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Swiss Federal Institute of Aquatic
Science and Technology

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Water Treatment and Safe Storage

EPFL, ENV 402: Sanitary Engineering in Developing Countries
2024
Loïc Fache

A little about me

- Bsc & Msc Environmental engineering EPFL (2023)
- Project officer in the water safety management group (Eawag-Sandec) (Feb 2024- present)
- Looking at safe water supply, prevention against recontamination, and participatory processes for safe water management

Learning objectives

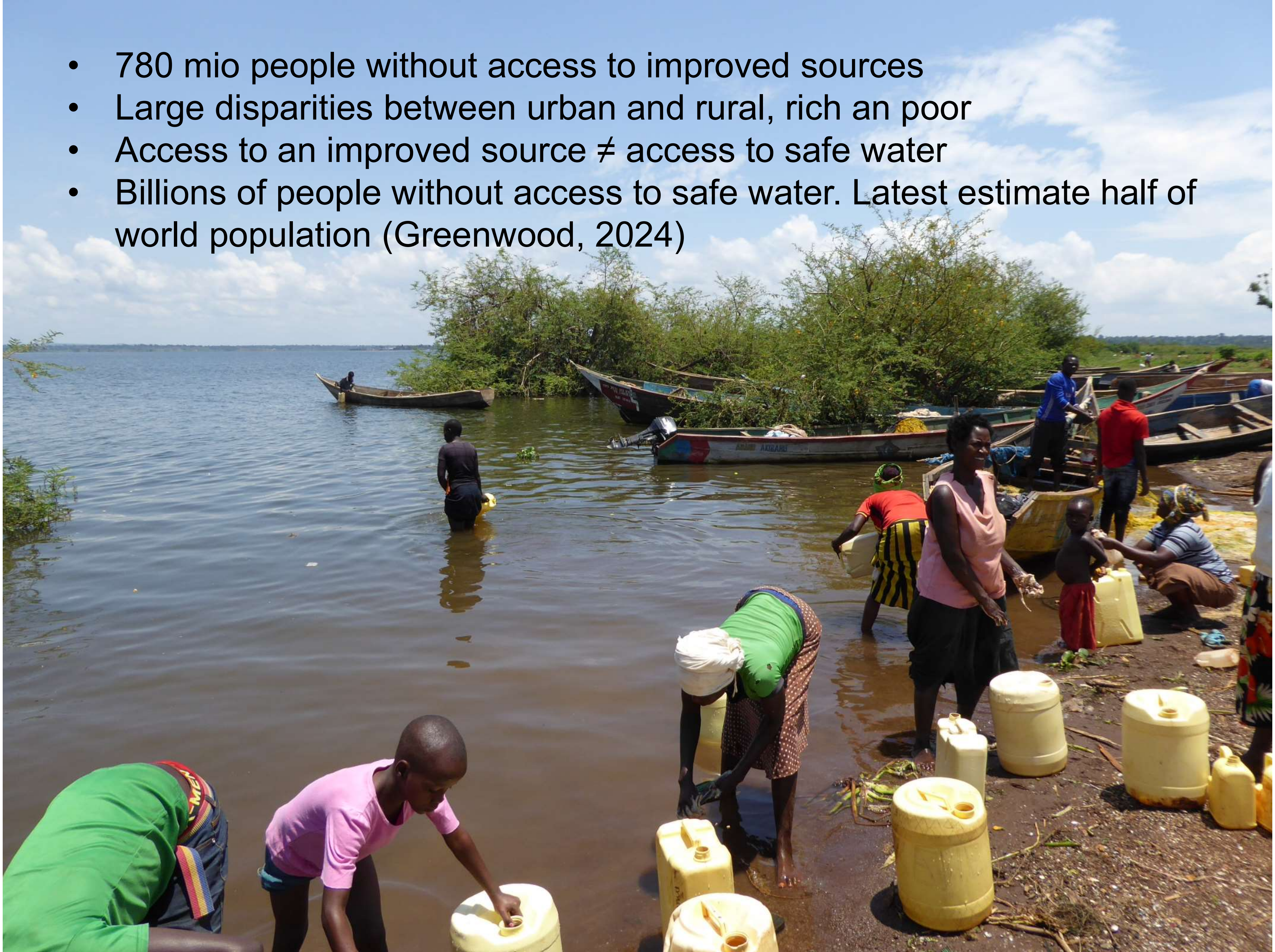
1. Understand what kind of strategies are required to provide sustainable access to safe water and support its consistent consumption in low income areas

2. Understand the principles, strengths and limitations of water treatment and safe storage technologies that can be applied in this context

3. Know what kind of financial and business elements have to be considered for drinking water treatment at community scale (water kiosks) and at household scale (household water treatment)

4. Be aware of behavior change interventions required to increase demand for safe water

- 780 mio people without access to improved sources
- Large disparities between urban and rural, rich an poor
- Access to an improved source ≠ access to safe water
- Billions of people without access to safe water. Latest estimate half of world population (Greenwood, 2024)



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UN General Assembly resolution, July 2010

"*recognizes* the right to safe and clean drinking water and sanitation as a human right that is essential for the full enjoyment of life and all human rights."

Criterion	UN Human Rights Council 2010
Sufficient quantity	Availability
Continuity of service	
Safe for health	Quality/safety
Aesthetically acceptable	Acceptability
Time/distance required to collect	Accessibility
Suitable for use by all, including young, old, disabled, etc	
Affordable	Affordability

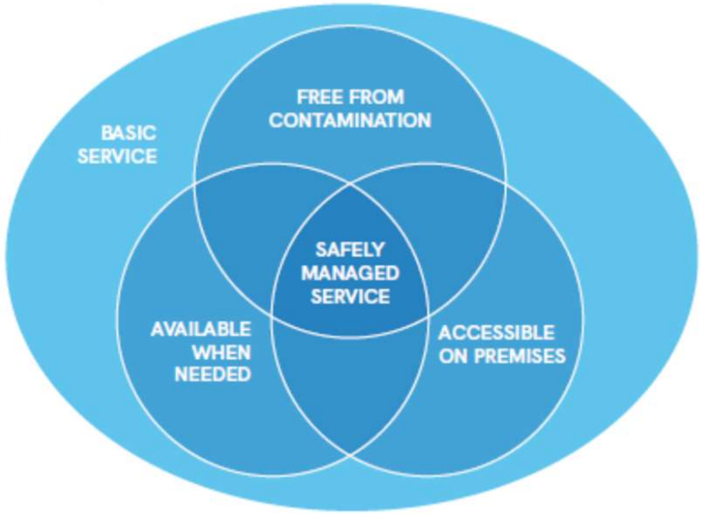
SERVICE LEVEL	DEFINITION
SAFELY MANAGED	Drinking water from an improved water source that is located on premises, available when needed and free from faecal and priority chemical contamination
BASIC	Drinking water from an improved source, provided collection time is not more than 30 minutes for a round trip, including queuing
LIMITED	Drinking water from an improved source for which collection time exceeds 30 minutes for a round trip, including queuing
UNIMPROVED	Drinking water from an unprotected dug well or unprotected spring
SURFACE WATER	Drinking water directly from a river, dam, lake, pon[d,] stream, canal or irrigation canal

***Note:** Improved sources include: piped water, boreholes or tubewells, protected dug wells, protected springs, rainwater, and packaged or delivered water.*

SDG 6.1

By 2030 achieve universal and equitable access to safe and affordable drinking water for all

- proportion of population using safely managed drinking water



Diarrhoea reduction associated with improving drinking water services

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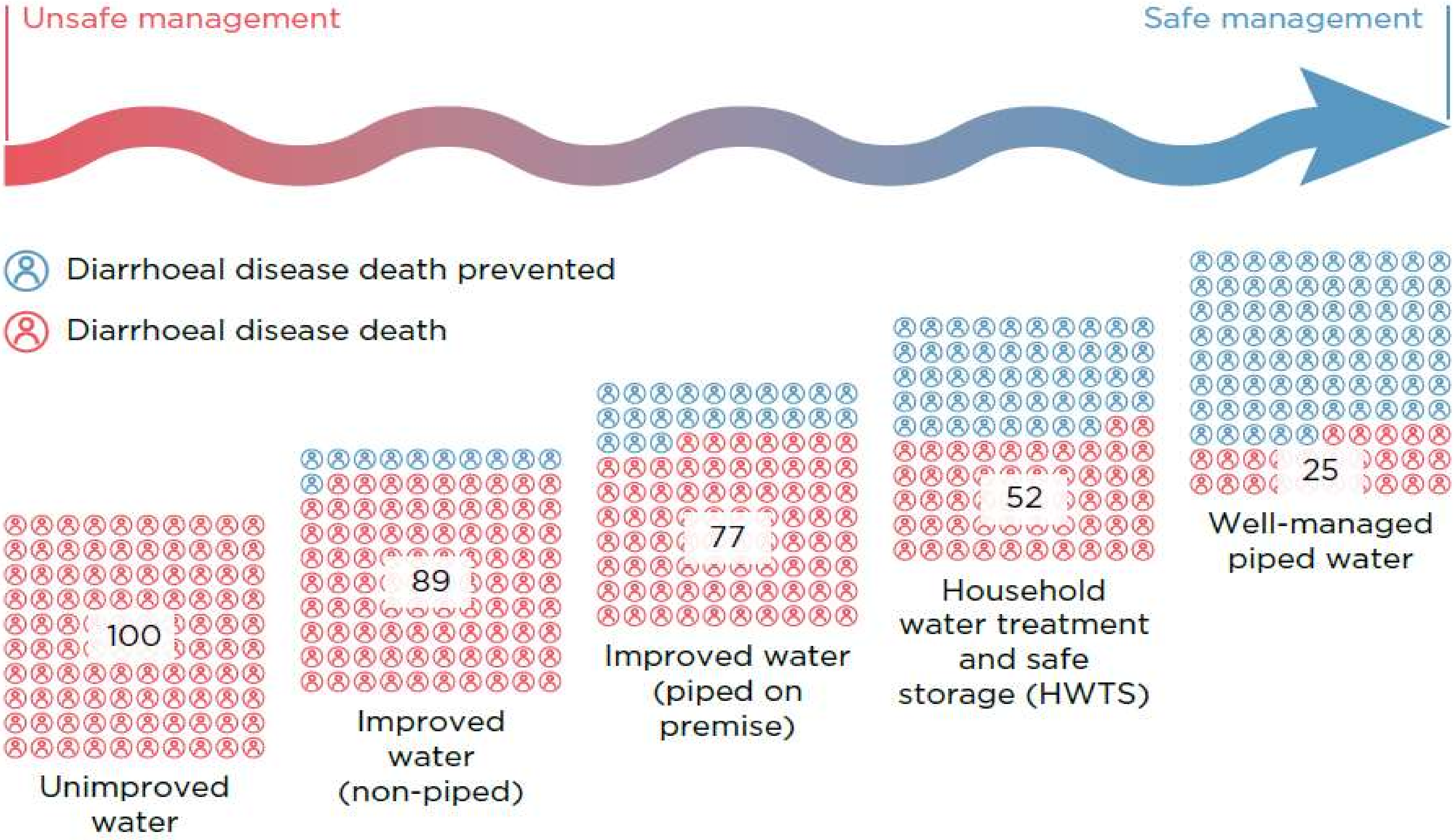

