An Elegant Solution for Safe Water on Tap

Cornell University

AguaClara

Monroe Weber-Shirk

AguaClara

For More Information

- AguaClara Website
- Research Wiki: Current Research
- AguaClara Design Tool: CAD Drawings
- Photos of AguaClara projects
- Course notes on Sustainable Municipal Drinking Water Treatment: Theory!
- AguaClara LLC: Social Enterprise
- Monroe Weber-Shirk: email

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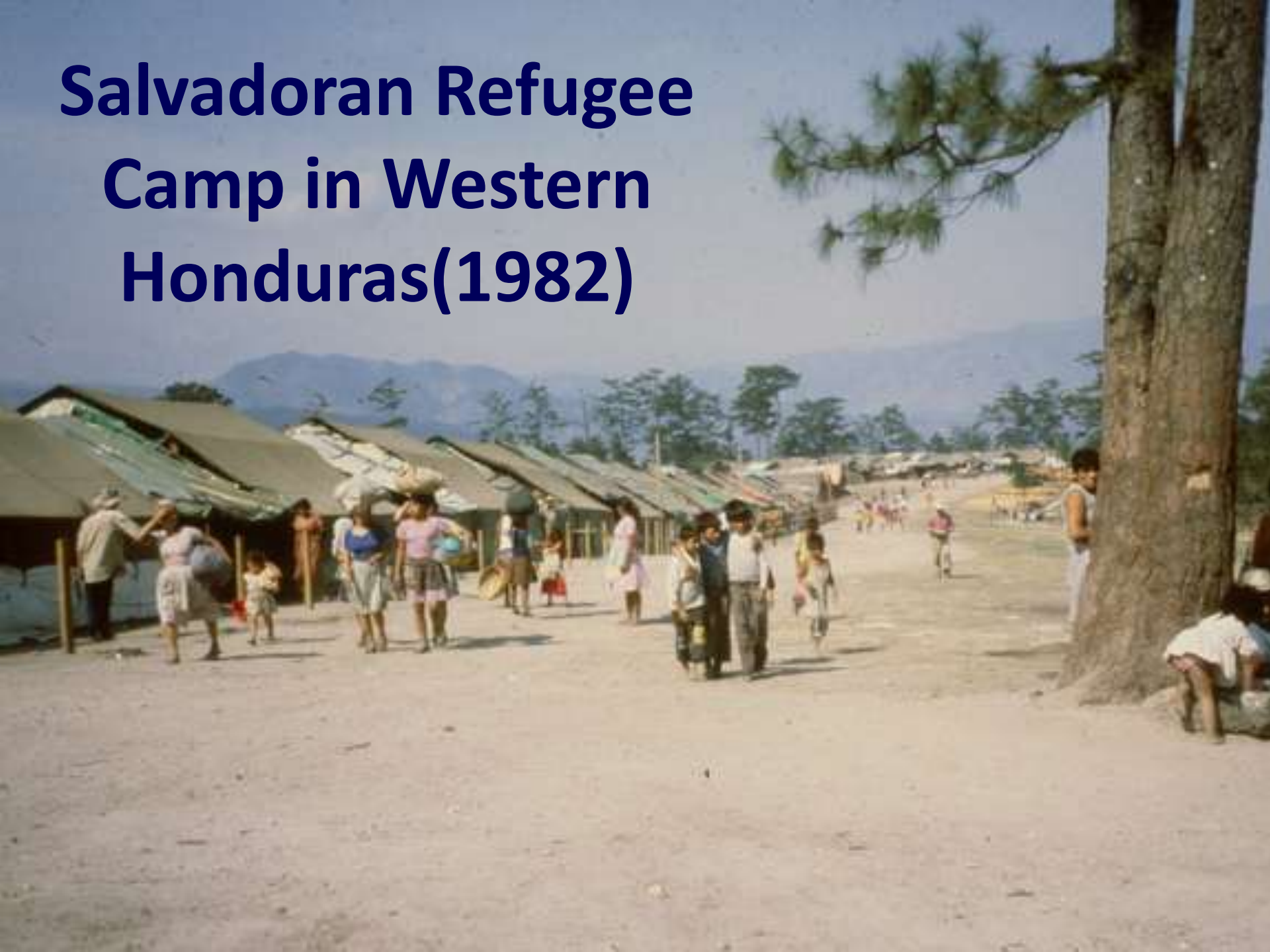
Objectives

- Reflect on technology options and the criteria we use to select technologies especially for small water systems
- Reflect on the relationship between technology choices and failure rates
- Explore additional design objectives including simplicity, elegance, sustainability, energy efficiency, operator centered
- Learn how smart hydraulics can replace electronics to create resilient water treatment processes
- Reflect on the potential nexus between AguaClara and AMEC

Salvadoran Refugee Camp in Western Honduras(1982)



Salvadoran Refugees Waiting for water (1982)

What is AguaClara?

- AguaClara Cornell: A team of 60 students at Cornell University that researches, invents, and designs municipal water treatment technologies
- AguaClara LLC: A social enterprise that designs and deploys sustainable drinking water treatment technologies
- Water treatment technologies that are resilient, high performing, low cost, simple to operate, zero electricity, zero patents

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Research, Invent, Design, Empower

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AguaClara Design Tool

AguaClara

Open Source!

Design Methods

Select Language

http://designserver.cee.cornell.edu/designs/

AguaClara Plant

The EtFlocSedFi Method creates a AguaClara water treatment plant based on the user input of a desired plant flow rate (Only use for flow rates between 6L/s and 70L/s).

Request an AguaClara Plant design

Flocculator

The Flocculator Method creates a flocculator based on the user inputs of a flow rate, height and length.

Request a Flocculator design

Sedimentation Tank

The SedimentationTank method creates a sedimentation tank(s) based on a desired flow rate.

Request a Sedimentation Tank design

Stacked Rapid Sand Filter

The SRSF method creates a stacked rapid sand filter based on a desired plant flow rate.

Request a Stacked Rapid Sand Filter design

Linear Flow Orifice Meter

The LFOM method creates a linear flow orifice meter based on the target range of head and flow rate.

Request a Linear Flow Orifice Meter design

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Innovation Circle

New Theories

Research Laboratory

$$pC^* = \frac{9}{8}\log(e)\cdot W\left(\frac{8}{9}\Gamma\phi_0^{\frac{8}{9}}\frac{t\varepsilon^{\frac{1}{3}}}{d_{Colloid}^{\frac{2}{3}}}\frac{\eta_{Coag}}{V_{Capture}}\right)$$

Design Studio

Journey Inward

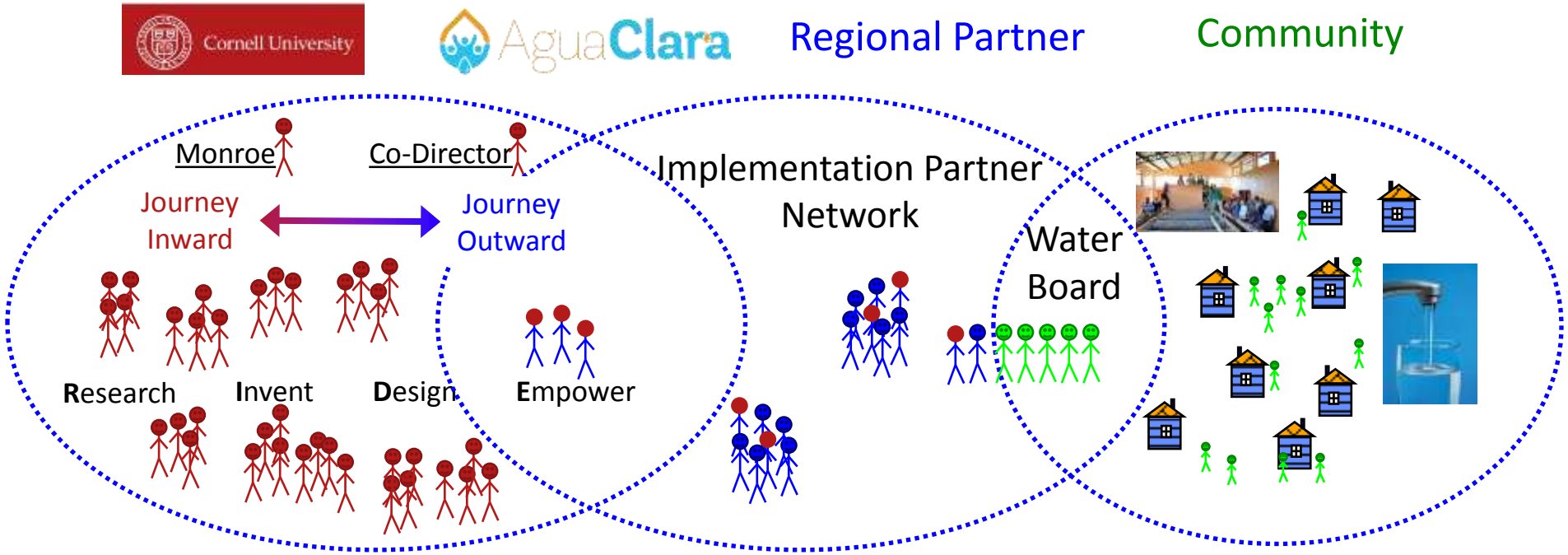
Journey Outward

Safe water on tap

Sustainable Infrastructure

Innovation: From Cornell

Labs to Safe Water on Tap



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What is the conventional high tech solution?

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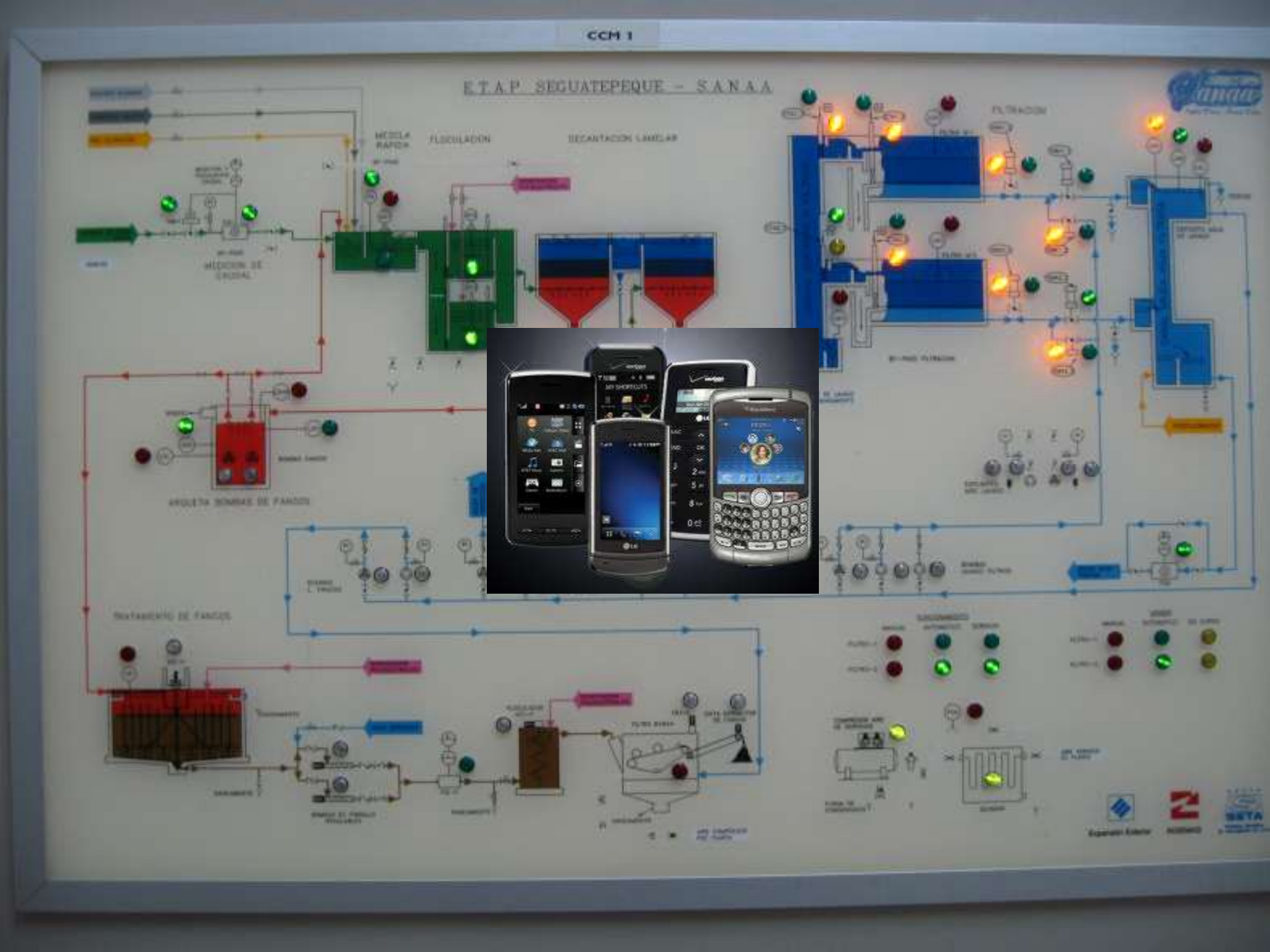
- Technologies from the early 1900's: Flocculation – sedimentation – filtration – disinfection
- "Advances" over the last 50 years have focused on automation and increased use of electricity

