were about 100 CFU/100 ml , variations of counts up to 30,000 CFU/100 ml were observed. The raw water quality was similar during evaluation of Safir and ceramic filters. Bothe filters showed a strong reduction of *e.coli* counts on the permeate side. In case of Safir, values of up to 2 CFU/100 ml were observed which did not increase much at the tap or in the cup. For ceramic filter, 0 CFU/100 ml was observed after the filter candle but a stronger increase was measured at the tap and in the cup.

Table 22 shows Log removal values (LRV) between source and cup, storage and tap and permeate and membrane which indicate the increase in water quality due to intervention, performance of the filter in general and performance of the membrane/ceramic candle filtration. Low values for Encanto Pampa can be explained by the low concentrations of e.coli in raw water. For San Benito LRV values for e.coli of about LOG 2 are observed for both Safir and Ceramic filter. In case of other coliforms, lower LRV values were observed for Safir than for Ceramic filter. One of the possible reasons of this difference is the re-growth of other coliforms in the clean water tank in safir filter which is not observed in ceramic filter in such extent due to possible protection by colloidal silver used as impregnation in ceramic candles.

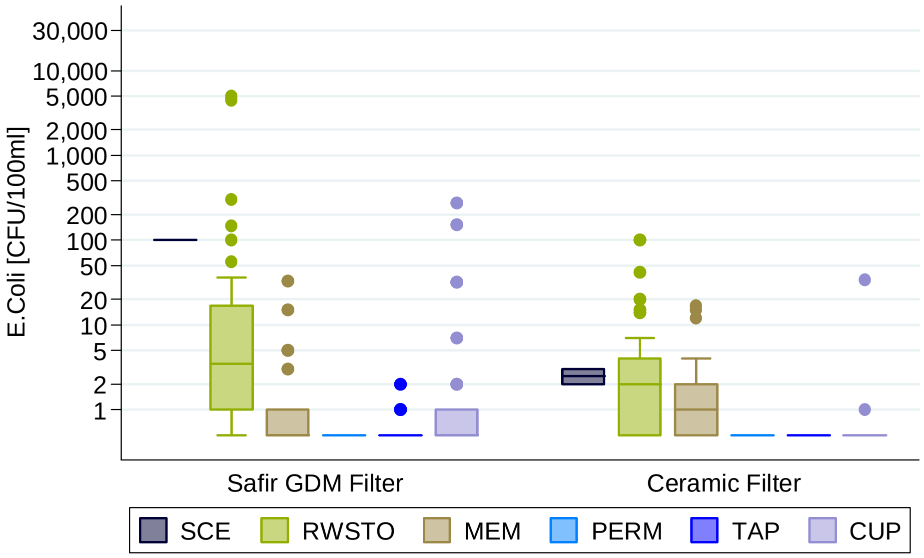
Summarizing, safir filter and cermic filter tested in this study showed good microbial removal values. The LRV of about 2 has been observed for both filters with contaminated water in San Benito. However, Safir fitler showed lower reduction of other coliforms comparing to ceramic filter. We assumed that this indicates regowth of other coliforms on the clean side of the membrane reduced in ceramimc filter by the influence of colloidal silver. This should be evaluated in more detail in the lab.

Table 22 Log removal values (LRV) for e.coli and other coliforms for ceramic and safir filters measured between different sampling points over the pathway of the filter (Derksen and Graf, 2013)

$LRV = \log_{10}(\frac{C_A}{C_B})$		LRV ***E.Coli***			**LRV *other coliforms***		
		Source to cup	**Storage to tap**	**Membrane tank to permeate**	**Source to cup**	**Storage to tap**	**Membrane tank to permeate**
ceramic filter	**Total**	2.20	1.54	1.27	2.67	2.85	2.90
	Encanto Pampa	0.50	0.71	0.44	2.26	2.31	2.38
	San Benito	1.55	2.16	2.07	1.60	3.23	3.38
safir filter	**Total**	1.90	1.42	1.19	0.19	0.90	1.15
	Encanto Pampa	n.a.	1.13	0.30	n.a.	0.47	0.56
	San Benito	1.84	1.96	2.06	0.04	1.60	1.73