Source: WHO WASH Strategy 2018-2025

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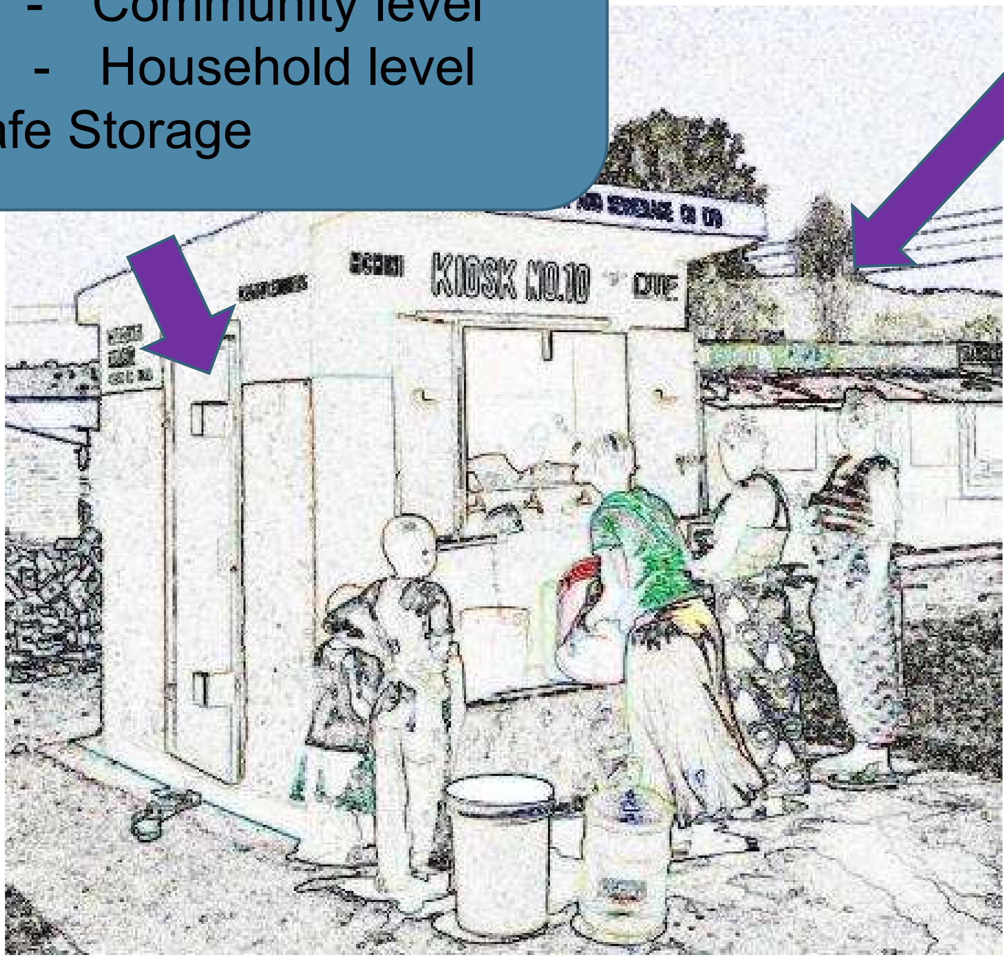
Elements of sustainable safe water consumption

Technology
Drinking water treatment
- Community level
- Household level

Safe Storage

Finances
- Business management
- Demand
- Price of water
- Price of HWTS products
- Supply chains



Behaviour
- Demand
- Know-how & capacity
- Consistent consumption

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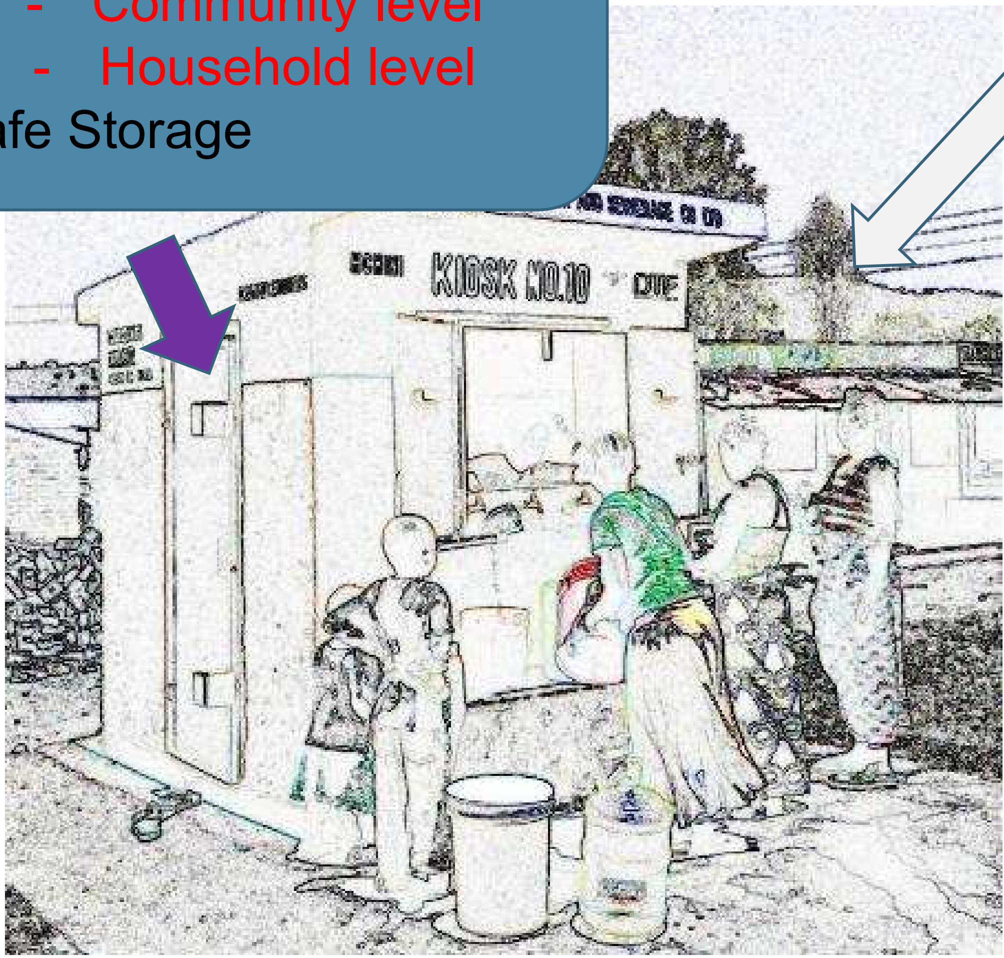
Water Treatment Technologies

Technology
Drinking water treatment
- Community level
- Household level

Safe Storage



Finances
- Business management
- Demand
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Behaviour
- Demand
- Know-how & capacity
- Consistent consumption

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Water treatment

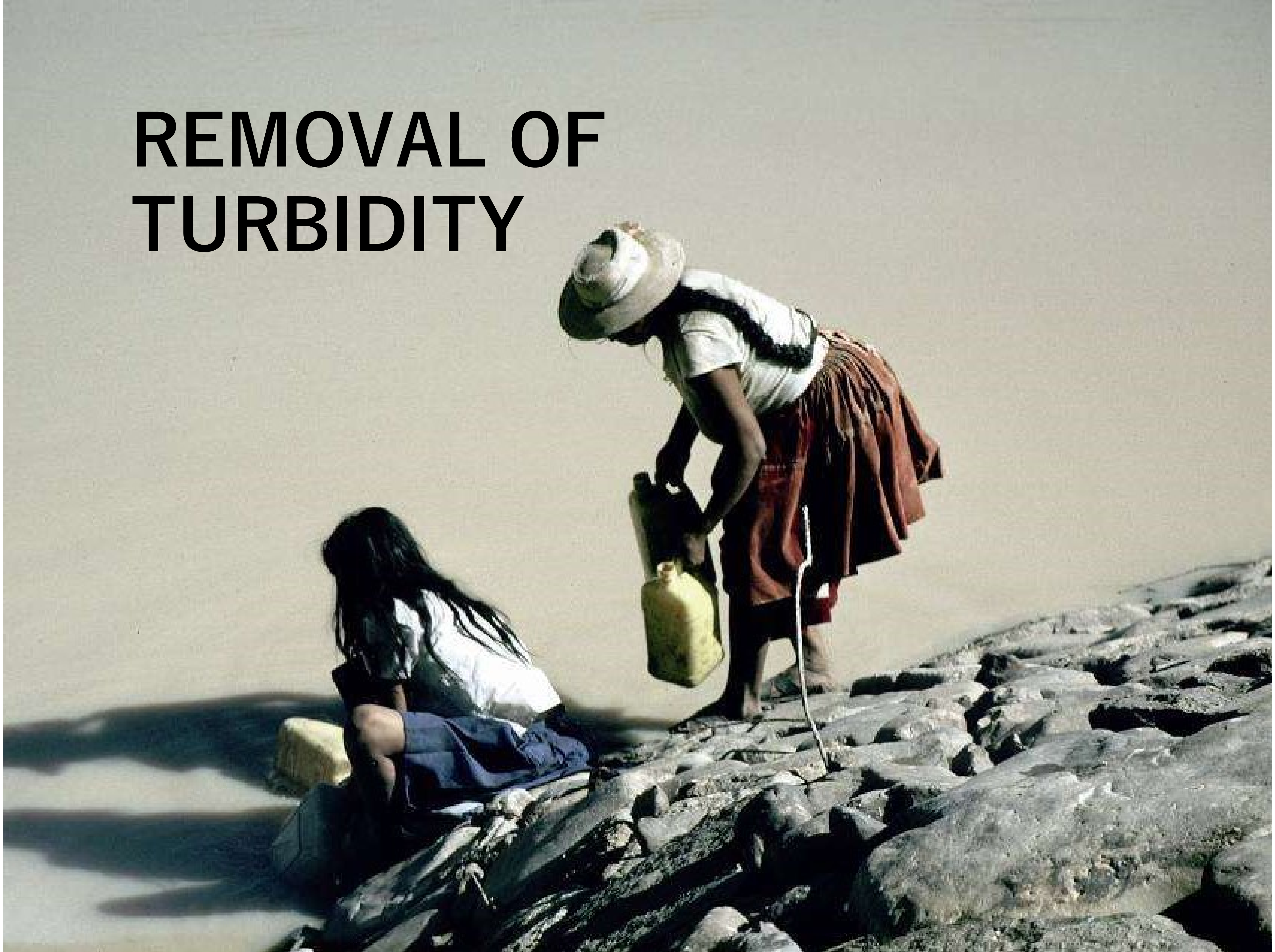
Physical	Chemical	Biological
• boiling • heating (fuel and solar) • settling • filtering • exposing to the UV radiation in sunlight or lamps	• coagulation-flocculation and precipitation • adsorption • ion exchange • chemical disinfection with germicidal agents (e.g. chlorine)	• biologically active layer in slow sand filters.

Safe storage

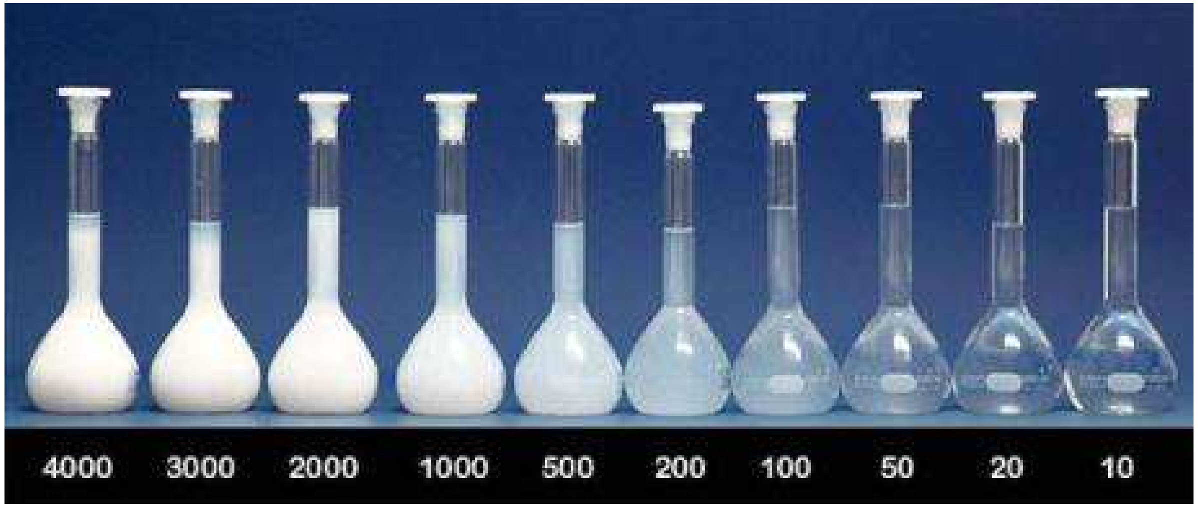
Water treatment at different scales

Large scale centralized system	Decentralized, community treatment or Water Kiosk	Household water treatment
A large number of people are supplied – high quality requirements Complex systems ➢ High cost (investment & operation) ➢ Complex O&M Responsibility with government or private company	System less complex ➢ easier O&M ➢ lower cost Operated by community, challenge for capacity building O&M Financing through the sale of treated water Need to create demand	Low-tech solutions Responsibility for financement, O&M is with household Need to create demand and build capacity Treatment at point of consumption reduces risk of recontamination

REMOVAL OF TURBIDITY



Threat of turbidity for water treatment



< 5 NTU is generally acceptable to consumers

Turbid waters challenge treatment processes.