➢ Increased cost, reduced reliability, more difficult to maintain, reduced useful life (cell phone life)

➢ 50% of the high tech plants that were installed in Honduras since 2003 have been abandoned


CCM 1
ETAP SEGUATEPEQUE - SANAA
MEZCLA RAPIDA
FLOCULACION
SEDIMENTACION LAMELAR
FILTRACION
MEDICION DE CAUDAL
ARQUETA BOMBAS DE FANGOS
TRATAMIENTO DE FANGOS

What happens when high tech water meets small town?

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- Software expires and no one is able or willing to pay for the upgrade
- Electronics fail
- Everything that moves fails!
  - Valves, pumps, compressors
- Electricity bill is too high
- Entire treatment plant is abandoned
- 3 year average life for package plants installed in Africa – World Bank Engineer

Simple, Elegant, or Complicated?

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"For the simplicity on this side of complexity, I wouldn't give you a fig. But for the simplicity on the other side of complexity, for that I would give you anything I have."

— Oliver Wendell Holmes Sr.

Simple, Elegant, or Complicated?

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- ***"Any intelligent fool can make things bigger, more complex, and more violent. It takes a touch of genius — and a lot of courage – to move in the opposite direction."***

  --- E.F. Schumacher

- ***"Simplicity is the ultimate sophistication."***

  --- Leonardo da Vinci

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Elegant Solution

- Solves the problem very well
- No unnecessary complexity
- Easy to understand
- Simple and beautiful
  - Bicycle
  - Windmills

- Context matters in defining elegant!

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Pride of Ownership

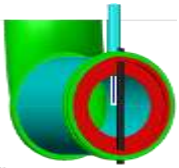
- What happens when the check engine light goes on in your car?
- What do you do if your bicycle brakes need to be adjusted?
- What does the plant operator do if the chemical feed stops working?

We want the plant operator to diagnose and fix the problem without needing to call anyone.

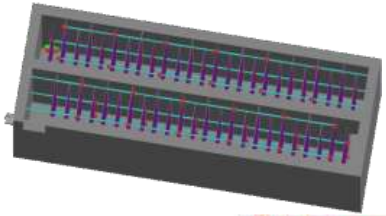
AguaClara Technologies

- Chemical dosing

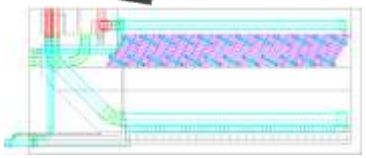
- Rapid Mix



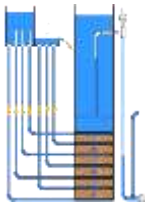
- Flocculator



- Sedimentation



- Filtration



- Conclusions

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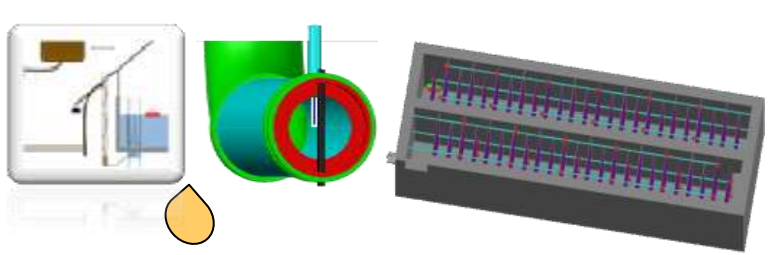
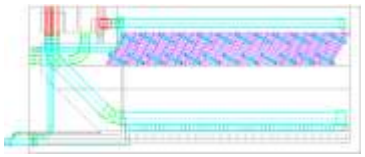
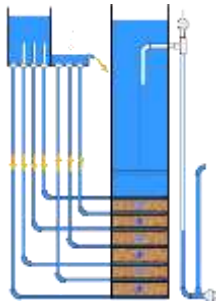
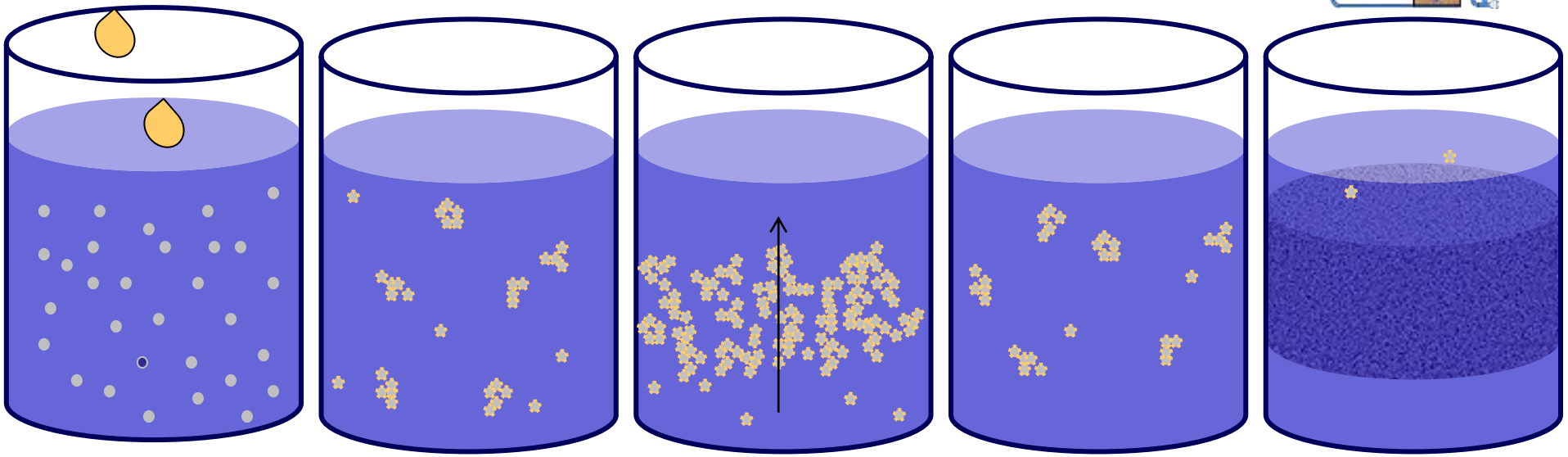
Stages of colloid removal

Coagulation	Flocculation	Floc Blanket	Sedimentation	Filtration









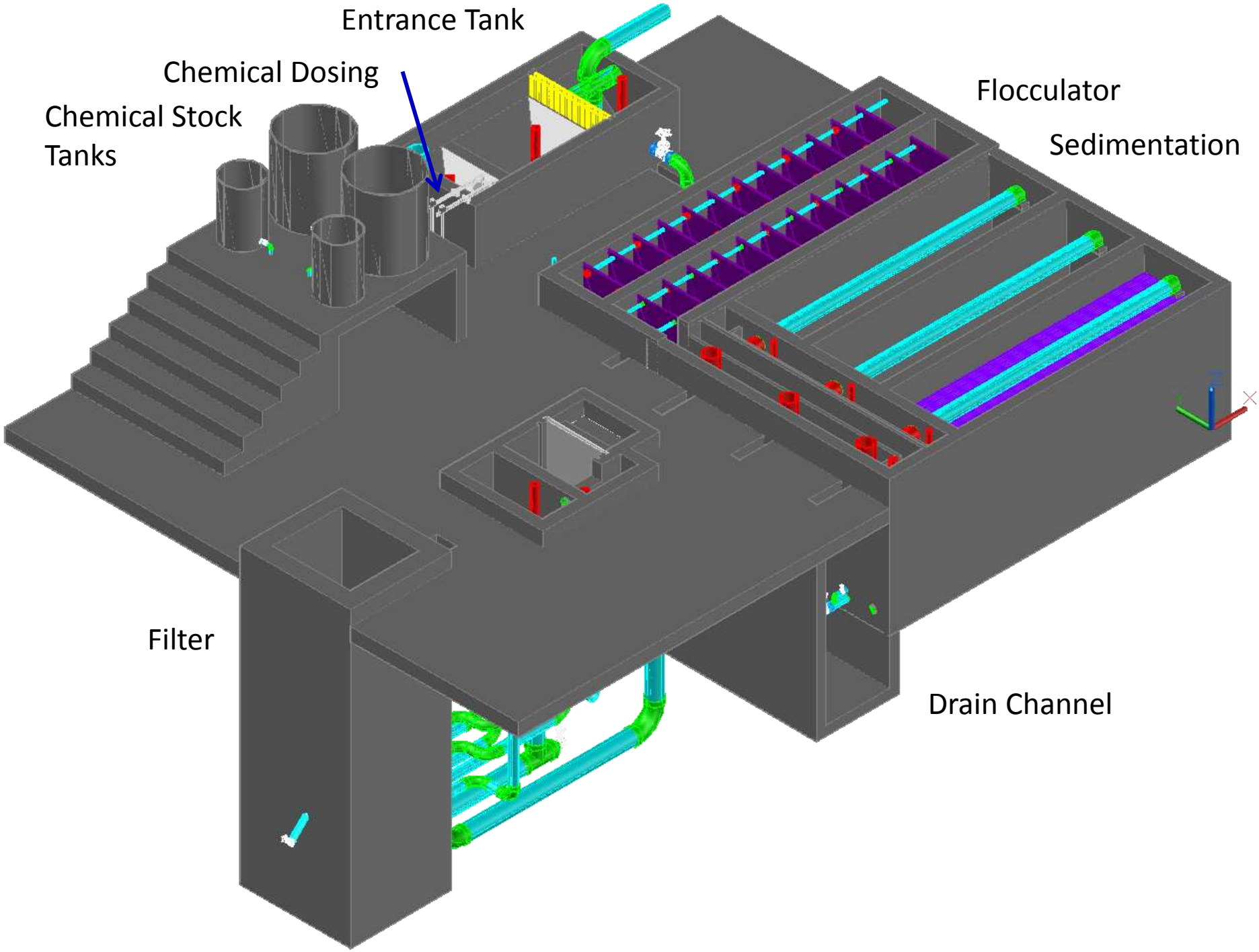
Nanoglob deposition

Collisions

More Collisions

Gravity!