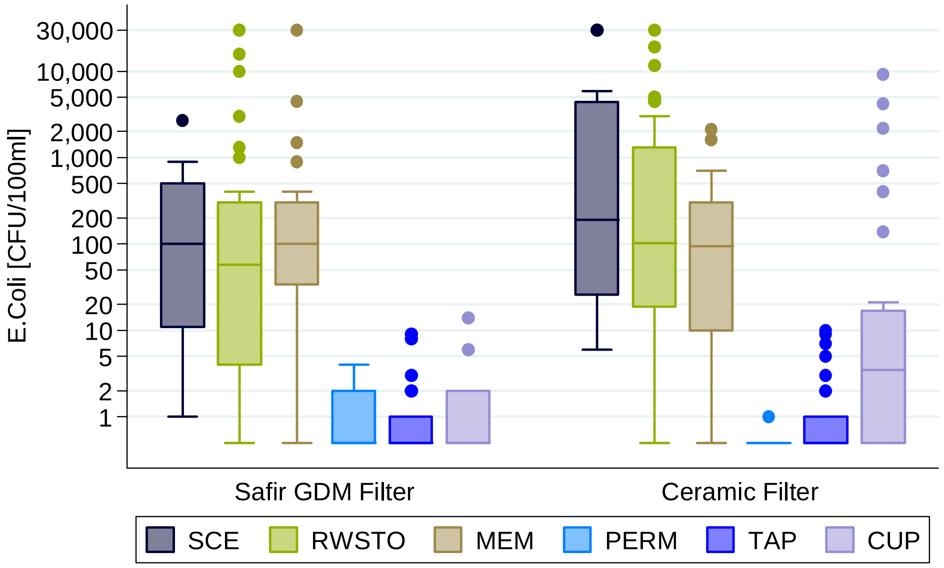
3.4.4. Chemical and Physical water quality parameters

Lack of dissolved oxygen can cause a problem for the biofilm on the membrane, when conditions get anaerobic. In Encanto Pampa, average oxygen is measured always above 6.5 mg/l which is absolutely fine. In the shallow wells of San Benito, values are very low and often found <1mg/l when measured directly in the well. However, the values measured further along the pathway through the filter (Figure 51), water is aerated as soon as it gets in contact with the atmosphere. Although concentrations remain lower than in Encanto Pampa, values measured in the raw water storage vessel (RWSTO), the raw water tank (MEM) or the tap pose no risk for the development of the biofilm.



Safir n: SCE 11 RWSTO 44 MEM 22 PERM 11 TAP 33 CUP 33
Ceramic n: SCE 2 RWSTO 33 MEM 21 PERM 11 TAP 32 CUP 11

Figure 49 *E.Coli* over the pathway of the safir and the ceramic filter respectively in the peri-urban area of Encanto Pampa. SCE - source water, RWSTO-raw water storage tank, MEM - membrane tank, PERM - permeate tube, TAP - at the tap of the filter, CUP - cups used in households for drinking. The number under the graph next to the water type code means the number of samples measured. (Derksen and Graf, 2013)



Safir n: SCE 21 RWSTO 33 MEM 22 PERM 10 TAP 31 CUP 10
Ceramic n: SCE 25 RWSTO 43 MEM 22 PERM 11 TAP 33 CUP 32

Figure 50 E.Coli over the pathway of the safir and the ceramic filter respectively in the rural area of San Benito. SCE - source water, RWSTO-raw water storage tank, MEM - membrane tank, PERM - permeate tube, TAP - at the tap of the filter, CUP - cups used in households for drinking. The number under the graph next to the water type code means the number of samples measured. (Derksen and Graf, 2013)

Electric conductivity is low in both study areas and does not show a trend over the pathway of the filter. pH is lower in the tropical areas of San Benito (see raw water quality characteristics in table 26). For both areas, no change in pH was observed in safir filter. For San Benito, slight increase of pH in ceramic filter was observed. We suppose that activated carbon filled in the ceamic candles might adsorb some of the organic acids causing low pH values leading to the increase of the pH. Neither pH nor conductivity seem to have any influence on the performance of the filter.

Figure 52 shows that turbidiy values over 60 NTU were observed in raw water in some cases and the variations of the turbidity was high. Independently on turbidity in raw water, decrease of turbidity to 0-1 NTU was observed in all cases in Safir and Ceramic filters.