- use up chemical disinfectants
- cause premature clogging of filters
- block UV radiation
- stimulate bacterial growth

Coagulation & Flocculation

Coagulation and flocculation remove turbidity (suspended solids) and can reduce color and some dissolved componds.

Coagulants used:

<u>Alum</u> Aluminiumsulfate ($Al_2(SO_4)_3 \cdot nH_2O$)

•Widely available, inexpensive

•Crystals or powder

•**<u>Iron salts</u> ($FeCl_3$ or $Fe_2(SO_4)_3 \cdot nH_2O$)**

•Less common

•Less soluble than aluminium

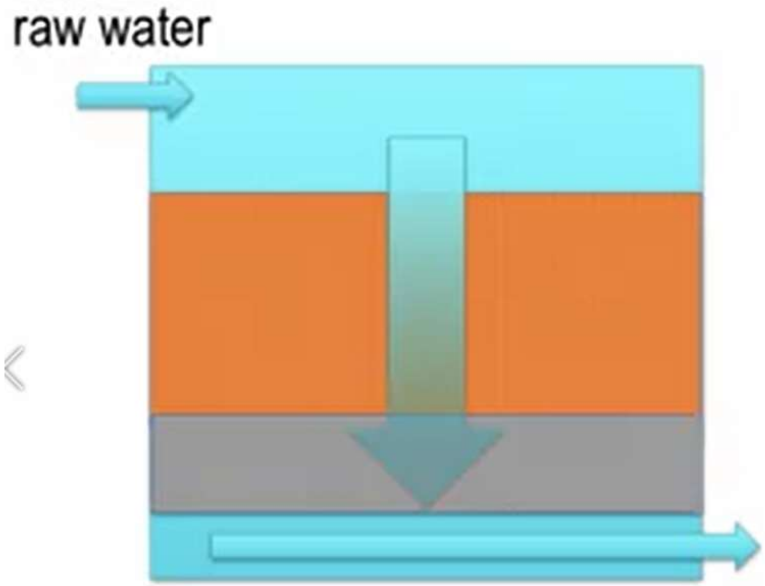
⇨ broader effective pH range

•**<u>Crushed seed of Moringa oleifera</u>**

Process

- **Coagulation**: metal ions (e.g. Al^{+3}) destabilize negatively charged colloids, and form hydroxide flocs ($Al(OH)_3$).
  - Alkalinity addition may be necessary (pH is reduced)
- **Flocculation:** flocs collide and grow.
- **Sedimentation**: the growing flocs settle out of solution.
- **Filtration**: remaining suspended flocs are removed.

Rapid Sand Filtration

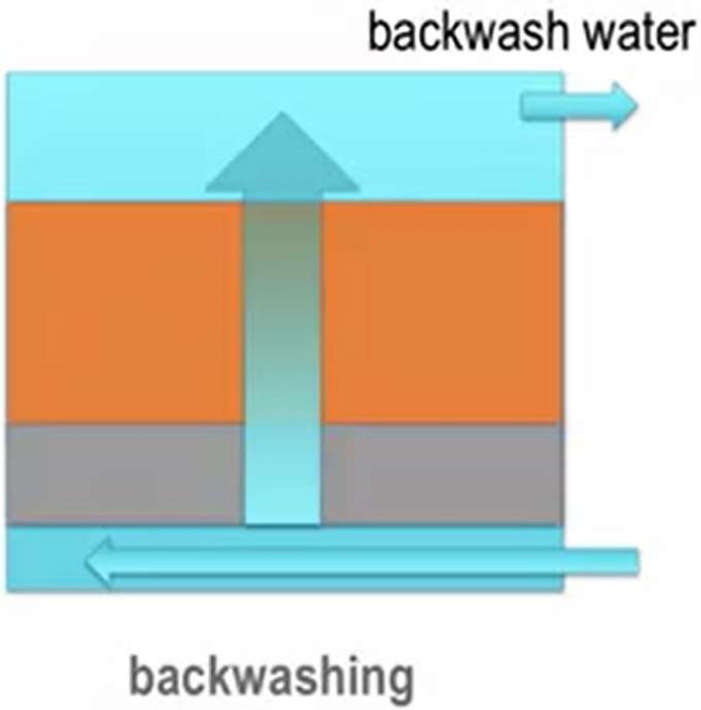


supernatant water

sand layer

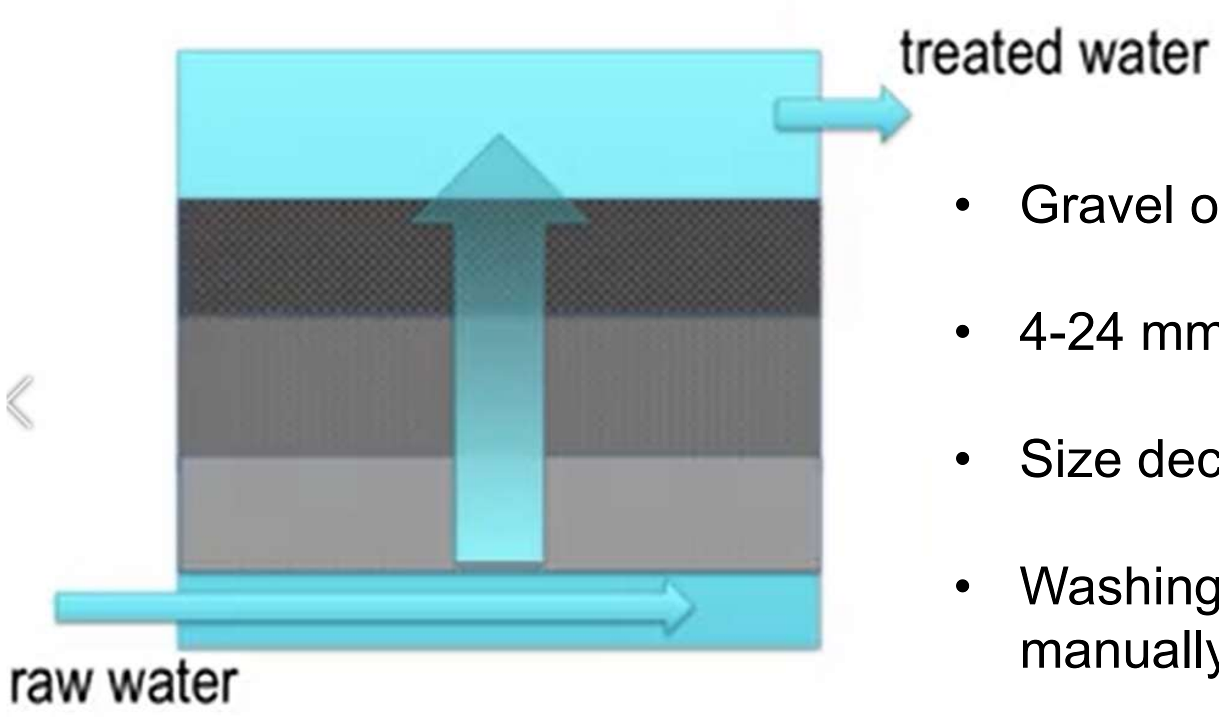
gravel layer

underdrain



Downflow filtratrion
Approximately 1-40 m/h

Roughing Filtration



- Gravel or other filtration material
- 4-24 mm
- Size decreases with flow direction
- Washing by draining the filter or manually removing the top layer

Upflow layer filtratrion
Approximately 0.3-1.5 m/h

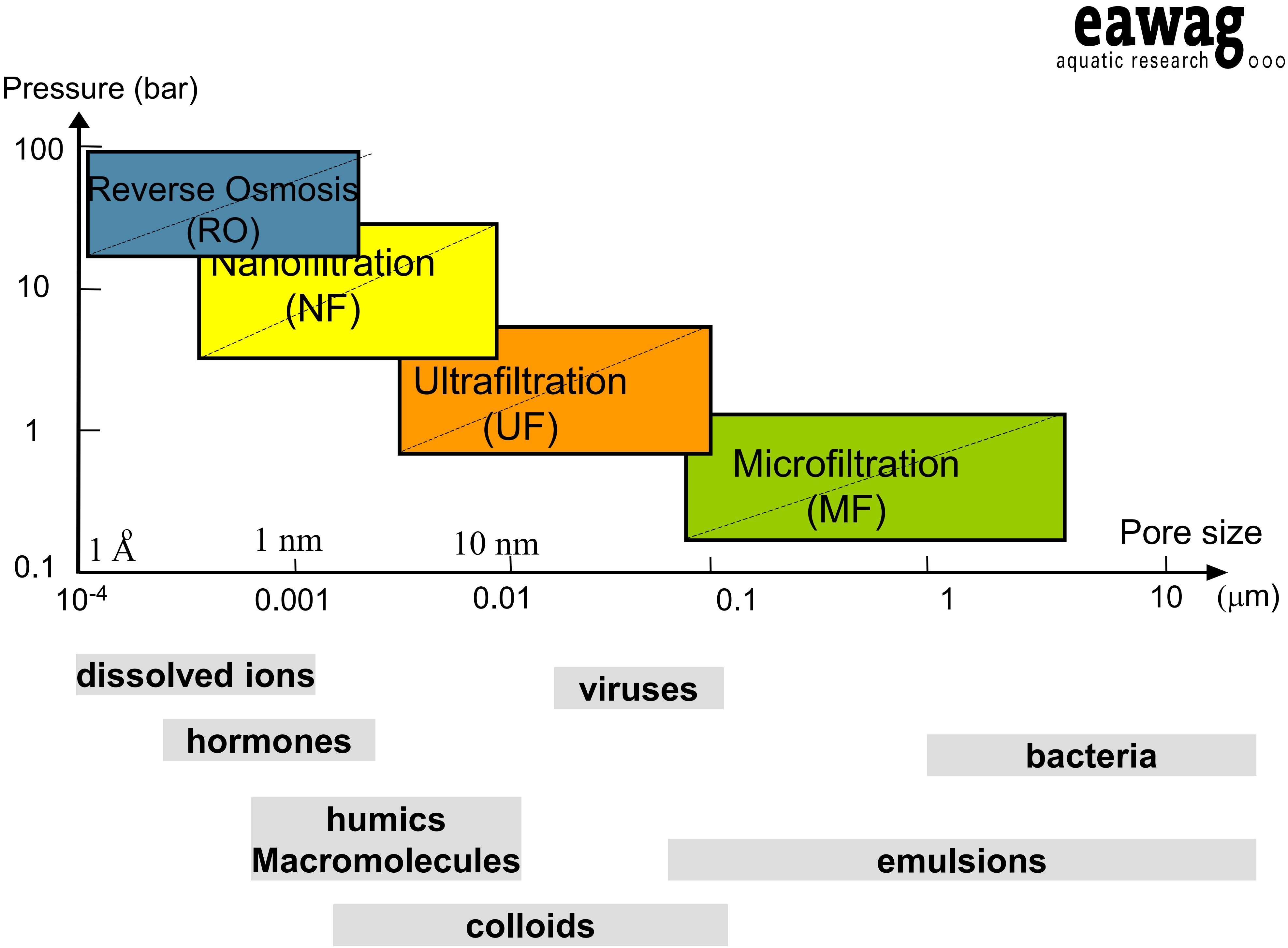
PHYSICAL WATER TREATMENT

Sand-, Gravel & Ceramic Filtration

Type	Efficiency	Applicability
Roughing Filtration	Removal of turbidity	Semi-centralized ○ *Only pretreatment* ○ *Local production*
Rapid Sand Filtration	Removal of turbidity	Semi-centralized ○ *Only pretreatment* ○ *Local production*
Slow Sand Filtration	1-2 Log Bacteria, Protozoa, Heavy metals, organic matter	Centralized/ Household ○ *Medium cost* ○ *Local production*
Ceramic Filtration	2 Log Bacteria & Protozoa no viruses	Household ○ *Low cost* ○ *Local production*