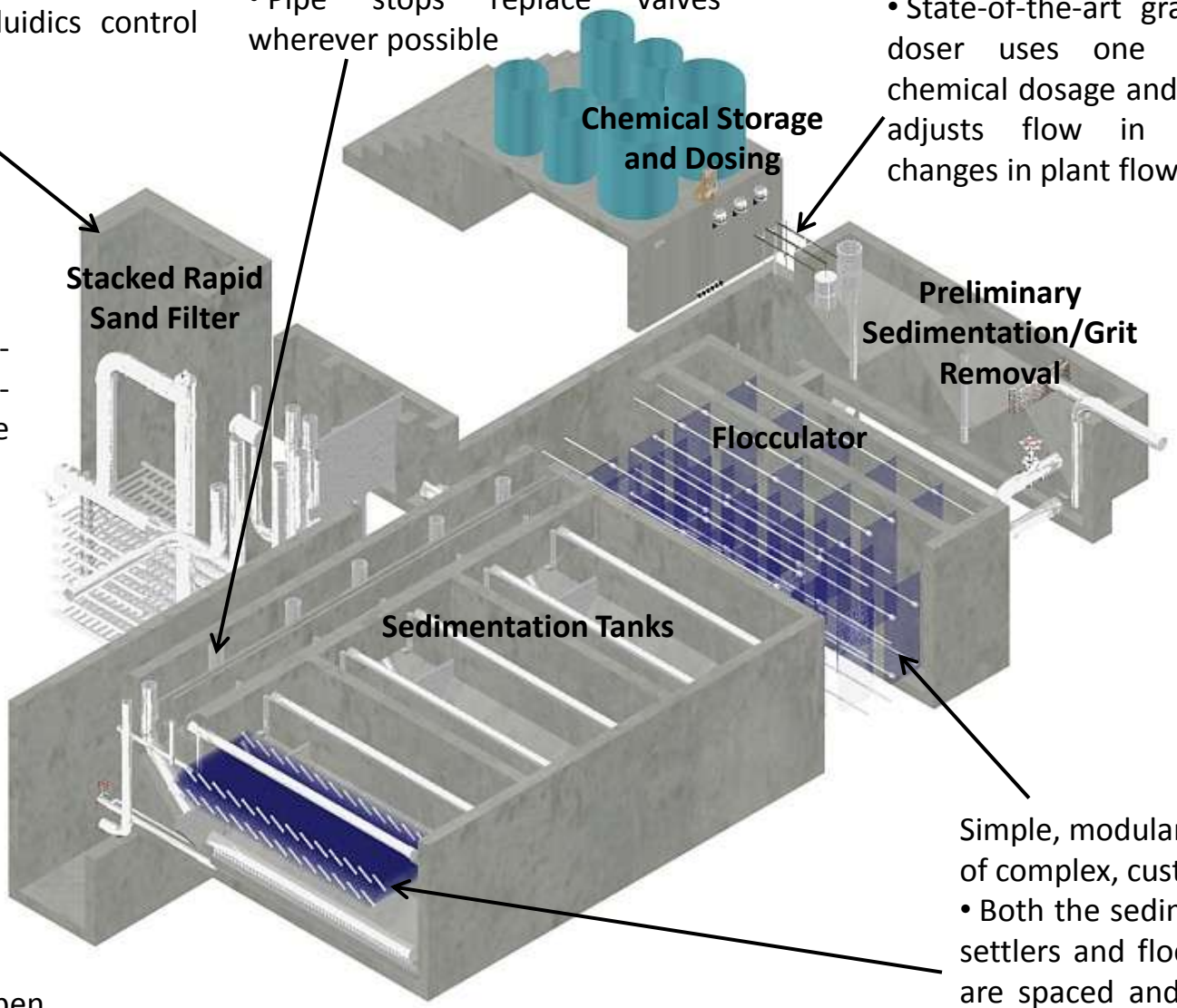
Last chance!


Entrance Tank
Chemical Dosing
Chemical Stock Tanks
Flocculator
Sedimentation
Filter
Drain Channel

AguaClara stacked rapid sand filter uses six times less area than conventional rapid sand filters and uses a single valve fluidics control system

Reduce the use of expensive parts
• Pipe stops replace valves wherever possible

Eliminate complicated control panels, chemical pumps, computers, or other electronics
• State-of-the-art gravity chemical doser uses one step to set chemical dosage and automatically adjusts flow in response to changes in plant flow rate



Inexpensive, easily-replaceable, locally-available, long-life components
• PVC pipe
• polycarbonate sheets
• manual valves

Simple, modular pieces instead of complex, customized parts
• Both the sedimentation plate settlers and flocculator baffles are spaced and held together using PVC pipe and caps. They can be removed easily for tank inspection.

All reactors are open, observable, drainable, and easy to clean

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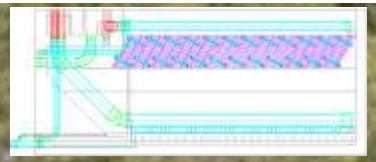
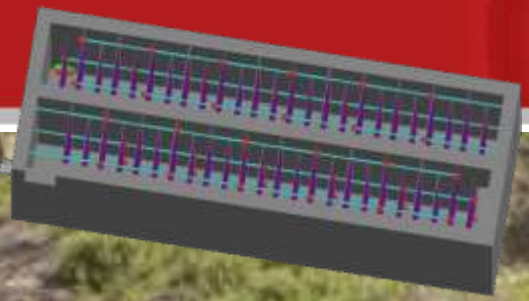
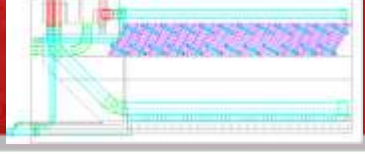
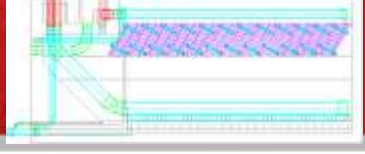
Flocculator Channels










3/4 Hp
Broquero 5/8"

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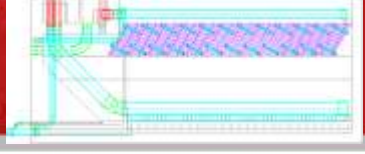

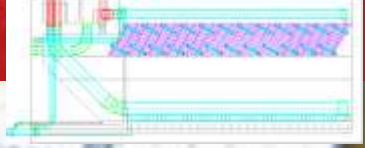

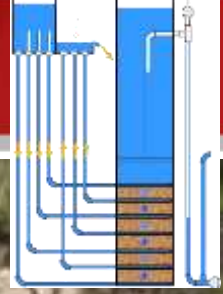

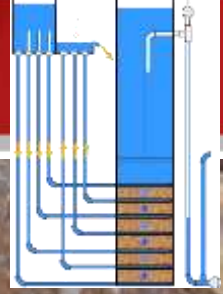

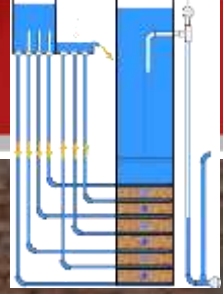

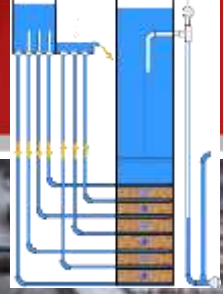

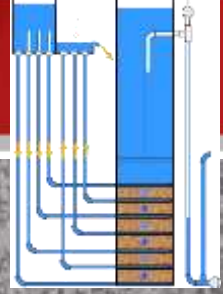

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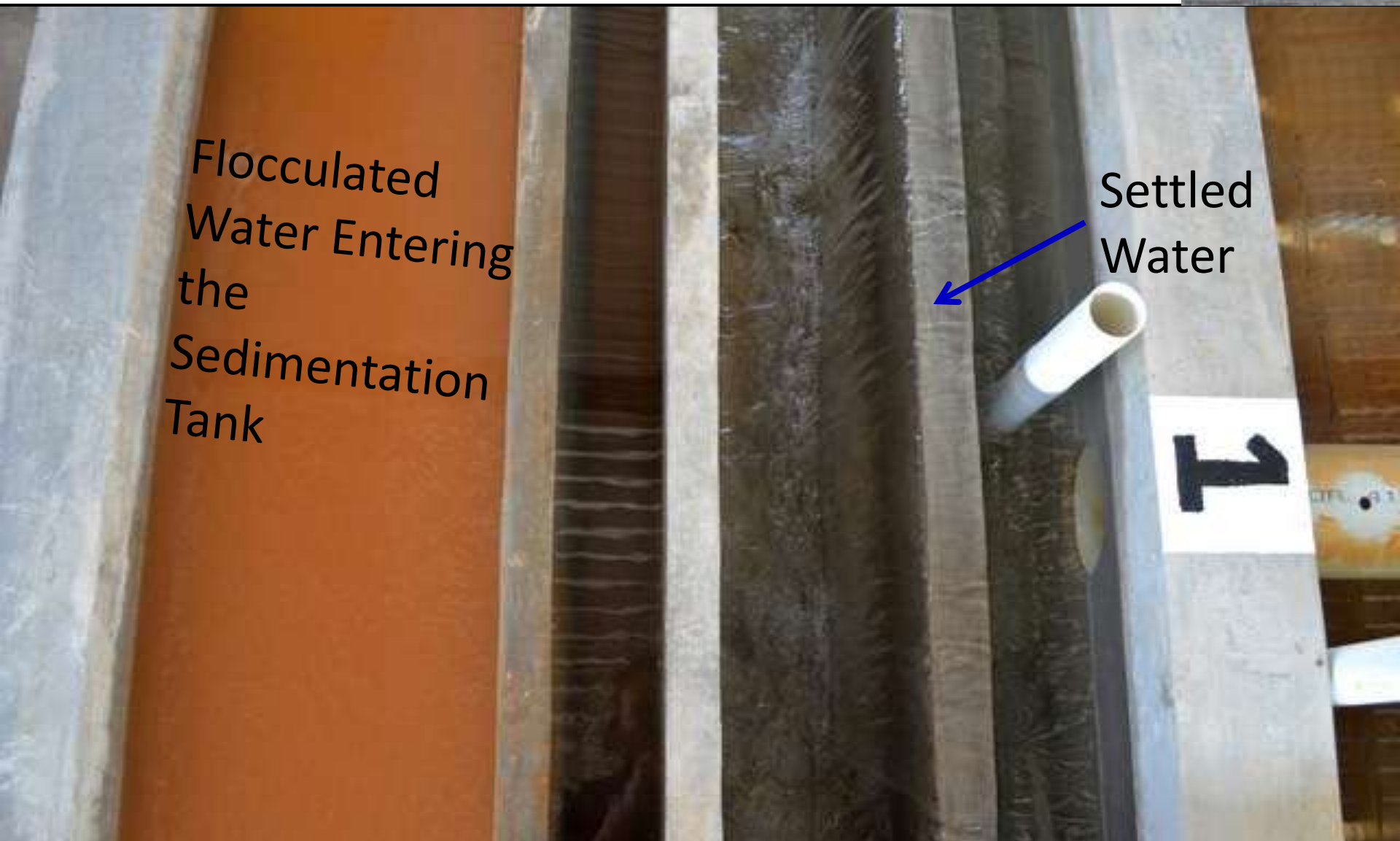
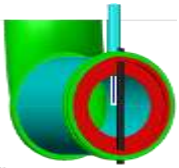


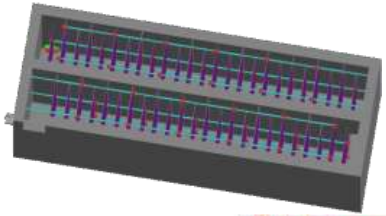
AguaClara Technologies

- Chemical dosing

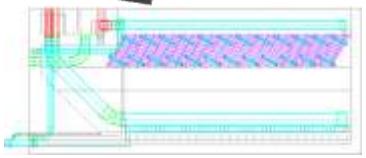
- Rapid Mix



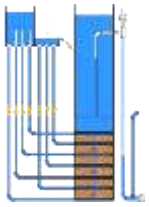
- Flocculator



- Sedimentation



- Filtration



- Conclusions

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Chemical Dosing

- Chemical dosing is the single most important determinant of successful operation
- Many plant operators don't know the concentration of the coagulant that they are using
- Chemical pump controls are complicated

- $Q_{Plant}C_{Plant}=Q_{Stock}C_{Stock}$
- What does the operator have to do to figure out the dose?