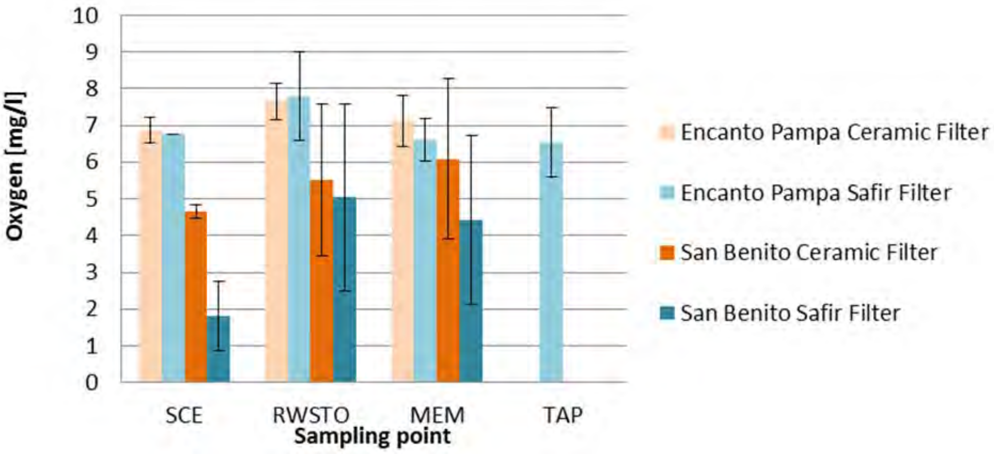


Figure 51 Devolution of dissolved oxygen over the pathway of the safir and ceramic filter respectively. Error bars represent one standard deviation in positive and one standard deviation in negative direction from the mean (Derksen and Graf, 2013)

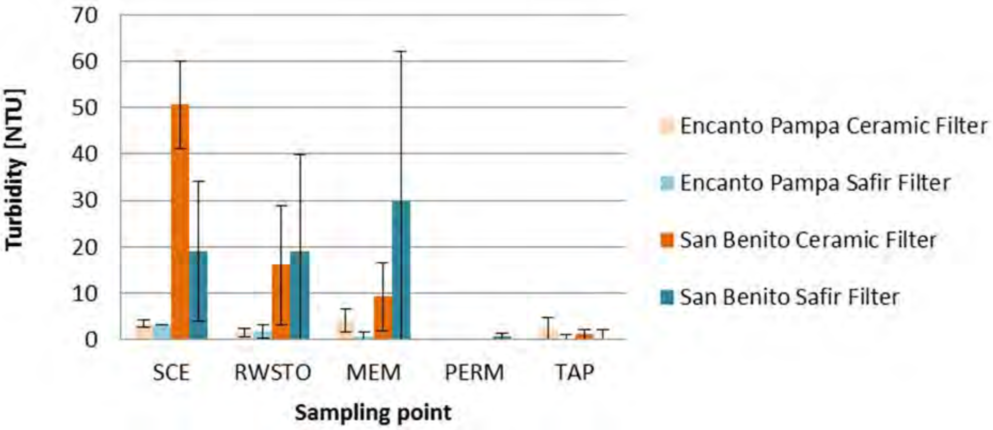


Figure 52 Devolution of turbidity over the pathway of the safir and ceramic filter respectively. Error bars represent one standard deviation in positive and one standard deviation in negative direction from the mean. (Derksen and Graf, 2013)

The concentrations of free and total iron were measured during monitoring, but no correlation between iron concentration and the flux found. In case of San Benito, a decrease of iron concentration was observed at each measuring point within the filter as shown on figure 53.

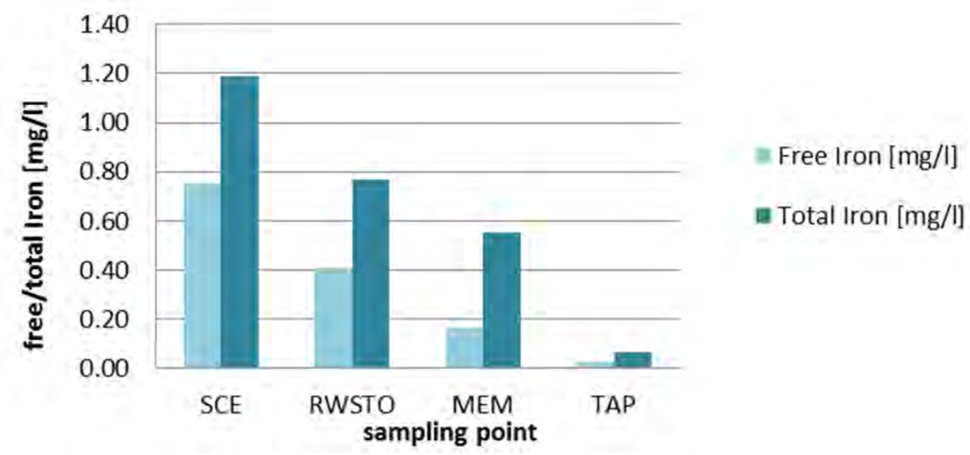


Figure 53 Devolution of free and total iron over the pathway of the safir filter in San Benito (Derksen and Graf, 2013).

We suppose that such decrease can be explained by oxidation and precipitation of free iron in the raw water, storage tanks and membrane tanks and chemical equilibriums between free and bound iron.

3.5. Summary of the evaluation of the filter functionality

Filter use. All filters except of one in Kenya and all filters in Bolivia were used regularly and none of the filters failed due to technical reasons. Filters were mostly filled 1-7 times a week in Kenya with an average value of about 4 times per week, and about 3-7 times in Bolivia, with an average value of about 6 times per week. In general, filters were used more frequently when people used turbid water sources with high microbial contamination as their own source of water.