Slow Sand Filtration

Microbial performance	• 1-2 Log Bacteria, Protozoa, • Heavy metals, organic matter • Limited effectiveness against viruses
Advantages	• Removal of organic matter, heavy metals • Bio-reactor, reduced risk of recontamination • Very robust and local materials for construction • No requirement for chemicals or energy
Limitations	• Limited effectiveness against viruses • Needs matured biological layer to be effective («Schmutzdecke»); build up >10 days • Schutzdecke is destroyed if sand dries out • Filter is clogging at high turbidity (>100 NTU)
Application	• Household • Centralized treatment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Pressure (bar)
100
10
1
0.1
Reverse Osmosis
(RO)
Nanofiltration
(NF)
Ultrafiltration
(UF)
Microfiltration
(MF)
1 Å
1 nm
10 nm
Pore size
10-4
0.001
0.01
0.1
1
10
(μm)
dissolved ions
viruses
hormones
bacteria
humics
Macromolecules
emulsions
colloids

Biosand filter

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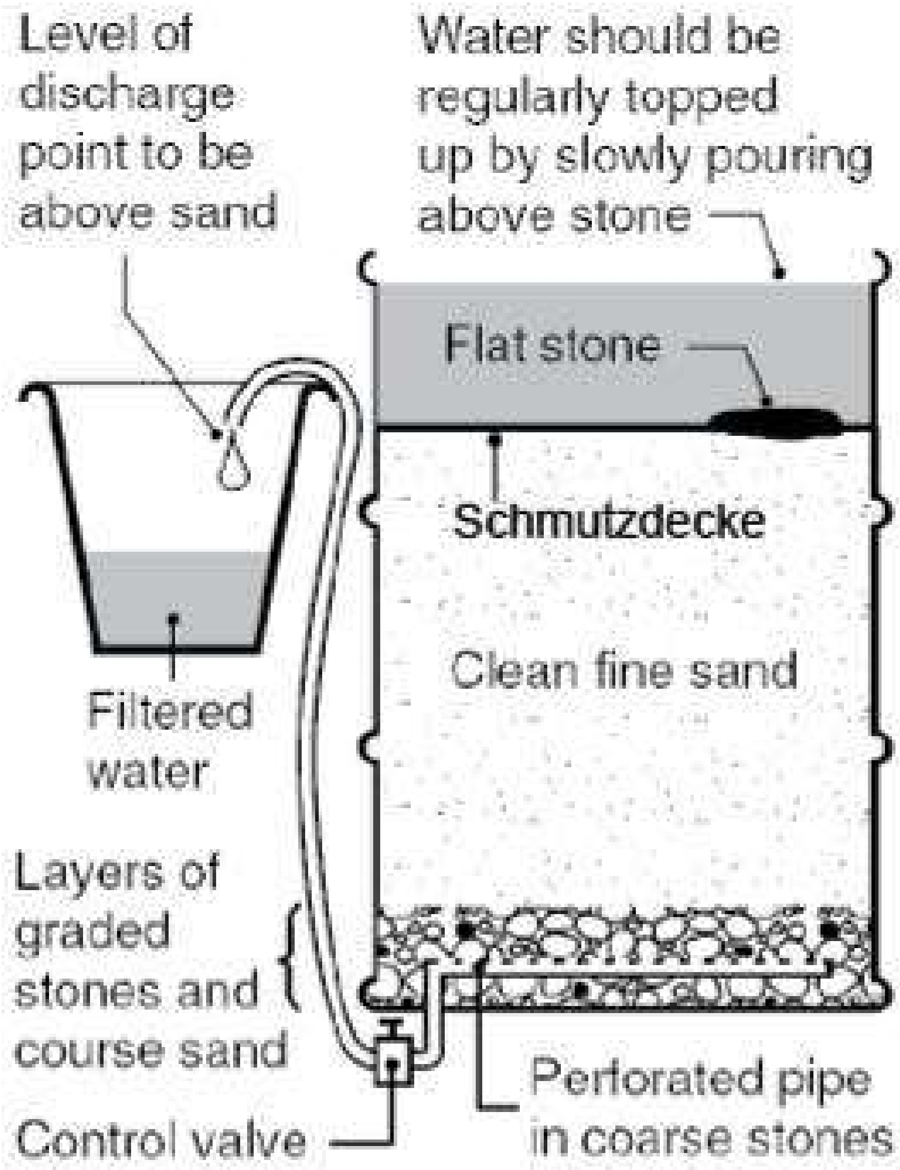

1. **Predation: Microorganisms within the "schmutzdecke" (biological layer) consume bacteria and other pathogens found in the water.**

2. **Mechanical trapping and adsorption: Sediments, cysts and worms trapped in the spaces between the sand grains/ or adsorbed to the material.**

3. **Natural death: Food scarcity, suboptimal temperatures and short life span will cause pathogens to die off.**

Household Design

Biosand Filters

300,000 distributed

www.purefilteredwater.com

Cost for household products: ~30 USD

Membrane Filtration

Type	Efficiency	Applicability
Membrane Filtration (Microfiltration)	2-3 Log Bacteria & Protozoa, no Viruses	Centralized, Semi-centralized, Household
Membrane Filtration (Ultrafiltration)	4 Log Bacteria & Protozoa, 4-5 Log Viruses Colloids	Centralized, Semi-centralized, Household
Membrane Filtration (Reverse Osmosis)	>5 Log Bacteria, Protozoa, Viruses Humics, dissolved ions	Centralized, Semi-centralized ○ *high-tech* ○ *very expensive* ○ *discharge or brine problematic*

Membrane Filtration

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- Polymeric membranes used for filtration (fe. Polyethersulfon (PES)) hollow fiber membranes/ flat sheet membranes
- Systems with smaller pore size require higher pressure
- For traditional systems: regular backflushing and disinfection of membranes required

Laminated flat-sheet membranes

Hollow fibre and capillary membranes

Gravity Driven Membranes

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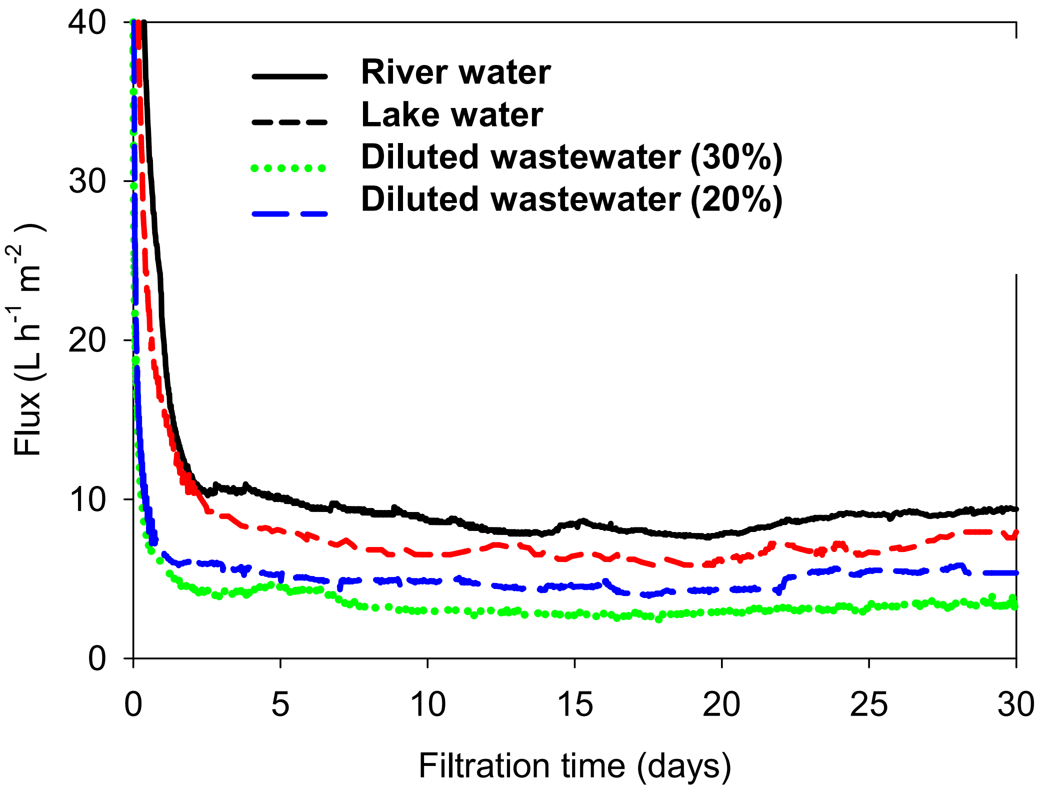
Flux stabilization
-No crossflow
-No backflush
-No cleaning



Flux stabilizes on a level of 4-10 (L $h^{-1}m^{-2}$) for at least 2 years

Membrane Filtration (traditional systems)

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Mainly reverse osmosis in water kiosks

Microbial performance	• Depending upon pore size of membrane: (see slide 22)
Advantages (gravity driven system)	• High efficiency • High flow • Turbidity is reduced
Limitations	• Fouling of membranes -> Requires regular back-flushing and chemical disinfection • Pretreatment required for turbid water • Complex system, high cost • Product must be imported in most areas • Requires supply chain for replacement parts • Difficult discharge of brine in RO-systems • Recontamination risk during storage

Membrane Filtration (GDM)

Microbial performance	• Micro- or Ultrafiltration: depending upon pore size of membrane
Advantages	• Simple to use • Works well with turbid water (GDM) • No requirement for chemicals or energy • Formation of a biofilm on membranes (GDM)
Limitations	• Some systems require regular backflushing (Skyjuice) • Membranes must be imported -> difficult supply chains • Medium cost • Recontamination risk during storage
Application	• Household • Community scale • Centralized

Example of filters

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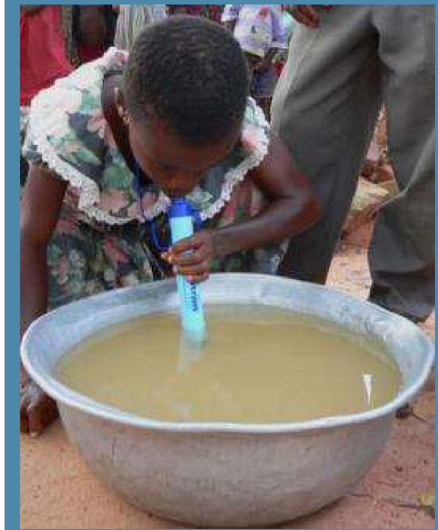


Lifestraw personal
Microfiltration, 100nm
sucking, backflush
Cost: 25 USD/ 40 USD

Sawyer Water Filter
Ultrafiltration, 20nm
Siphon-filter
hydrostatic pressure, backflush
Cost: 50 USD

Martin Membranes
Ultrafiltration, 20nm
hydrostatic pressure, no backflush
Cost: 60 USD

Ceramic filtration

Water is filtered through porous ceramic material.

Removal effectiveness depends on size of the pores in the clay. Most filters are effective at removing protozoa and bacteria, but not at removing viruses.

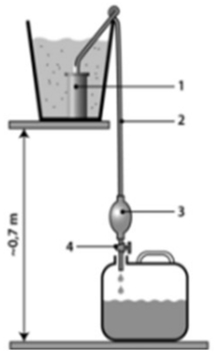
Higher quality ceramic filters treated with bacteriostatic silver in the lab:

- Protozoa reduction > 99.9% (3 log)
- Bacteria reduction > 99.99% (4 log)

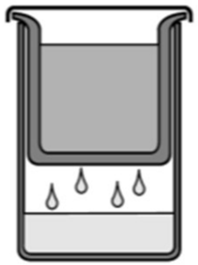
Slow flow: 1-2 litres per hour (per candle)

Regular cleaning required if turbid water is used

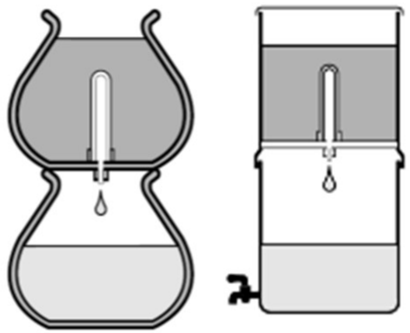
Cost about 10 to 30 USD



Siphon filter



Porous jar



Candle with jars

Ceramic Filtration

Microbial performance	• 2 Log removal of bacteria and protozoa • Limited effectiveness against viruses
Advantages	• Simple to use • Turbidity is reduced • Local production possible • One-time investment • No requirement for chemicals or energy
Limitations	• Recontamination risk during storage • Quality of locally produced filters is variable • Requires regular cleaning (especially if water is turbid) • Low filtration rate (1-3 Liters per hour) • Fragility: frequent filter breakage and difficult transport
Application	• Household

Ceramic filters in Cambodia – direct sales and MFI

Product	Tunsai ceramic filter
Organizations	Hydrologic social enterprise
Sales approach	Door-to-door sales by trained sales agents and in MFI group meetings Tunsai: 12.5 USD Super-Tunsai: 22 USD
Outcome	Direct sales: 16.4% of HHs MFI groups: 43.1% of members High rates of consistent use (74%)

- Microfinance loans quickly outperformed direct sales model → Financing is a key trigger for purchase
- Importance of design: Super Tunsai outsold Tunsai by 17:1

Boiling

The oldest method

Never applied at centralized scale

Often at household scale

Ideally, the water is cooled and stored in the same vessel in order to minimize chances of re-contamination.