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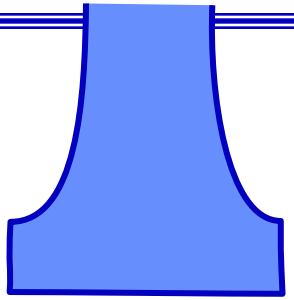
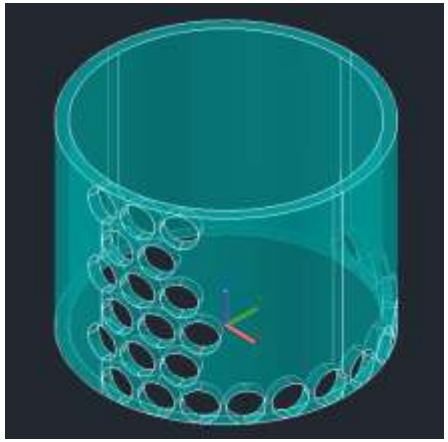
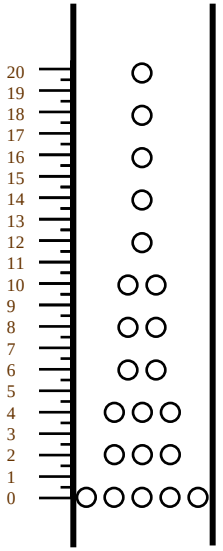
Linear Flow Orifice Meter



- Sutro Weir is difficult to machine
- Mimic the Sutro weir using a pattern of holes that are easily drilled on site
- Install on a section of PVC pipe in the entrance tank





Invented by AguaClara team member David Railsback, 2007

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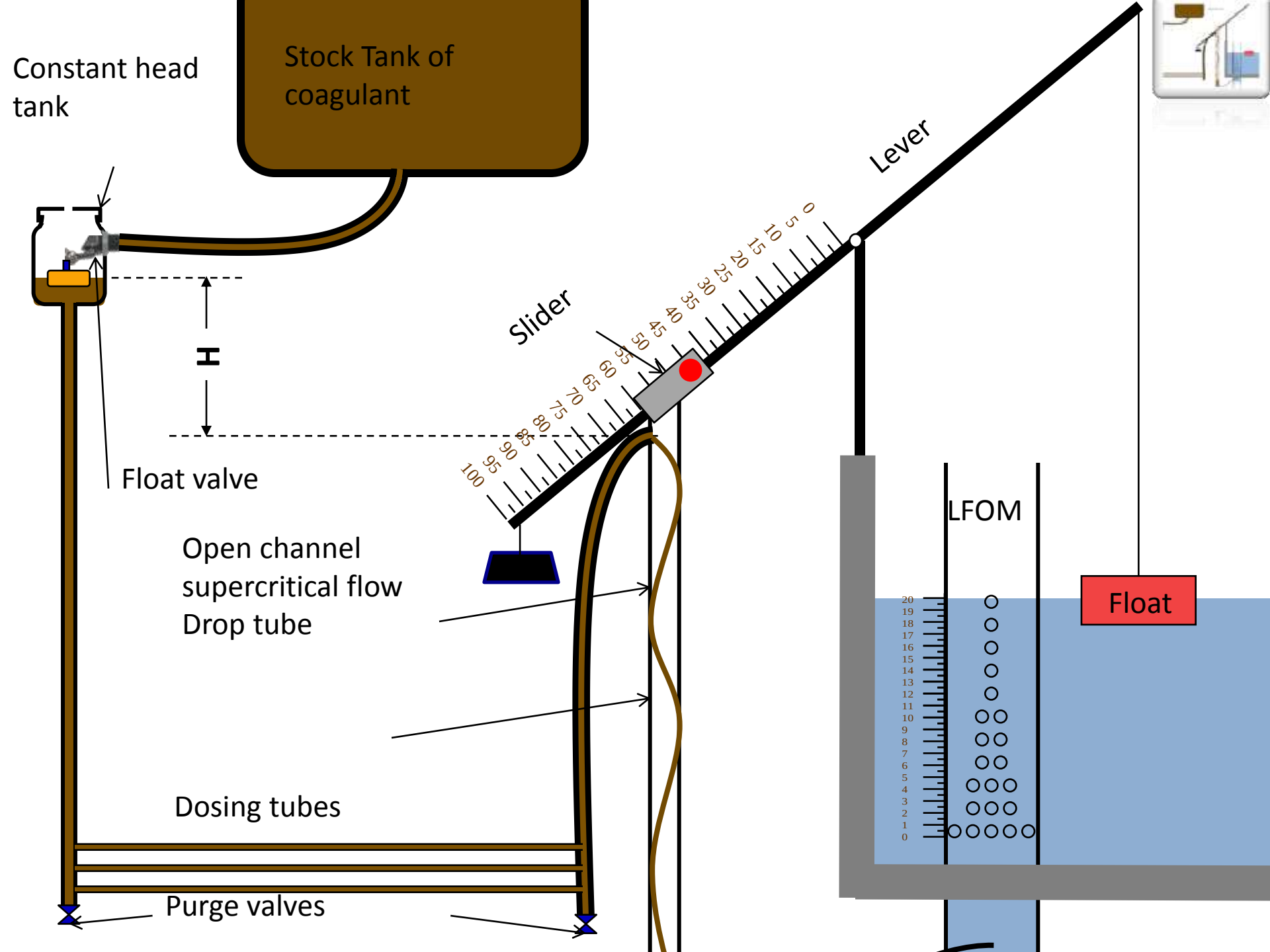
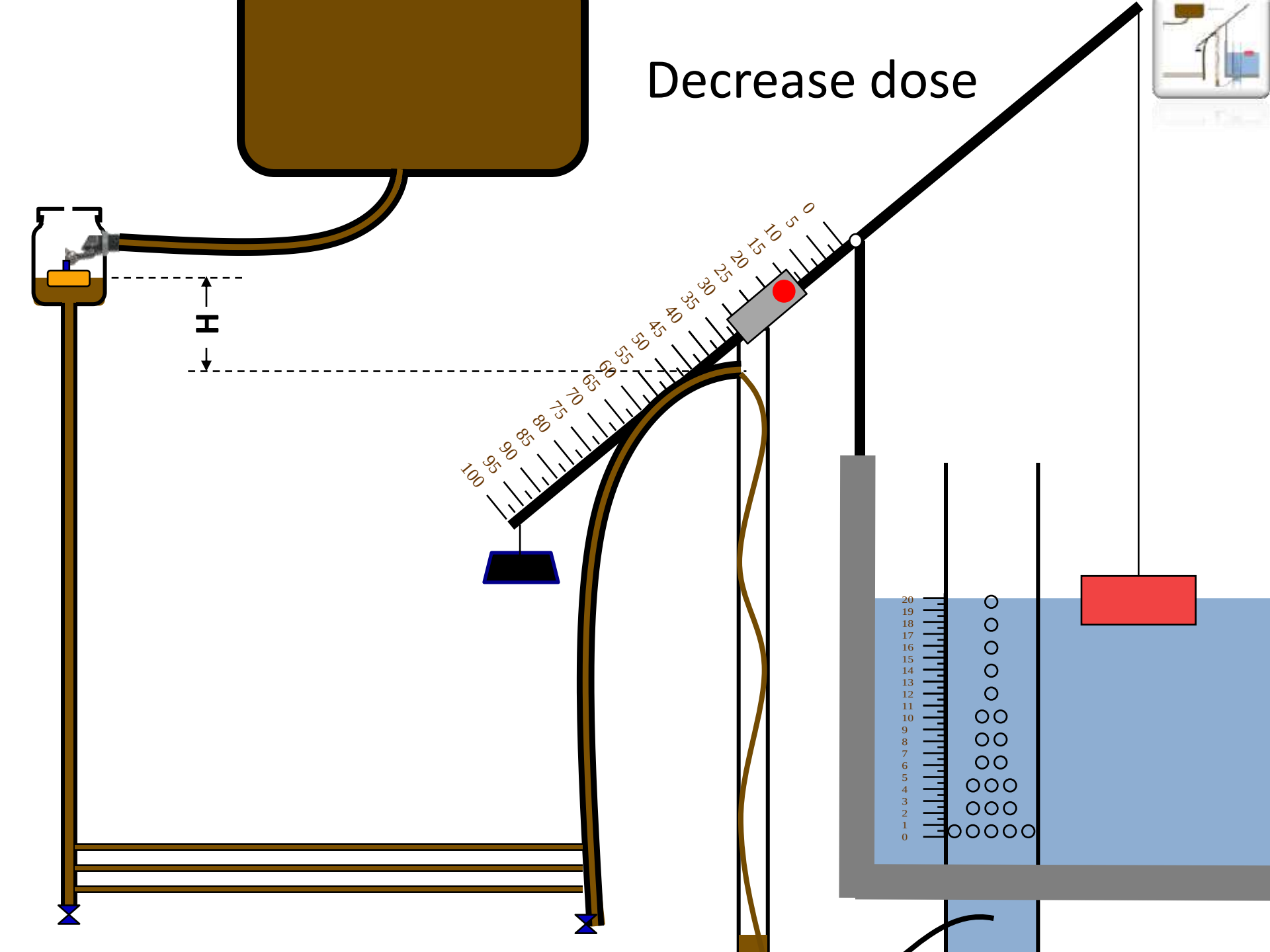
Linear Orifice Meter

Photo by Lindsay France


Constant head tank
Stock Tank of coagulant
H
Float valve
Slider
Lever
Open channel supercritical flow Drop tube
Dosing tubes
Purge valves
LFOM
Float