Water flux and flow rate. None of the filters clogged during the field studies in Kenya and Bolivia in spite of high content of organic matter and turbidity in some water sources. The stable fluxes were achieved for all water sources and varied between 2 and 13 L/hm2 depending on water source and water level in the filter. In general, water sources with high turbidity and TOC levels showed lower flux values which did not depend considerable on pressure, while ground water and tap water sources with low turbidiy and TOC showed higher flux values which increased with an increase of water level and thus hydrostatic pressure in the filter. All households were generally satisfied with the flowrate obtained with the filter, although in case of Bolivia, lower flowrates were measured due to twice lower membrane area used in Safir prototypes. In case of San Benito when turbid water sources were used to fill the filter, GDM filter Safir showed stable and consistent performance while ceramic filters clogged or showed reduced flowrates and needed to be cleaned regularly.

Microbial water quality. Laboratory investigations of the UF membrane shows that log removal values of at least LOG 5 can be achieved for removal of bacteria and MS2 phages used as proxy for viruses with fouled membranes. Field evaluations showed that Log removal values of LOG2 were observed for e.coli in the field, mostly due to the fact that concentration of e.coli in the raw water was in the range of 100 CFU/100 ml and higher LRVs were not possible to measure. Considerable recontamination at the tap was observed during filed evaluation in Kenya. The recontamination issues were reduced in Bolivia due to new design of the filter. In general, GDM filters performed similar to ceramic candle filters used in Bolivia regarding e.colli removal. In case of other coliforms, considerable regrowth have been observed in case of GDM filters in both field studies. This should be further considered in the filter design and further steps to reduce re-growth in the filters should be done.

Physical and chemical water quality parameters. Dissolved oxygen concentration is the parameter which was considered as limiting in the operation of the GDM filters. However, none of the filters ever experienced anaerobic conditions during regular intermittent operation. Even raw water with low dissolved oxygen values was oxygenated well enough during filling and dissolved oxygen limiting conditions did not occur. Other parameters such as conductivity and pH did not show any impact on the filter performance. Total and free iron concentration also did not have any impact on flux. Free iron was reduced significantly in the filter most probably due to oxidation and precipitation before the membrane. Turbidity was removed by filters completely. TOC was not tested regularly during both field studies. However considerable differences in the TOC level between different water sources were measured. The differences in flux values observed between different water sources, showed that water sources with higher TOC content and turbidity such as pond water and river water showed in general lower stable flux values that water sources with low TOC such borehole water and tap water. Thus, TOC should be further considered as one of the most important parameters which can be measured in the field conditions, which can influence the flux.

4. Concluding remarks

Functionality and design of the GDM filters for household use have been evaluated in laboratory and two field studies in Kenya and Bolivia. The results of the project show that GDM presents a unique opportunity for household water treatment as it is the only filter which does not require regular maintenance, is easy to use and is able to filter turbid water with high organic matter content without any difficulties. At least LOG 2 removal of bacteria was proven in the field and the laboratory investigations showed that GDM filters containing ultrafiltration membranes of 50-150 kDa cut-off are able to show LOG 4-5 removal of viruses after only 2 days of filtration. Both Kenya and Bolivia designs were well accepted by the users and the users were able to operate the filters without external help. In Bolivia, household using turbid waters were willing to pay for the Safir filter to be able to keep it also after the end of the study. A short visit in Kenya showed that at least few of the filters are still in operation although 3.5 years have passed already since the begin of the study. Thus, we see a huge potential for GDM filters for applications on household scale, especially for populations relying on turbid water sources.

However there are few critical issues related to GDM filtration which should be further considered. The major issue is that GDM filter as well as most other filters available on the markets in low-income countries does not provide any residual protection to the pure water. Water stored in the clean water tank can be re-contaminated if basic hygiene conditions are low. The question of the re-growth in the clean water tank is also not yet solved. The data show that some re-growth of naturally available bacteria can be observed. However the question if there is a risk of re-growth of pathogenic microorganisms in clean water tank remains unsolved und should be further evaluated.

One of the major questions remaining is the costs of the GDM household filters. The price of the membrane material is currently about 12-15 euro per 1 m^2. However, flat sheet membrane modules of 0.3-1 m^2 are not freely available on the market. Custom made solutions exist but the costs per 0.5 m^2 is at least 40 euro or more. Thus the production costs of the entire system can be estimated at 60 euro or more, depending on the type of housing used, who carries investment costs, place of production and other issues. Another question is the certification of the membrane modules. Most of the flat sheet modules are designed for membrane bioreactors and are not certified for drinking water treatment. Thus, certification would be required in order to be able to import the modules to the other countries.

5. References

5.1. Relevant GDM-related publications

5.1.1. Scientific publications

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5.1.6. Publications in preparation

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