Effective against almost all pathogens

Exceptions: some spores like anthrax

Question: How long should water be boiled?

Pasteurization

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Microorganisms	Temperature for 100 % Destruction		
	1 Min.	6 Min.	60 Min.
Enteroviruses			62 °C
Rotaviruses			63 °C for 30 Min.
Faecal Coliforms	at 80 °C complete destruction		
Salmonellae		62 °C	58 °C
Shigella		61 °C	54 °C
Vibrio Cholera			45 °C
Entamoeba Histolytica Cysts	57 °C	54 °C	50 °C
Giardia Cysts	57 °C	54 °C	50 °C
Hookworm Eggs and Larvae		62 °C	51 °C
Ascaris Eggs	68 °C	62 °C	57 °C
Schistosomas Eggs	60 °C	55 °C	50 °C
Taenia Eggs	65 °C	57 °C	51 °C

(Feachem, 1983)

Water does not have to be boiled in order to kill 99.9% of the microorganisms.
Heating up the water to 70°C for a few minutes has the same effect.

Boiling & Pasteurization

Microbial performance	• Disinfects all classes of pathogens
Advantages	• Common technology • Can be combined with cooking and tea boiling • Treats turbid water!
Limitations	• Recontamination risk during storage • High cost for fuel • Indoor air pollution • Time consuming application
Application	• Boiling only at household level • Community applications for pasteurization

Ultraviolet irradiation (UV-C)

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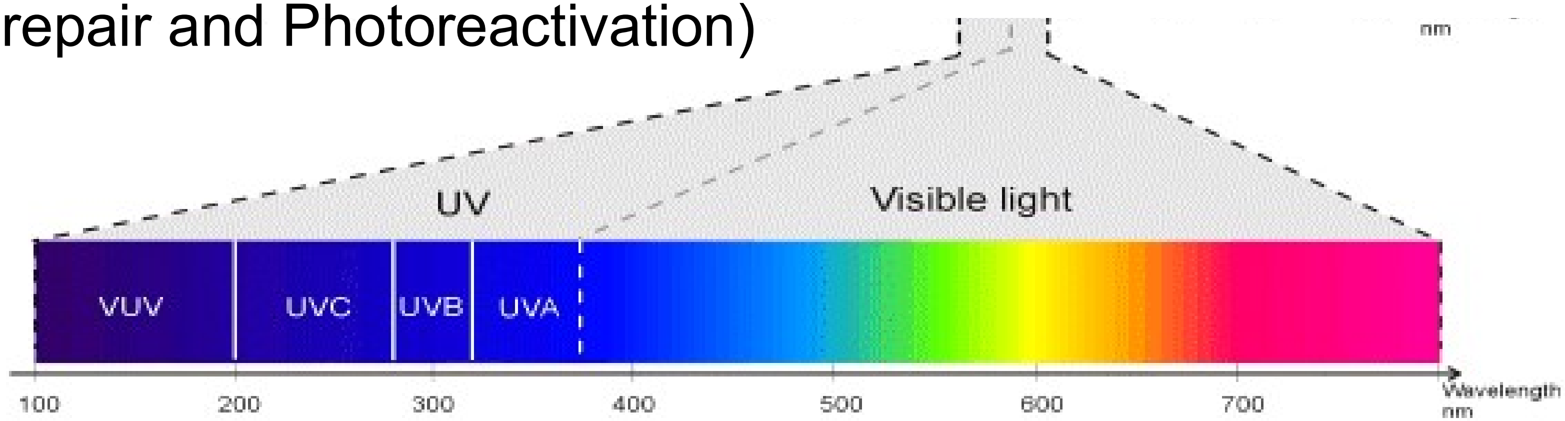
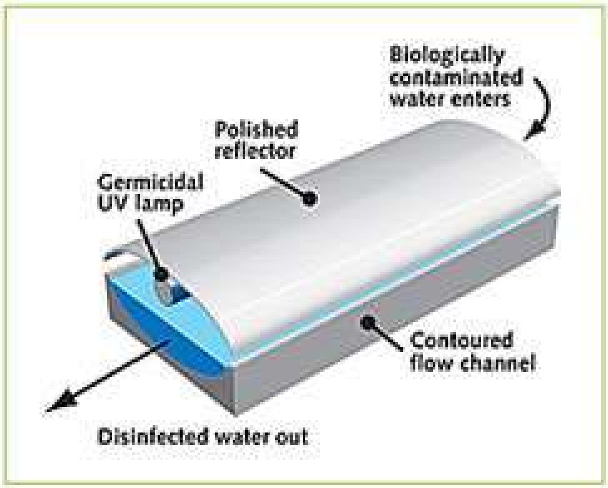
- Germicidal activity of UV-C-radiation (200-320 nm) used for water disinfection since early 20th century.
- All waterborne pathogens are disinfected at sufficiently high doses:
  - Bacteria, Cryptosporidium & Giardia: 1-10 mJ/cm^2
  - Viruses & bacterial spores: 30-150 mJ/cm^2
- Low pressure mercury UV-lamps: 50-150 mJ/cm^2
- With too low doses of UV radiation: Ability of bacteria and other microbes to repair UV-induced damage and restore infectivity (Dark repair and Photoreactivation)



UV radiation

Microbial performance	•	Effective against bacteria, protozoa and viruses
Advantages	• • •	Simple to use No change in taste in water Very fast treatment
Limitations	• • •	Highly turbid water needs pretretment Requires electricity Requires supply chain for replacement parts
Application	• •	Household Community Scale



Cost for household product: 80 USD
Low cost option under development

Solar Disinfection (SODIS)

- Contaminated water is filled into transparent plastic bottles and exposed to the sunlight for 6 hours.
- During exposure sunlight destroys the pathogenic bacteria and viruses.
- A solar radiation intensity of at least 500 W/m^2 is required during 5 hours
- A synergy of UV-A radiation and temperature occurs if the water temperature raises above 50°C
  ➔ after 1 hour of solar exposure the water is safe for consumption

Solar Disinfection

Microbial performance	• Effective against bacteria, protozoa and viruses (depending upon weather and container material)
Advantages	• Uses locally available materials (sunlight and PET-bottles) • Very low cost • No change in taste in water • Recontamination unlikely if stored in bottles used for treatment
Limitations	• Highly turbid water needs pretretment • Weather dependency • Long treatment time (some hours to two days) • Limited volume of water that can be treated • Requires a large supply of intact, clean and properly sized bottles
Application	• Only household

CHEMICAL TREATMENT

Chlorination

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•Free Chlorine, commonly used
- NaOCl, liquid Sodium Hypochlorite,
- $Ca(OCl)_2$ solid Calcium Hypochlorite, Bleaching Powder

•Sodium dichloroisocyanurate (NaDCC)
(Tablets, higher shelf-life)

•Water quality influences the inactivation.
FRC consumed by dissolved organic matter.

➢Turbidity < 5 NTU

➢6.8 < pH < 7.2

•Sometimes used: silver, iodine (not for longterm use)

➔Highly turbid water needs to be pretreated

➔Contact time: about 30 Minutes

Only method that provides residual disinfection! Protection against recontamination

Particular resistance of Cryptosporidium!

Dosage of chlorination

WHO recommendation for chlorination at the tap stand:
0.2 to 1.0 mg/L to protect water from recontamination

This concentration is not sufficient to protect water from unimproved open water sources (higher chlorine demand, more nutrients for regrowth)

- 2 mg/L <10 NTU
- 4 mg/L for 10-100 NTU
- This will provide 0.2mg/L after 24h storage

Water with higher turbidities: no chlorination!

- Formation of Trihalomethanes (potentially cancerogenic & bad smell)

Chlorination

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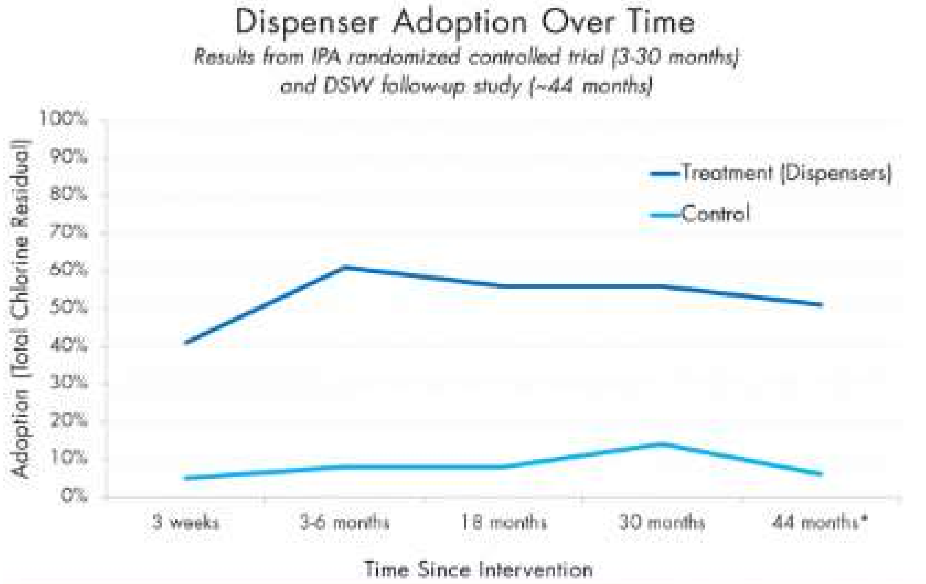
Microbial performance	• 2 Log removal of bacteria and some viruses • Ineffective against protozoan cyst such as Cryptosporidium parvum
Advantages	• **Residual protection against recontamination** • Simple to use • Local production is possible • Low cost
Limitations	• Highly turbid water needs pretretment • Strong taste and odour of treated water • Dosage might be difficult • Contact time essential for chemicals to react
Application	• Household level • Community scale • Centralized

Chlorine dispenser

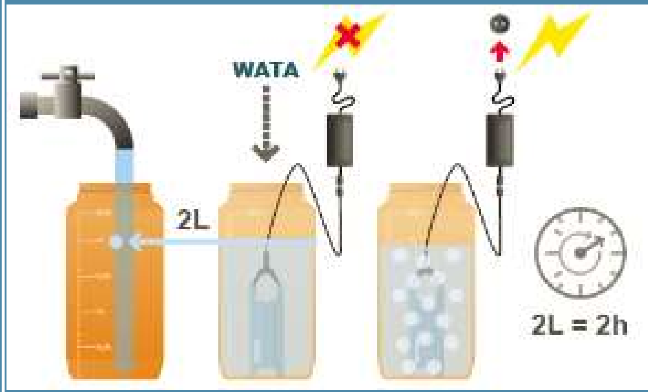
Marketing example

Product	Chlorine Dispenser
Organizations	Innovations for Poverty Action (IPA)
Sales approach	Cost for chlorine is integrated into the price of water 0.5 USD per year per person
Outcome	Evaluation in Kenya: 50-61% of people used chlorine dispenser regularly (compared to 6-14% in control group), and still used it after 2 years.

- The dispenser is a plastic tank with a valve that delivers a precise dose of chlorine at the water source.
- Community education & 1 community member is responsible for the dispenser
- Regular maintenance and supply of chlorine



www.poverty-action.org/chlorinedispensers



Safe Water System Liquid chlorine & storage	Aquatabs	WATA
• Local hypochlorite generation • Local Marketing of stabilized product • Safe storage • Low cost product	• Sodium **dic**hloroiso**c**yanurate (NaDCC) • shelf life 5 years	• In-situ chlorine production using electrolysis to produce 6 g/L chlorine solution from saturated brine (NaCl-Soluation) • Application in schools, health centers

Selection criteria for treatment methods

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- There is no "best" water treatment system. The choice depends on local criteria, such as water quality at the source, cultural preferences or financial possibilities.