Decrease dose
H
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
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100
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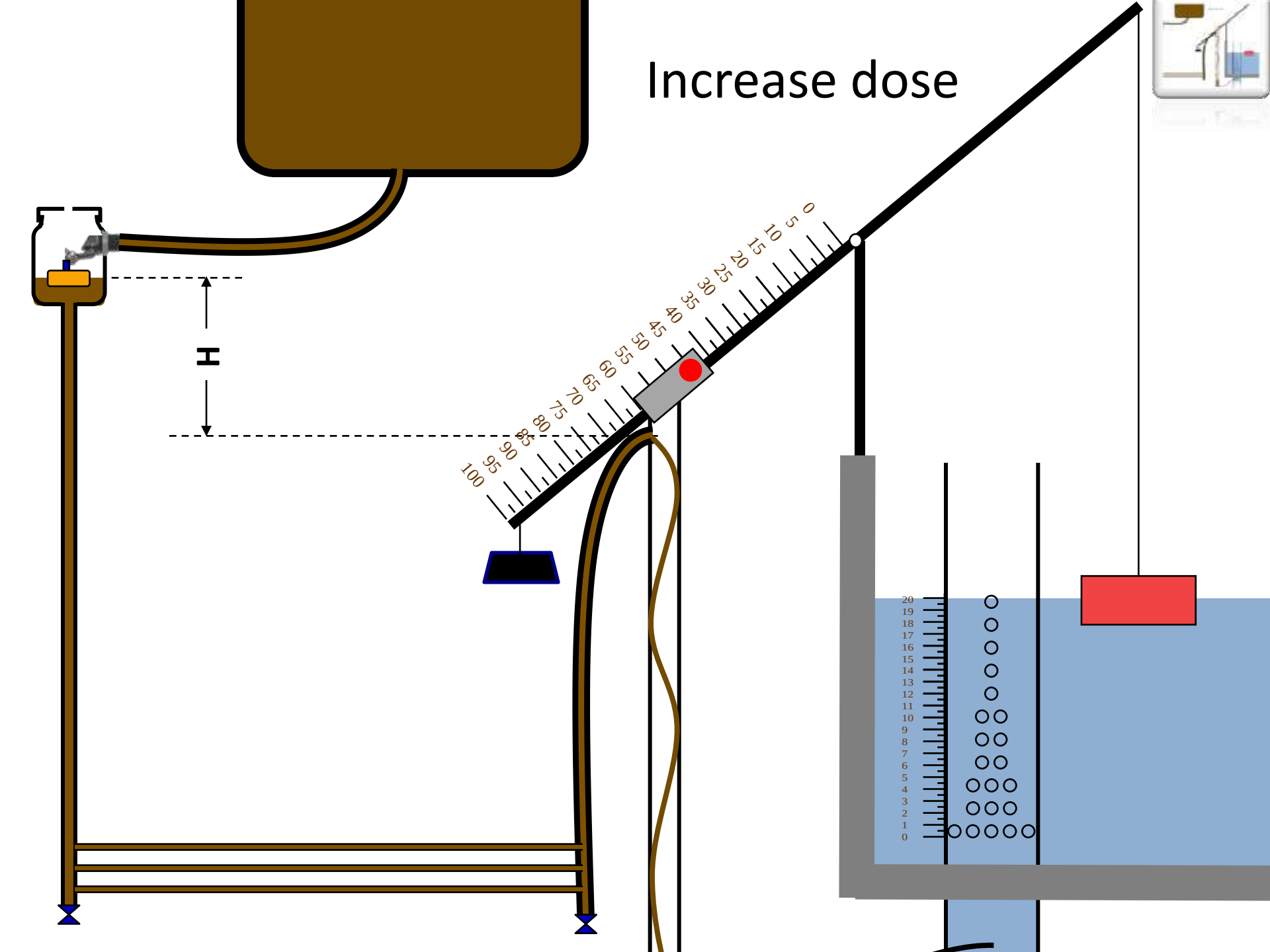
Increase dose
H
0
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20
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30
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40
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50
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60
65
70
75
80
85
90
95
100
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19
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6
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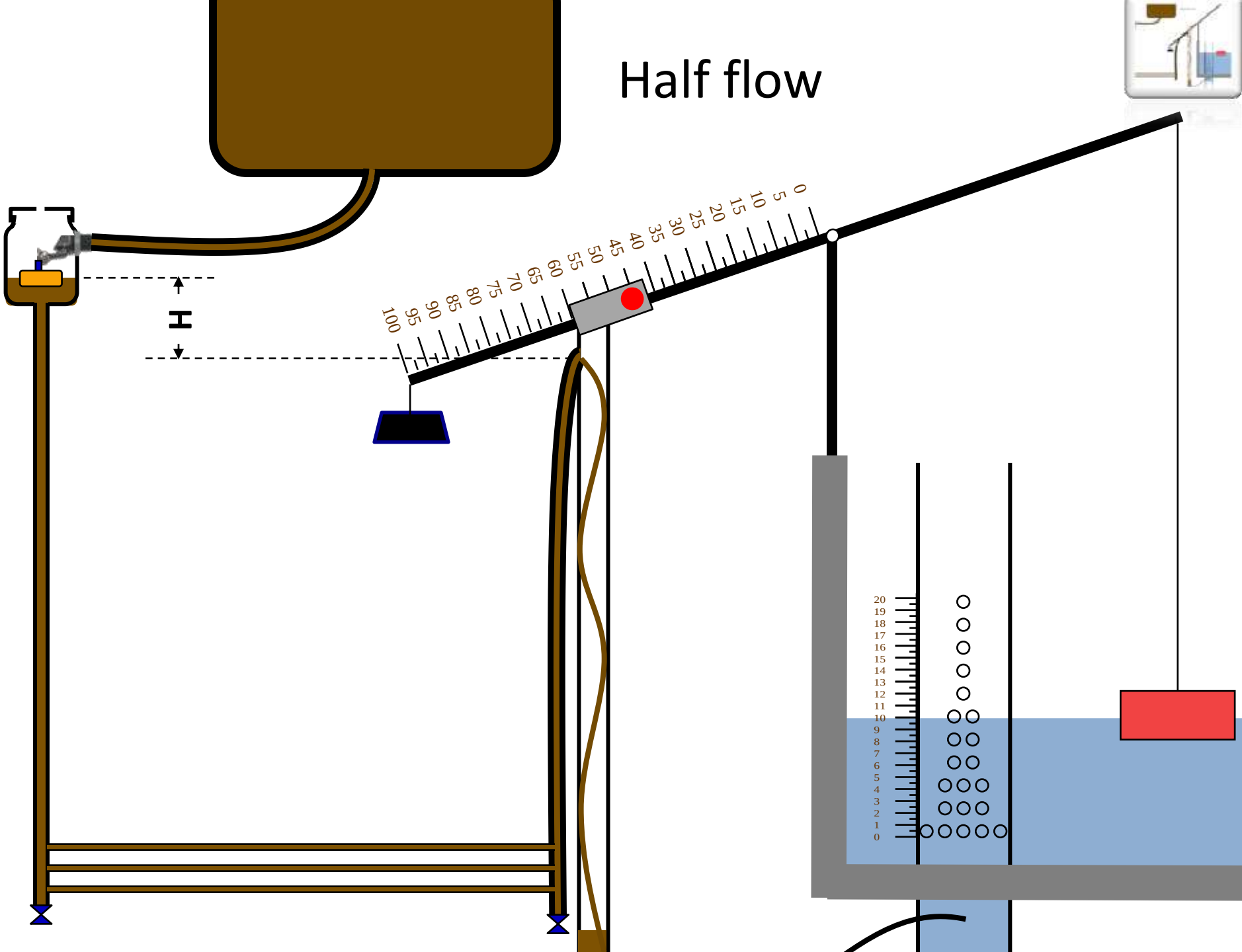
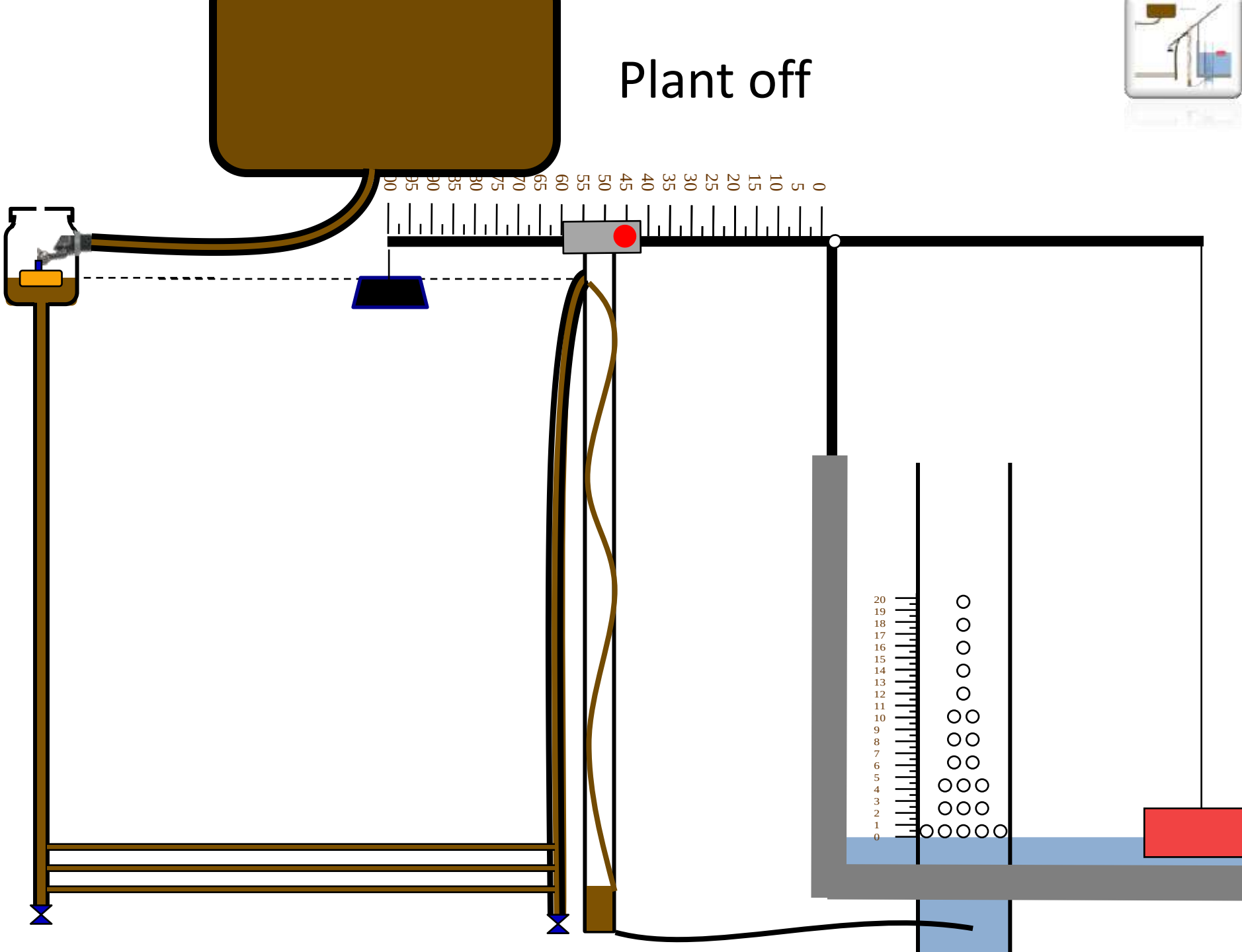
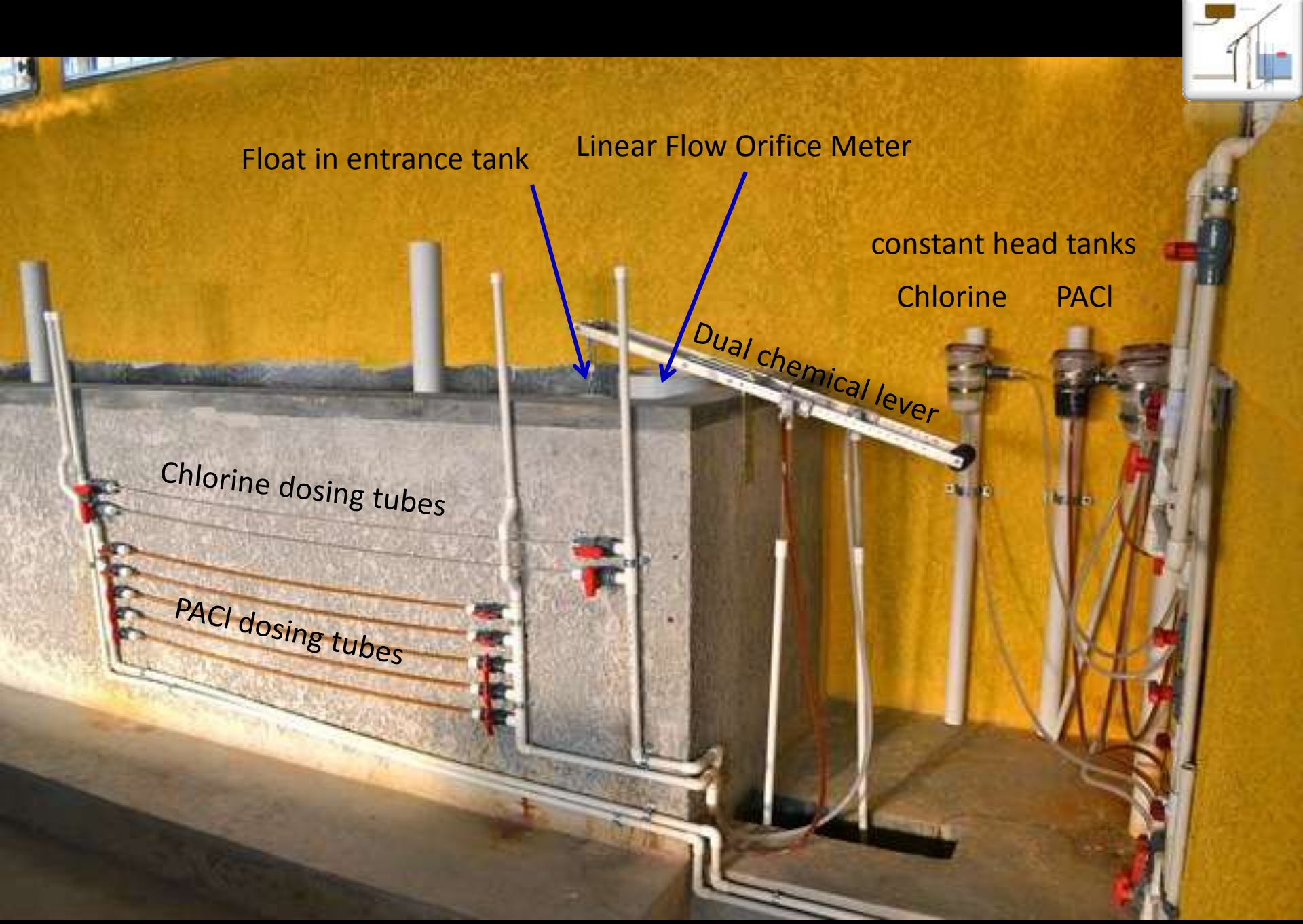
4
3
2
1
0