- Important selection criteria for products are:
  - Effectiveness
  - Durability (including no need for frequent replacement of parts)
  - Attractive design
  - Easy operation & maintenance
  - Affordability & cultural acceptability

- To entirely remove microbiological and chemical contamination as well as turbidity, a combination of different systems might be necessary.

Water Treatment Technologies

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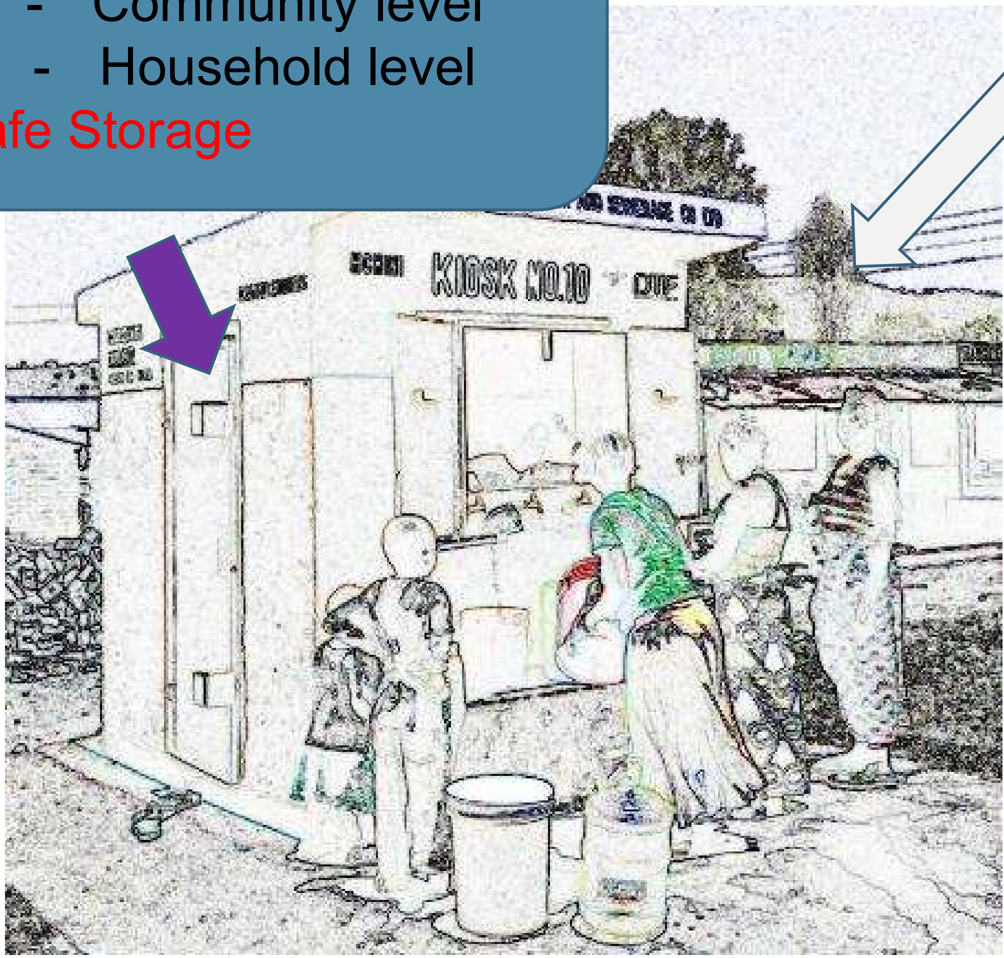
Technology
Drinking water treatment
- Community level
- Household level

Safe Storage

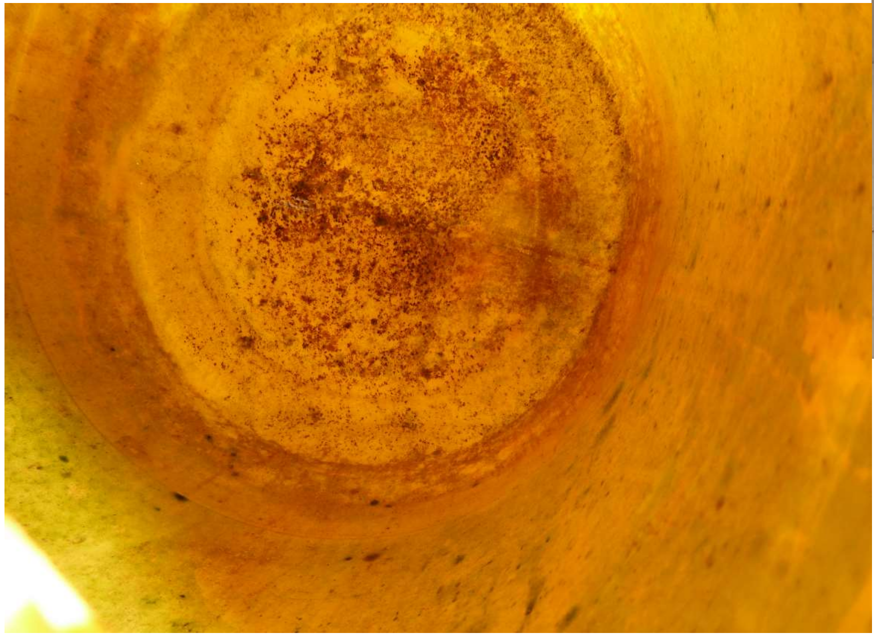


Finances
- Business management
- Demand
- Price of water
- Price of HWTS products
- Supply chains

Behaviour
- Demand
- Know-how & capacity
- Consistent consumption

Safe water at source ≠ safe at consumption

- Unreliable operation and supply (water supply networks)
- Leaky water distribution networks
- High risk of contamination during transport and handling



Disinfection and cleaning of storage containers

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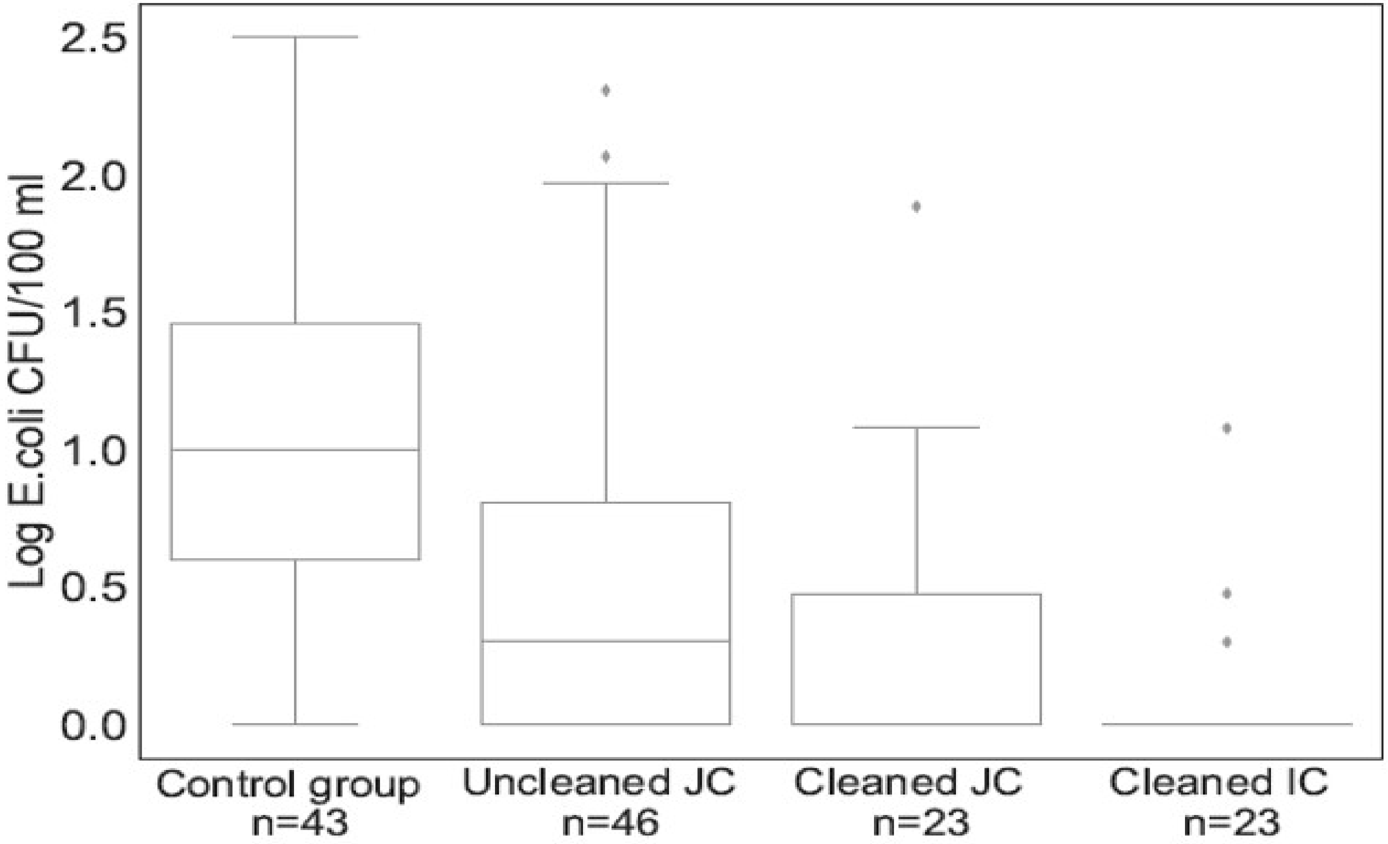

Control
- No chlorination at the kiosk
- No cleaning of jerrycan
- Normal jerrycans

Strategy I
Chlorination at the kiosk
No cleaning of jerrycan
Normal jerrycans

Strategy II
- **Chlorination** at the kiosk
- **Cleaning** of jerrycan
- Normal jerrycans (JC)

Strategy III
- **Chlorination** at the kiosk
- **Cleaning** of jerrycan
- Improved jerrycans (IC)

Likelihood of contamination in the home

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Observedwater management practice

Water Collection
- Well with hand pump
- Container rinsed with water, wiped with hand

Return Journey Home
- Collection container carried on head
- Most containers without lids

Transfer to Storage Container
- Water poured through a 'filter cloth' into storage container

Storage and Use
- Drawn using a beaker, ladle, or gourd
- Storage container kept covered

(Trevett, 2005)

Potential detoriation factors
- Dirty hands
- Dirty collection containers
- Dirty filtration cloths
- Dirty storage contaniers
- Insects
- Regrowth of pathogens

Safe water storage

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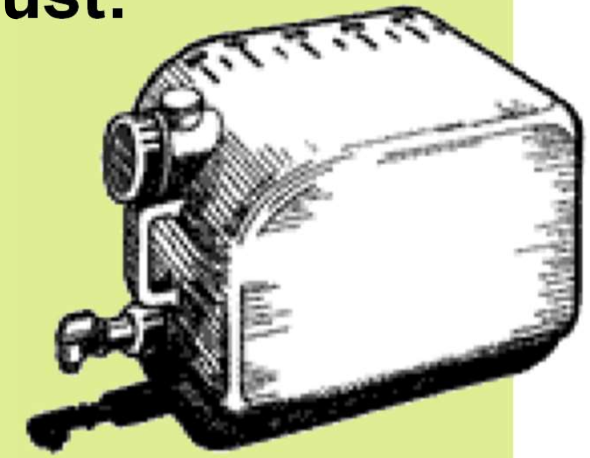
A properly designed safe storage system must:



be affordable, portable, durable, and easy to use

have a tap to withdraw water in a sanitary manner
(reduce contamination by hands or dipping utensils)

Have a coverable (screw-cap) opening for filling
and cleaning

be also suitable for water collection and transport

Chlorine for residual disinfection!

Elements of sustainable safe water consumption

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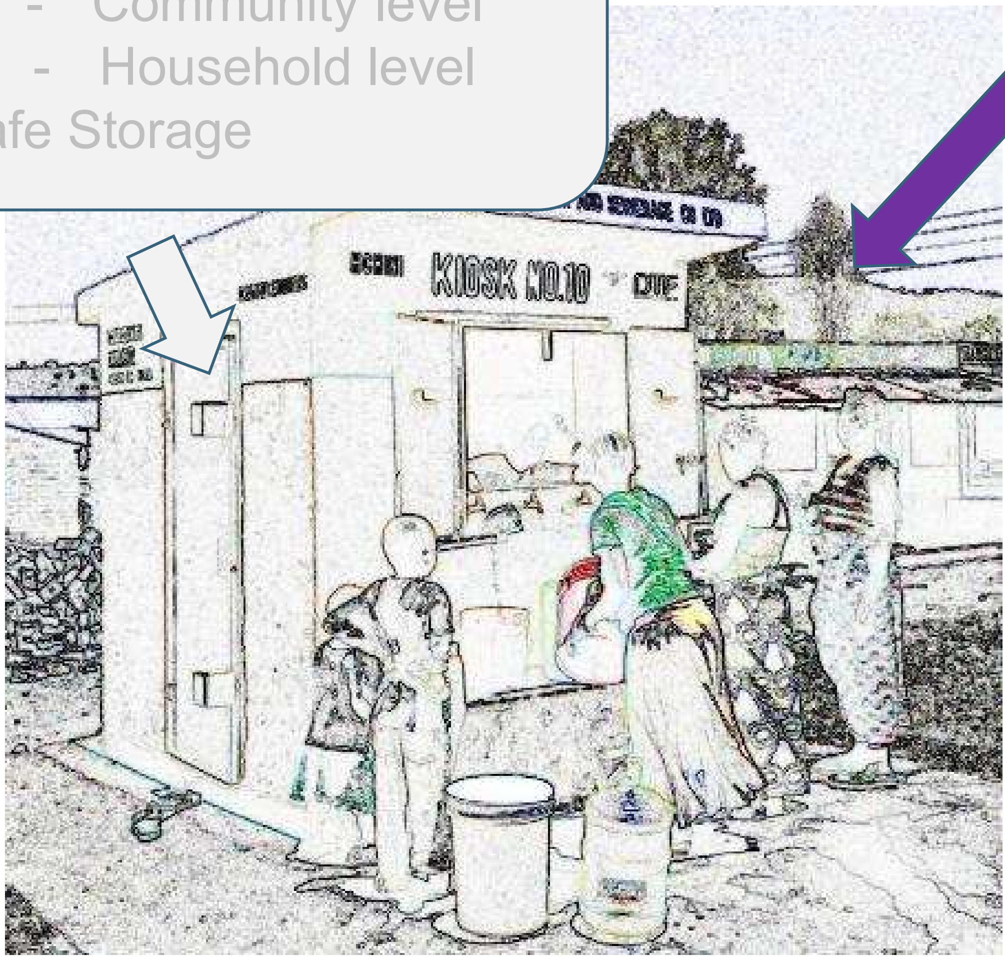
Technology
Drinking water treatment
- Community level
- Household level

Safe Storage

Finances
- Business management
- Demand
- Price of water
- Price of HWTS products
- Supply chains



Behaviour
- Demand
- Know-how & capacity
- Consistent consumption

Business Management of Water Kiosks

Financing of investment cost

Financing of O&M

Ownership Model

Capacity

-Technical
-Business Mgmt

Create income:
- Demand!

Acceptable price of water?

Additional revenue?

Business model approaches of Water Kiosks

Ownership model	Key activities; Value proposition	Customer relation and marketing	Nr of Customer s
• Public private partnership • Community managed system • Private Enterprise	• Sale of safe water • Sale of additional products (health products, electricity) • Transport of water	• Community training (often neglected) • Behaviour change campaign • Branding	Influenced by: • Population density • Other water sources • Attitude, Norms, Risk Awareness • (Promotion)

Key resources	Cost structure	Revenue structure	
• Technology • Management • O&M Capability	• Capex • Opex (salaries, maintenace, electricity etc.)	• Product sale • Donor support (Capex!) • Government support • Community support	

The world economic pyramid

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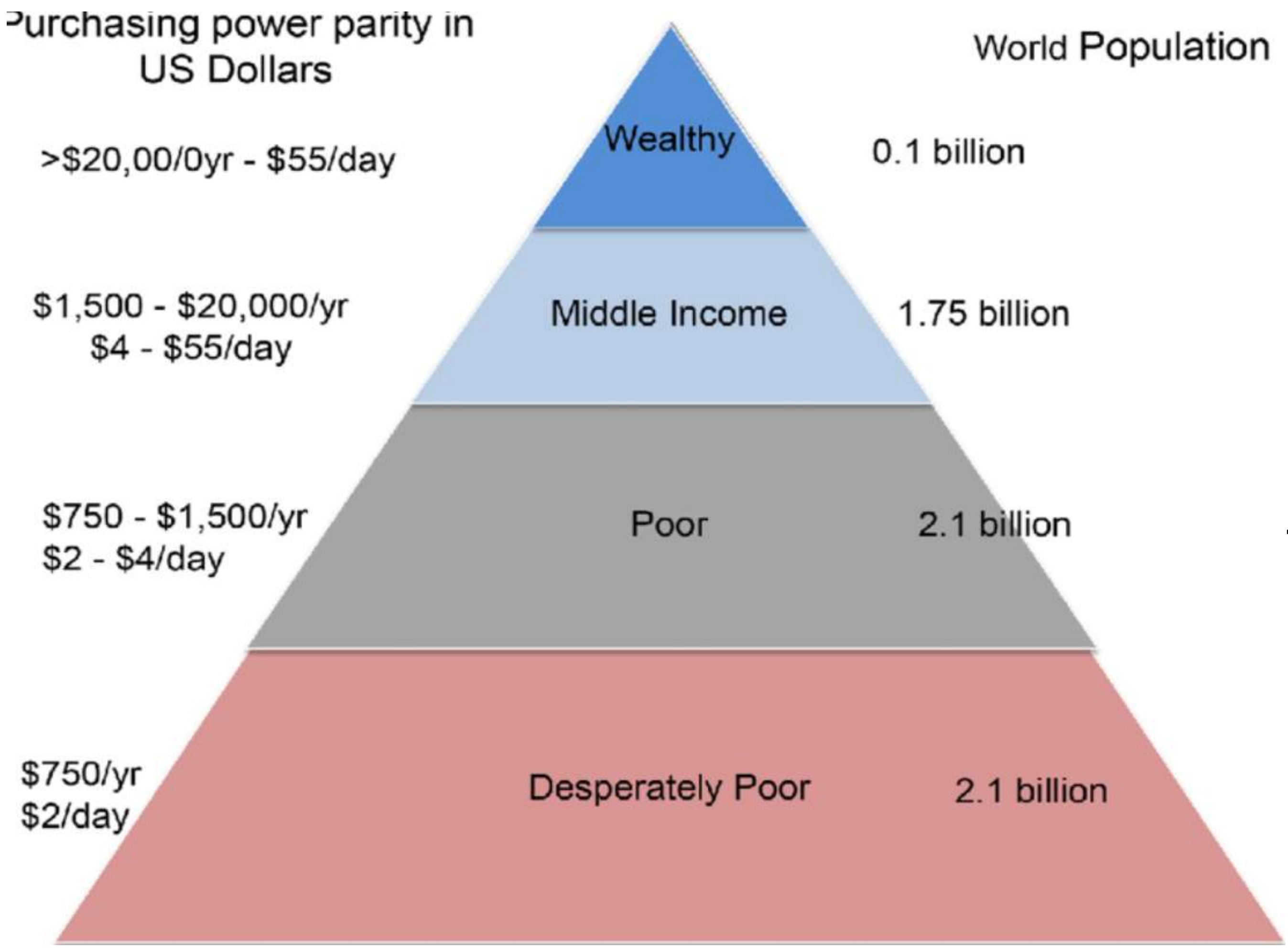

4 billion people at the bottom of the pyramid. Income less than 1500 USD/year

1 billion people — roughly one-sixth of humanity — per capita income is less than $1 per day

Prahalad (2009)

Influence of price on take up

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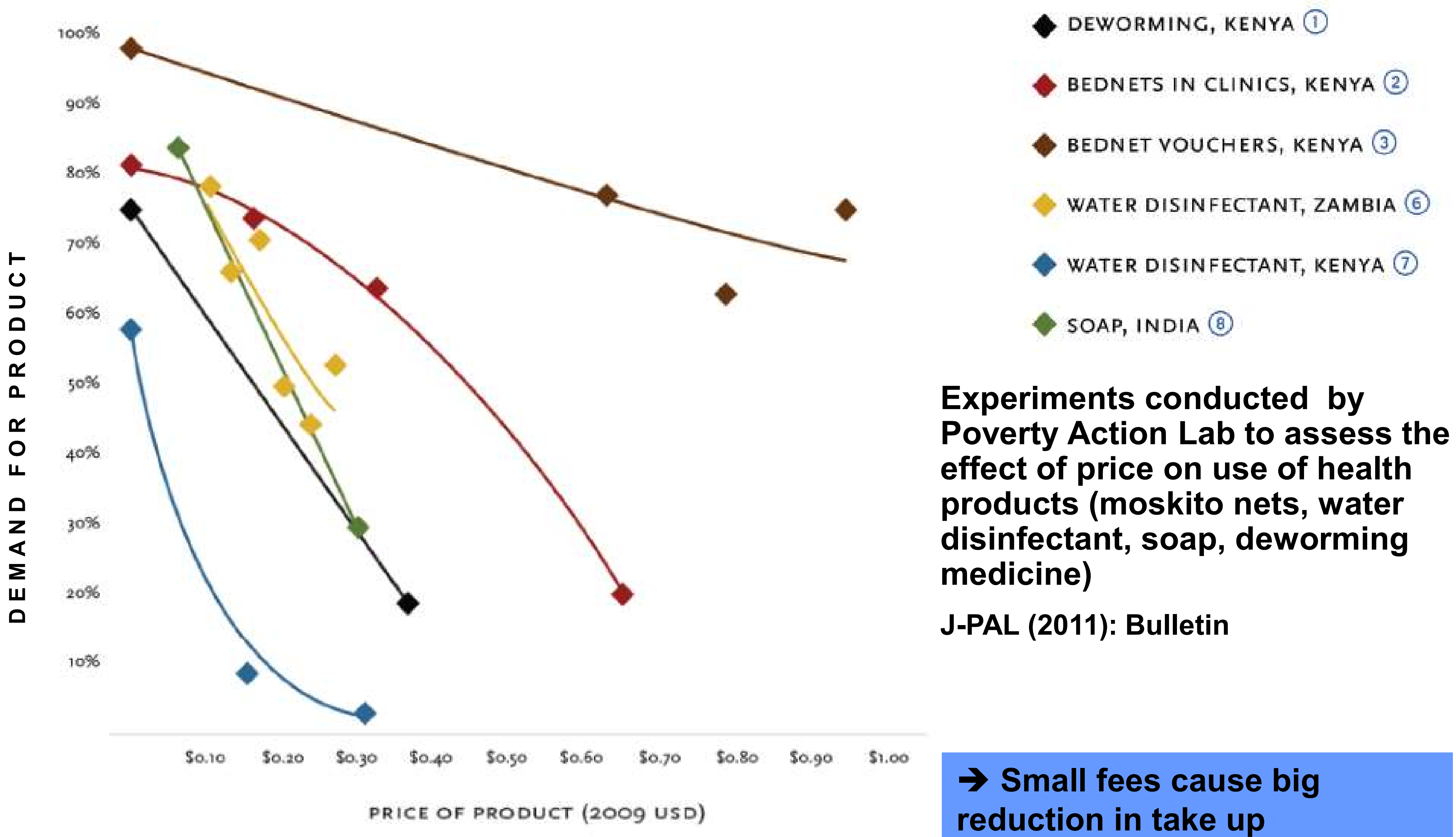

Experiments conducted by Poverty Action Lab to assess the effect of price on use of health products (moskito nets, water disinfectant, soap, deworming medicine)

J-PAL (2011): Bulletin

➔ Small fees cause big reduction in take up

Consumer financing: Affordability

"Sanitation and water facilities and services **must be available for use at a price that is affordable to all people**. The provision of services includes construction, maintenance of facilities, treatment of water and disposal of faecal matter. Paying for these services **must not limit people's capacity to acquire other basic goods** and services guaranteed by human rights, such as food, housing, health services and education."

Independent human rights expert

What means affordable?