Half flow


H
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Plant off

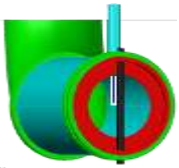

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 00
20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0


Float in entrance tank
Linear Flow Orifice Meter
constant head tanks
Chlorine
PACl
Dual chemical lever
Chlorine dosing tubes
PACl dosing tubes

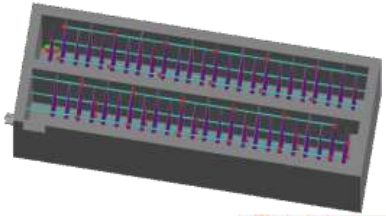
AguaClara Technologies

- Chemical dosing

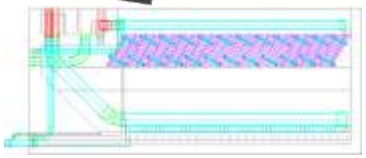
- Rapid Mix



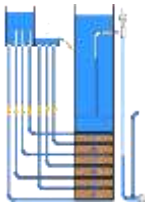
- Flocculator



- Sedimentation



- Filtration



- Conclusions

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Definitions

- Coagulation: The process of adding a sticky solid phase material (adhesive nanoglobs) that attaches to the colloids so they can attach to each other.
  (Note that this is not the traditional theory of charge neutralization.)
- Flocculation: The process of producing collisions between particles to create flocs (aggregates)

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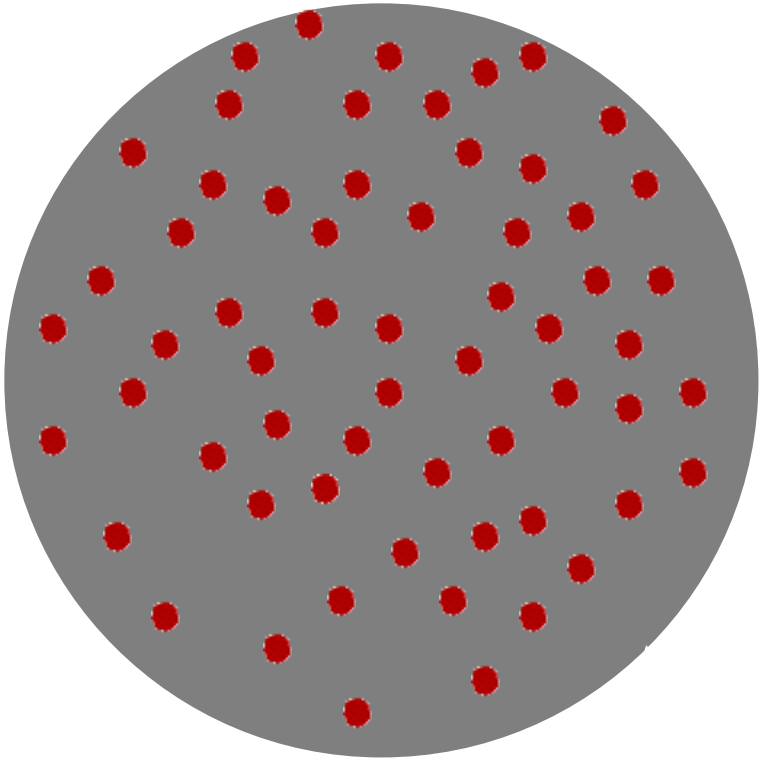
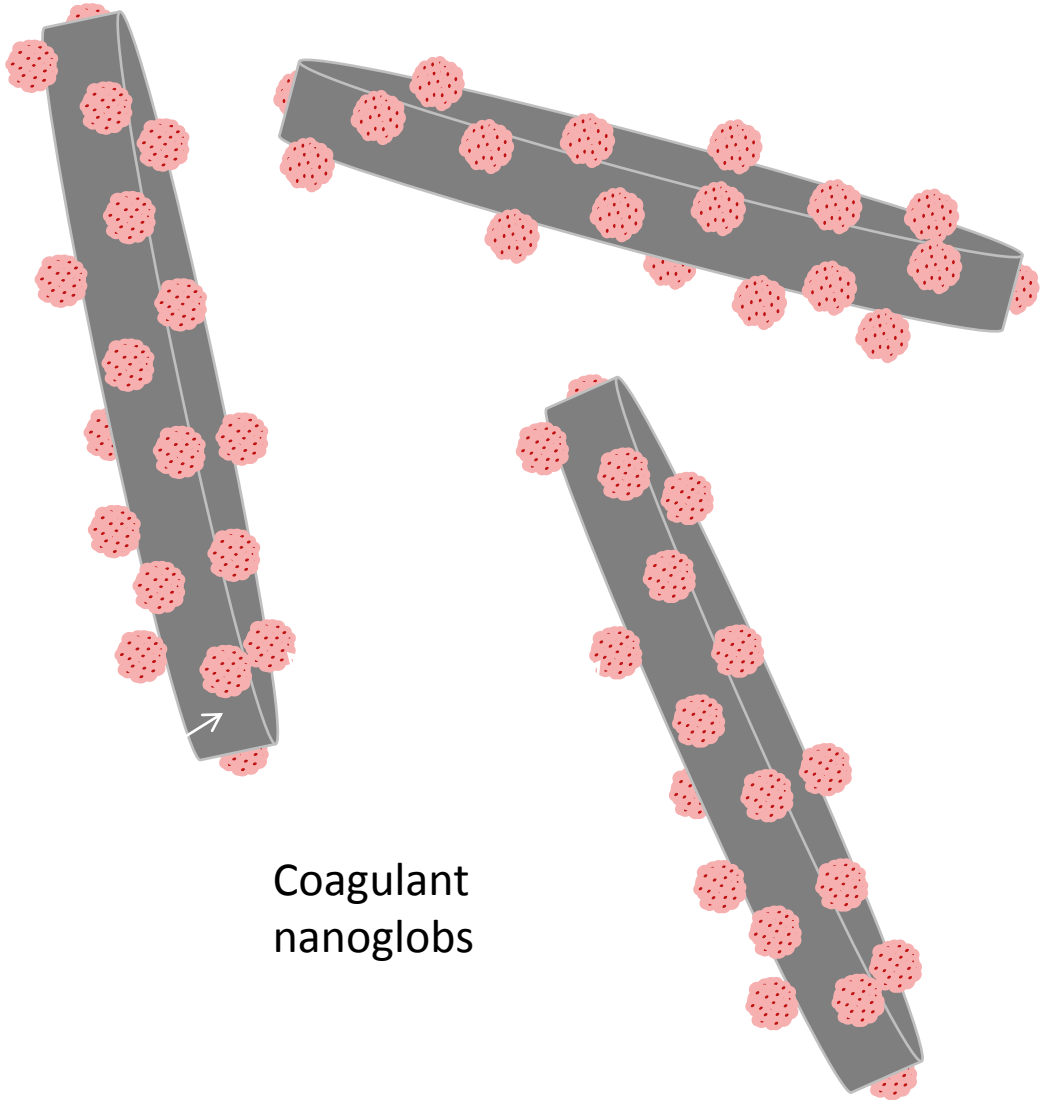
Coagulation Geometry



Clay platelets



Coagulant nanoglobs

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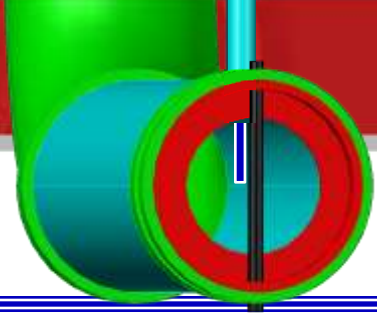
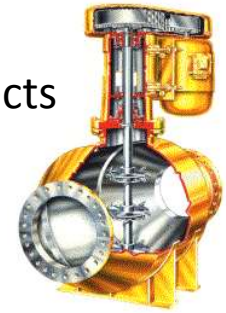
Traditional Design:
Mixing with a Propeller



Residence Time (s)	"velocity gradient" (G) (1/s)	Energy dissipation rate (W/kg)	Equivalent height (m)*
0.5	4000	16	0.8
10 – 20	1500	2.25	2.3 – 4.6
20 – 30	950	0.9	1.8 – 2.8
30 – 40	850	0.72	2.2 – 2.9
40 – 130	750	0.56	2.3 – 7.5

Energy!

No mention of scale effects

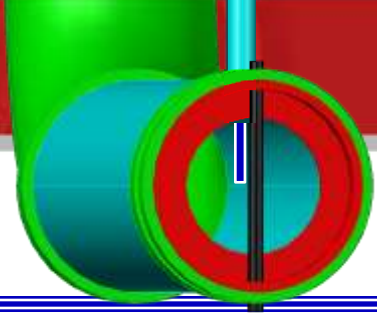


$$\Delta h = \frac{G^2 \nu \theta}{g}$$

from Environmental Engineering: A Design Approach by Sincero and Sincero. 1996. page 267

* A measure of mechanical energy converted to heat

Traditional rapid mix units



- Backmix mechanical reactors
- In-line blenders
- Hydraulic Jump
- In-line static mixers

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Mechanized Rapid Mix vs. Hydraulic Rapid Mix

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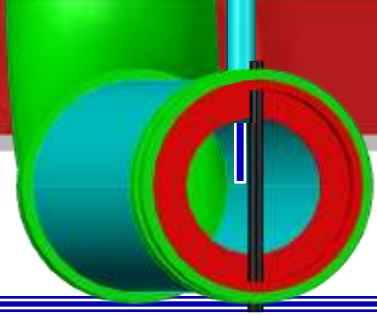
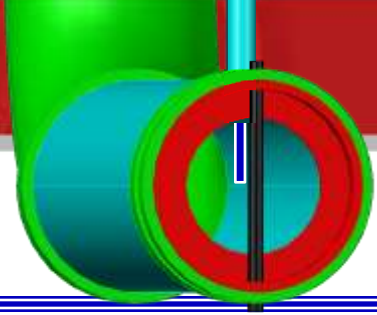


- Energy used for conventional rapid mix is equivalent to 6 m of potential energy
- After 25 years the electricity cost for a 100 L/s (2.3 mgd) mechanized rapid mix would be $230,000
- A 100 L/s AguaClara plant costs approximately $600,000
- The 25 yr energy cost for a 100 L/s package plant is 1.5 million USD!
- “Another way to give is to not take…”

Why might RAPID mix be necessary?