Optimal affordability: overall water cost less than 3% of the household budget

Intermediate affordability: overall water cost less than 5% of the household budget

Minimal affordability: overall water cost less than 7% of the household budget

Payment schemes

- Direct purchase (particularly of fast moving goods such as chlorine)
- Payment in installments
- Payment through credits (microcredits)
- Partial of full subsidy

Promoting household water treatment

- Safe water has low priority
- Low willingness to pay for products $\rightarrow$ low-cost products $\rightarrow$ difficulty to establish viable businesses
- Lacking supply chains and difficult access to products and replacement parts
- Need to create demand and establish consistent water treatment
- Behavior change is a long term process - much effort required to establish new habits

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Effective & Consistent use

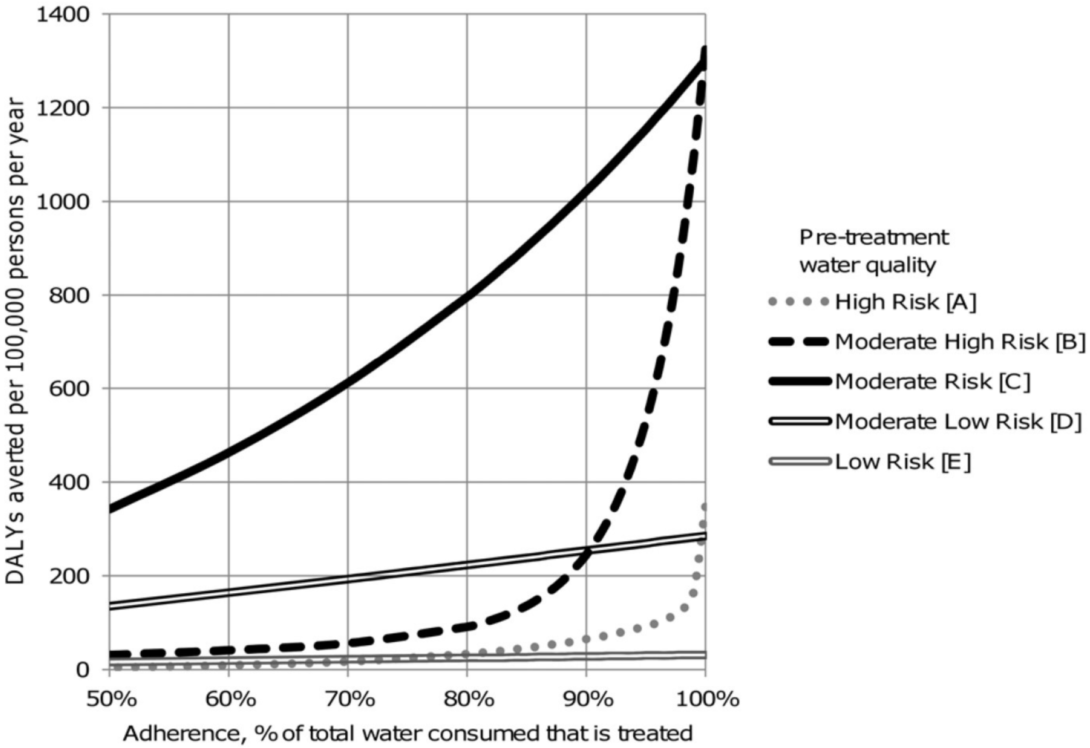
What is required to realize health improvements?

An effective option for water treatment

Efficacy: how well a method works under controlled conditions

Effectiveness: how well it works in the real world

Consistent use of the method/ consumption of clean water



DALYs averted per 100'000 persons per year, assuming:

- 2 log reduction in each pathogen class,
- Different raw water qualities
- Different levels of consistent consumption

Source: Brown J., Clasen T.,2012: High Adherence Is Necessary to Realize Health Gains from Water Quality Interventions, PLoS One

Can I do it?
What will others say?
How to manage it?
Do I like it?
What does it cost/ bring?
Am I at risk? Why?
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Psychological factors for behavior

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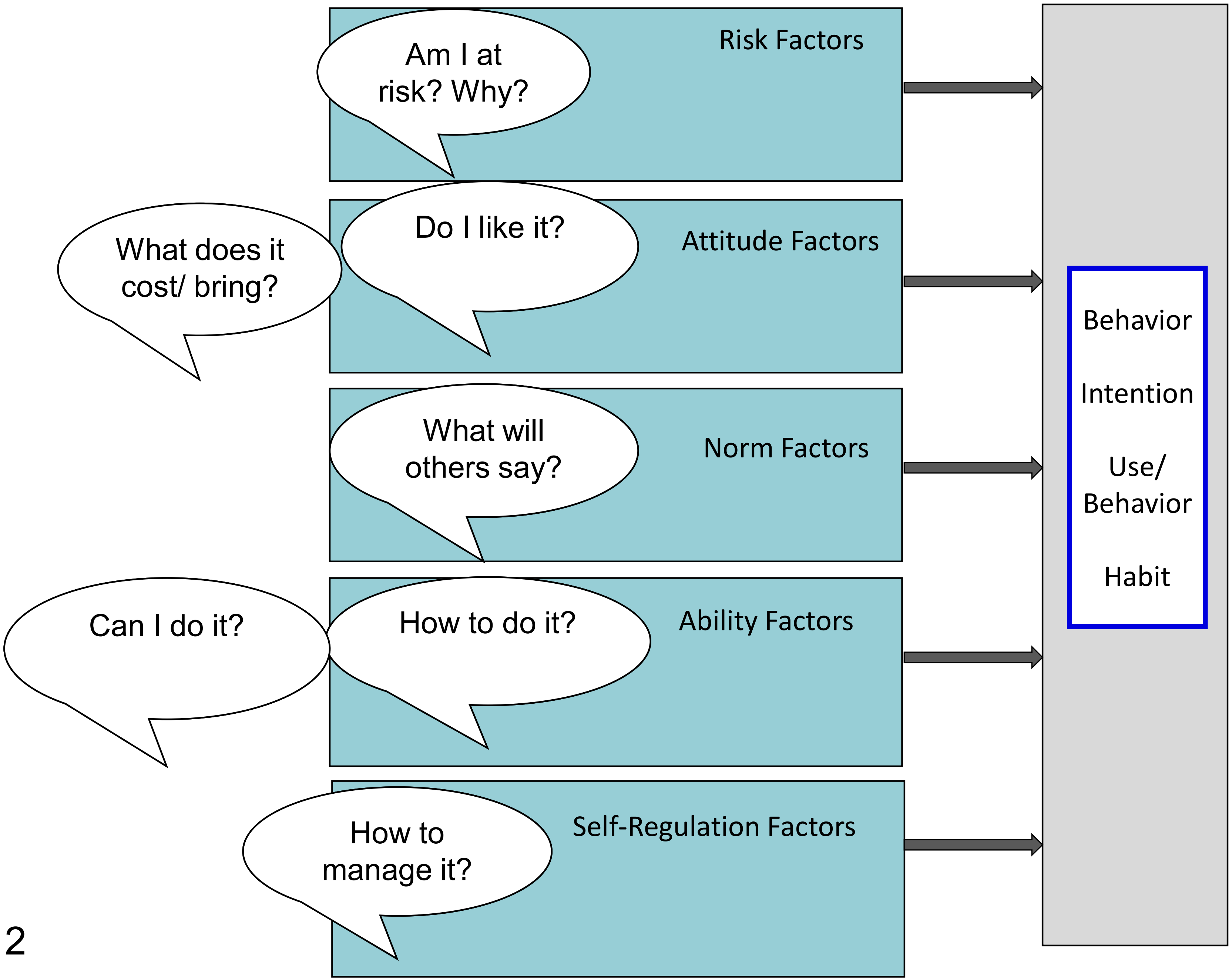
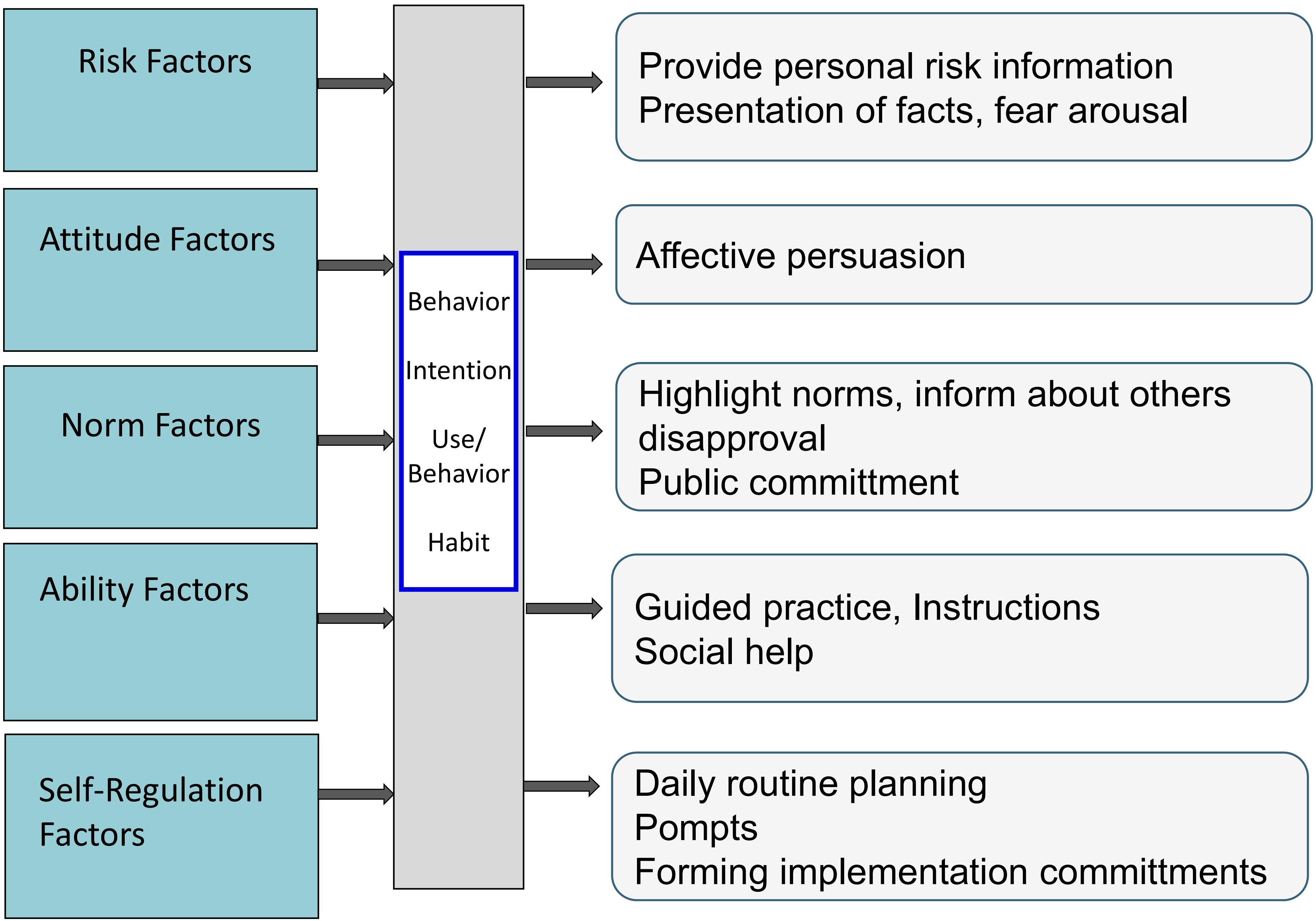


Mosler, 2012

Behaviour change



Influence factors… on behavior

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situation	campaigns	beliefs
external; unchangeable	**external; changeable**	**internal; changeable**
Individual: age, gender, education, economic status Community: water source, urbanization,	Communication channels • Mass Media (many people reached) • Interpersonal channels - household visits - trainings (less people more effective) Implementing organization Campaign content	Risk beliefs Attitudinal beliefs Normative beliefs Ability/ control beliefs Self-Regulation

Summary

- Access to safe drinking water is a UN-recognized human right
- Safe drinking water must be available, accessible, of safe quality, acceptable and affordable
- To ensure sustainable access to safe drinking water, there are 3 aspects we work on : technology, business, behavior.
- Several water treatment technology exist with each pros and cons. They must be careful chosen to be context-specific and best address the issues of the situation
- Carefully determined business models are essential to ensure the sustainability of a solution. Challenges include low willingness to pay, creating demand and creating ownership.
- Behavior change is often necessary and challenging to achieve. Campaigns can act on a number of different factors to effectively enable change.