- We need to mix the adhesive nanoglobs with the water
- But why RAPID?
- IF RAPID mixing matters then there must be something bad that happens if the mix is SLOW
  - Self aggregation of nanoglobs into microglobs
  - Nonuniform distribution of nanoglobs on colloids

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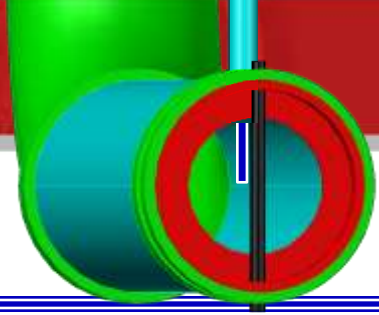
Rapid Mix: From macro to nano (in a few seconds)



Length scale

Transport Process

Result

m

mm

µm

nm

Rapid Mix flow dimension

Large scale eddies

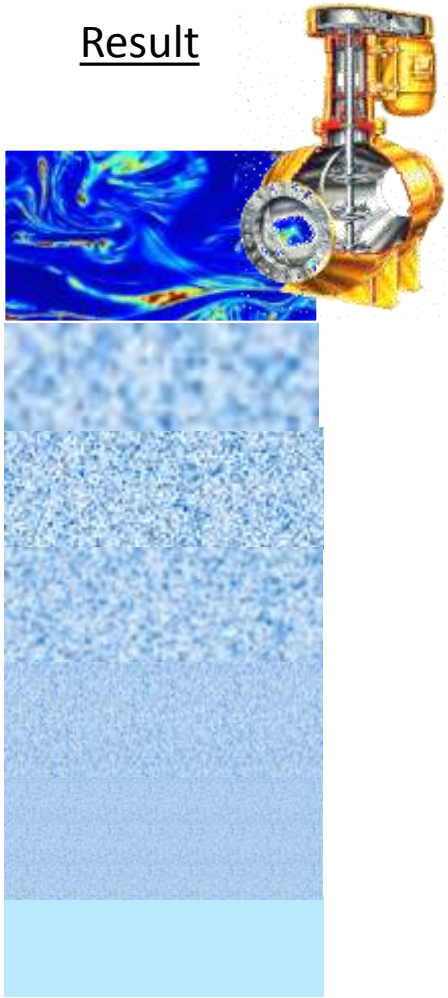
Small scale eddies

Kolmogorov scale

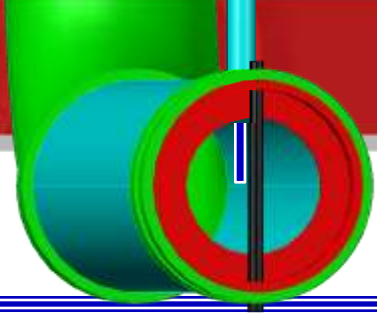
$$L_K = \left(\frac{\nu^3}{\varepsilon}\right)^{\frac{1}{4}}$$

Molecular diffusion

Molecular scale

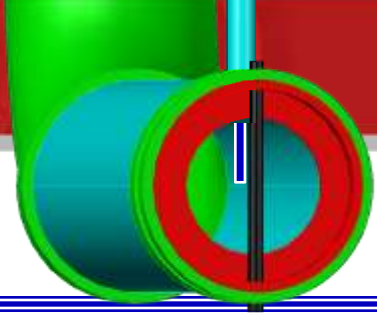


Three steps for mixing



- Large scale eddies to mix at the dimension of the reactor (Macro mixing)
  - Generate large eddies
- Small scale eddies to mix down to the Kolmogorov length scale (Micro mixing)
  - Generate energetic tiny eddies so that turbulence can mix to as small a scale as possible
- Molecular diffusion to finish the job

How do we generate intense turbulence?



- We need to be converting mechanical energy (kinetic energy) to thermal energy
- We want "concentrated" head loss! (this shouldn't be too hard to achieve!)
- Therefore use minor loss (related to a change in flow geometry) rather than major loss (from shear at the solid boundaries)
- Almost all minor losses are caused by **expansions (We need a flow EXPANSION)**

A Flow Expansion!

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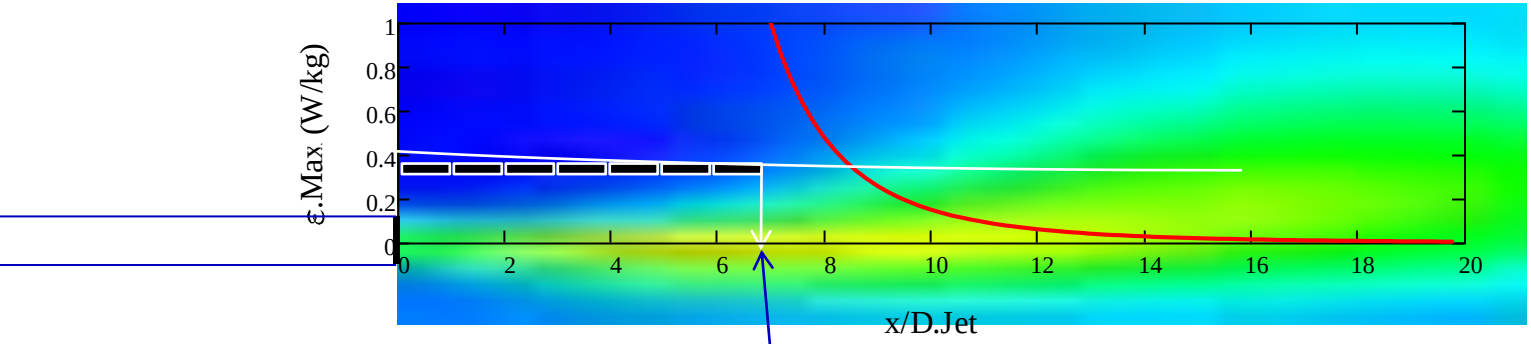
Jet Mixing



$$\varepsilon_{Max} \cong \frac{\left(\Pi_{RoundJet} V_{Jet}\right)^3}{D_{Jet}}$$

Average velocity in the jet at the point of discharge

$$\Pi_{RoundJet} \cong 0.4$$

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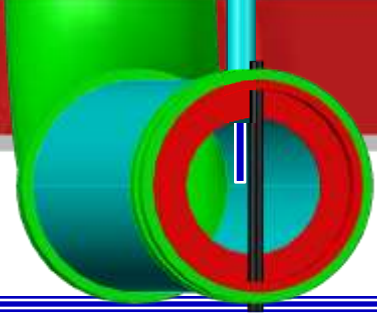
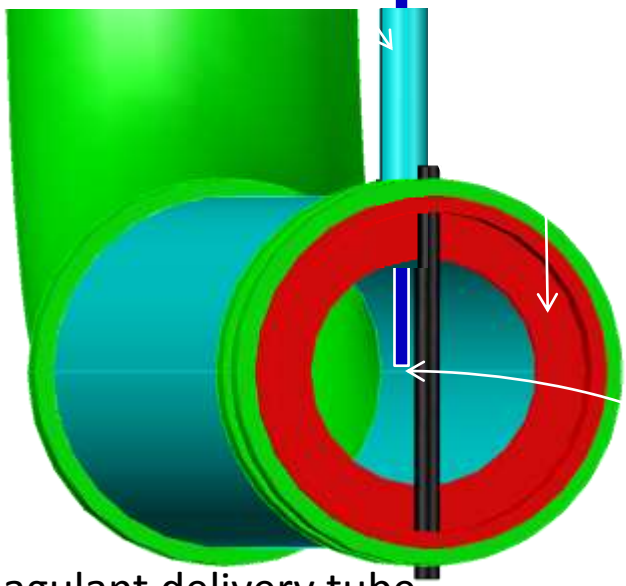
Rapid Mix in a Jet

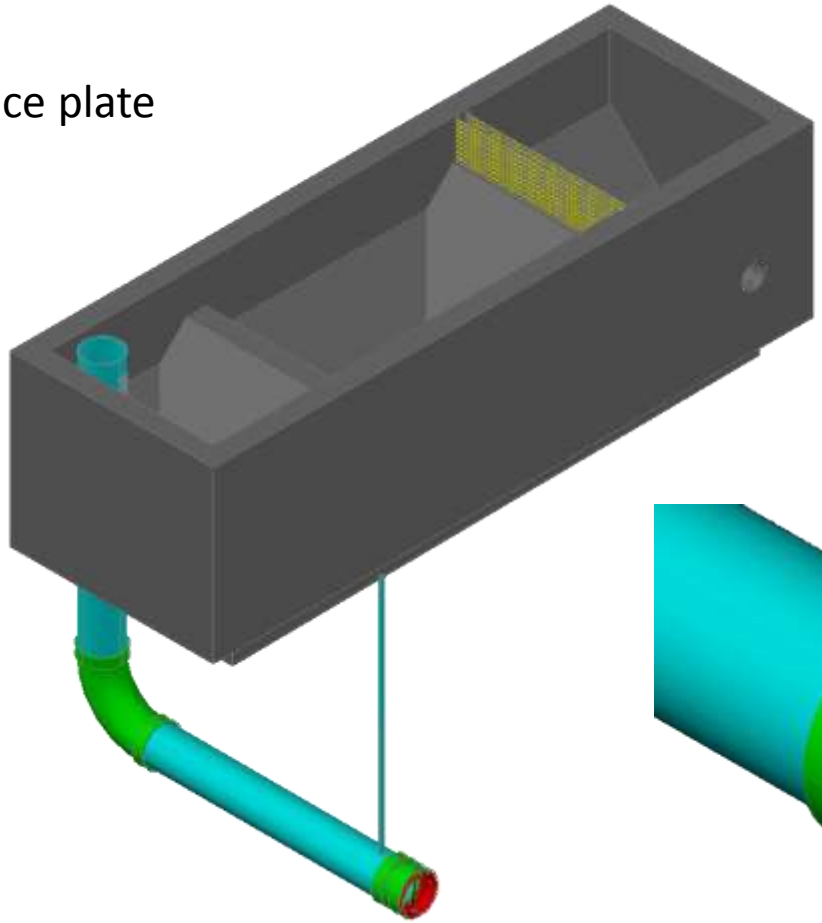


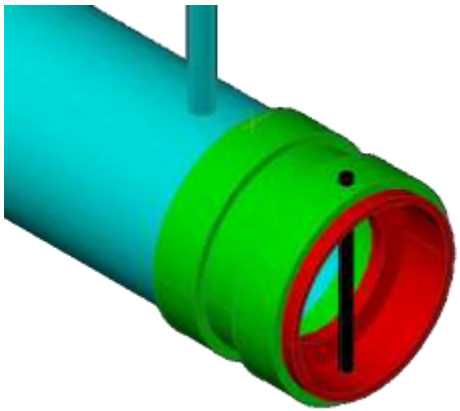
Pin to keep plate in place

Access pipe for coagulant delivery tube

Orifice plate







Coagulant delivery tube

AguaClara Rapid Mix Head Loss

Jet equations

$$\varepsilon_{Max} \cong \frac{\left(\Pi_{Jet} V_{Jet}\right)^3}{D_{Jet}}$$

$$V_{Jet} \cong \frac{\left(D_{Jet}\varepsilon_{Max}\right)^{\frac{1}{3}}}{\Pi_{Jet}}$$

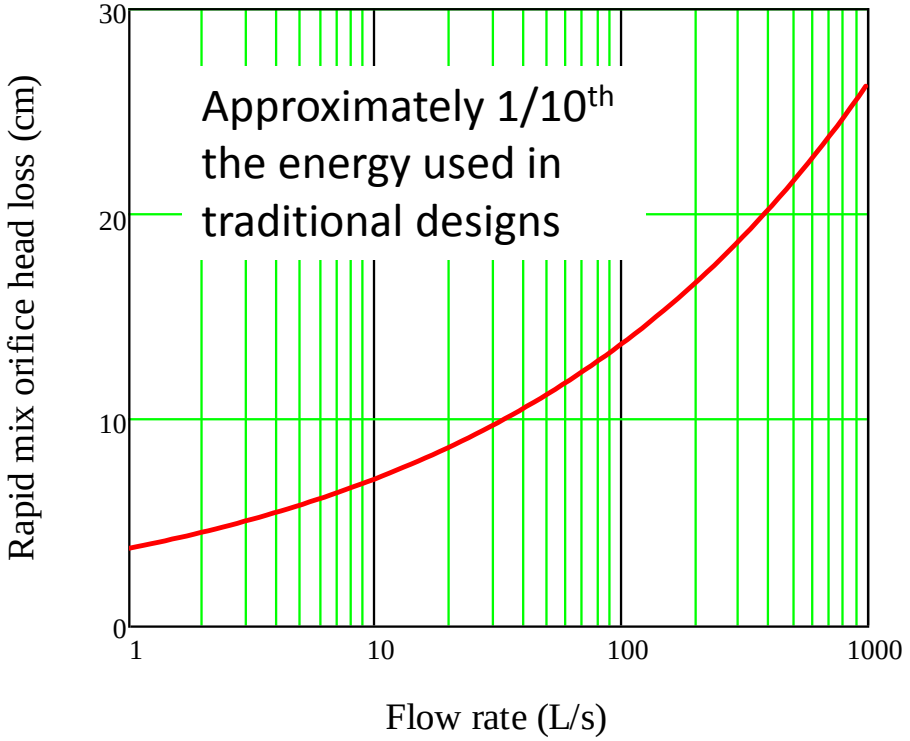
$$D_{Jet} \cong \left(\frac{4\Pi_{Jet} Q}{\pi \varepsilon_{Max}^{\frac{1}{3}}}\right)^{\frac{3}{7}}$$

This is one of the scale effects for rapid mix

Head loss equations

$$h_e = \frac{V_{Jet}^2}{2g} \qquad h_e = \frac{\left(D_{Jet}\varepsilon_{Max}\right)^{\frac{2}{3}}}{2g\Pi_{Jet}^2}$$

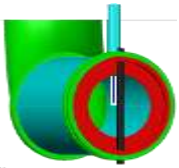
$$h_e = \frac{\left(\frac{4\Pi_{Jet} Q \varepsilon_{Max}^2}{\pi}\right)^{\frac{2}{7}}}{2g\Pi_{Jet}^2}$$



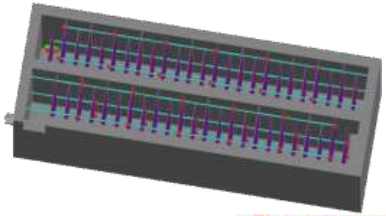
AguaClara Technologies

- Chemical dosing

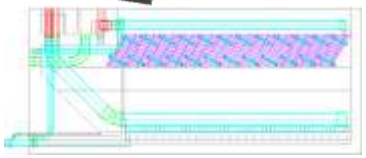
- Rapid Mix



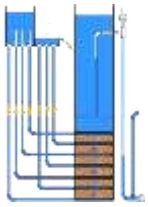
- Flocculator



- Sedimentation



- Filtration



- Conclusions

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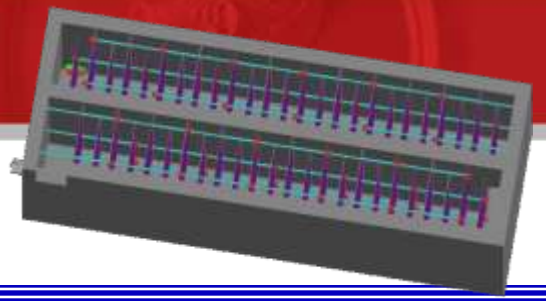
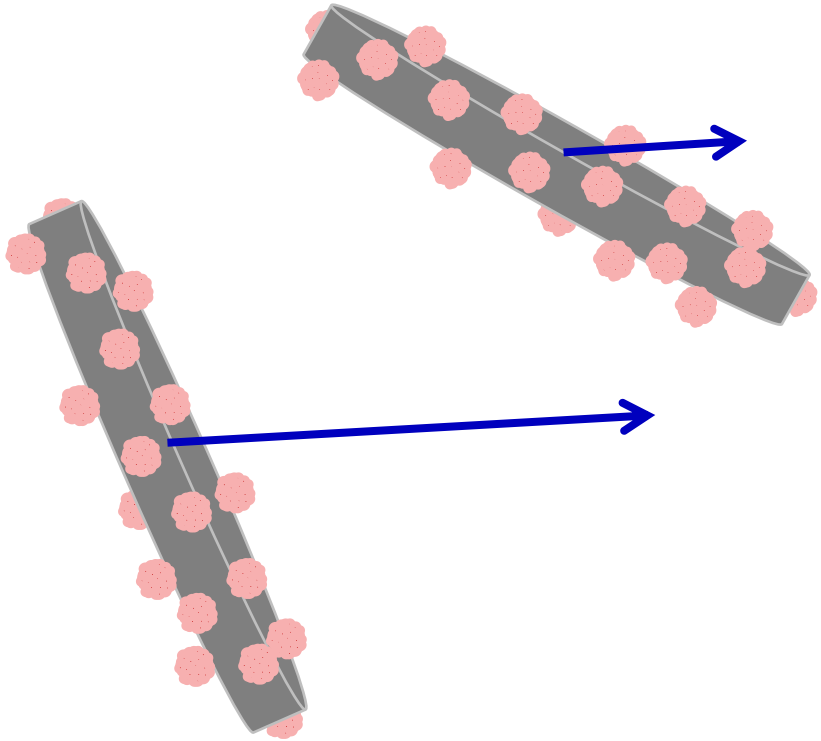
Flocculation



- Gentle collisions
- Need to generate relative velocity between particles including clay and pathogens
- Turbulence!
- Head loss
- Expansions
- Design based on energy dissipation rate (not velocity gradients)



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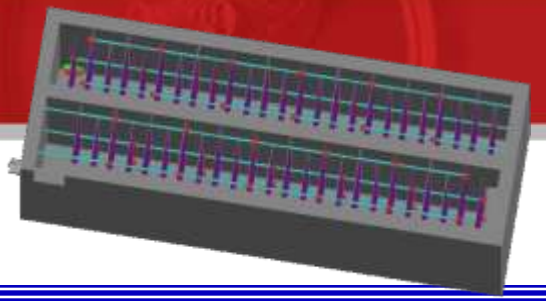
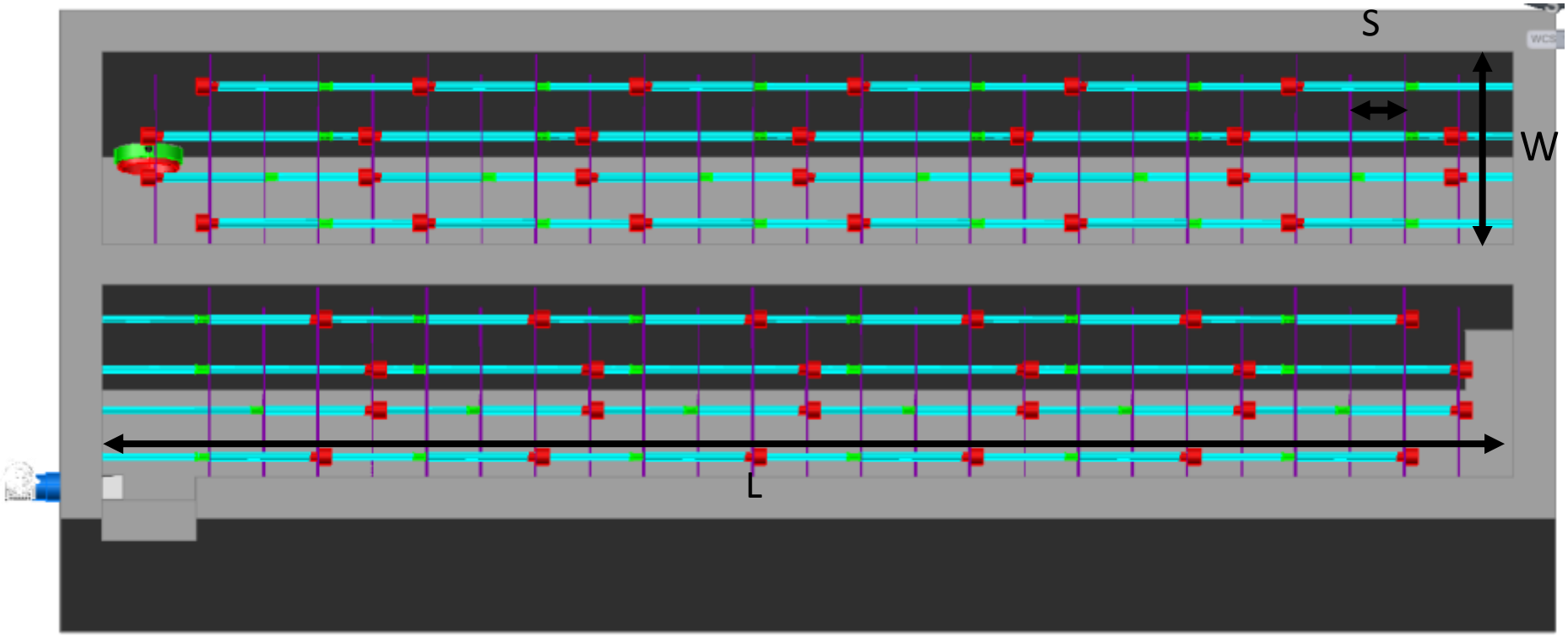
Flocculator



W = Width of the flocculator channel
S = Space between baffles
L = Length of a flocculator channel



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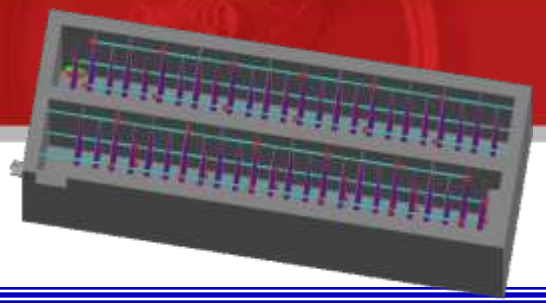
Flocculator Design



- Spacing of the baffles sets the velocity and the energy dissipation rate

Baffle minor loss coefficient

$$S = \left(\frac{K_B}{H \varepsilon_{Max}} \right)^{\frac{1}{3}} \frac{Q}{W}$$

Q ← Flow rate

W ← Channel width

Energy dissipation rate

Water depth

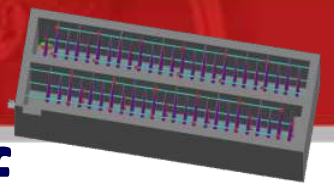
- Number of baffles sets the residence time and the total collision potential of the flocculator

Collision Potential for one baffle

$$\psi_B = \left(\frac{\Pi_{PlaneJet}^{\ 3}}{2\Pi_{VCBaffle}^{\ 4}} \right)^{\frac{1}{6}} K_B^{\frac{1}{3}} H^{\frac{2}{3}} = 0.96 H^{\frac{2}{3}}$$

Contraction coefficient for baffle

Flocculation Energy Dissipation Rate Tradeoff



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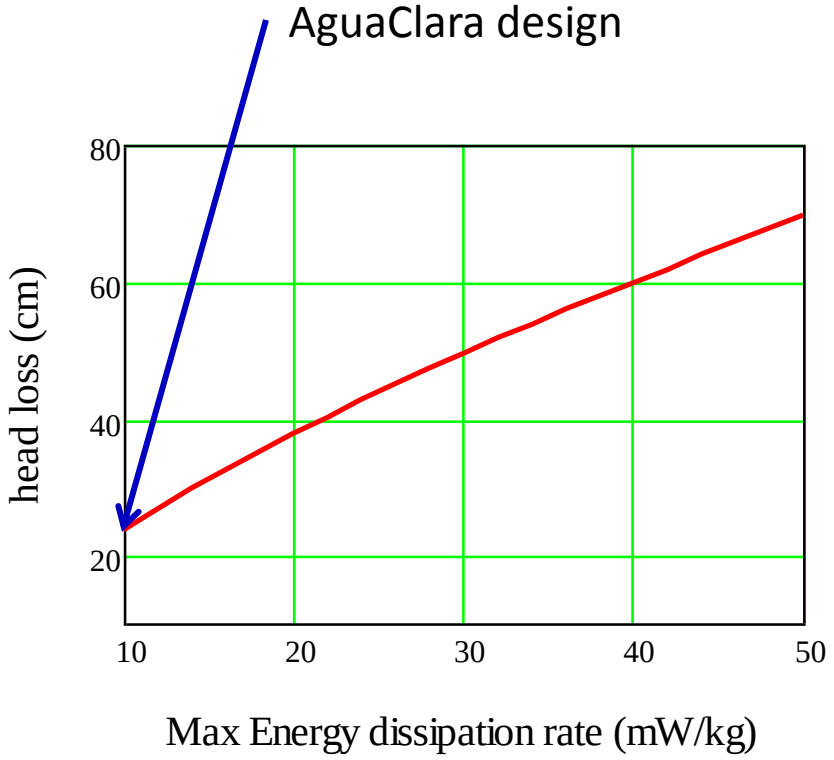
- High energy dissipation rate increases elevation differences in plant and decreases required residence time
- Low energy dissipation rate produces large flocs that will tend to settle in the flocculator

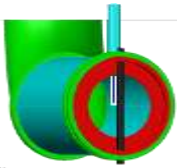


Assumes collision potential of 75 $m^{2/3}$ and H/S<5

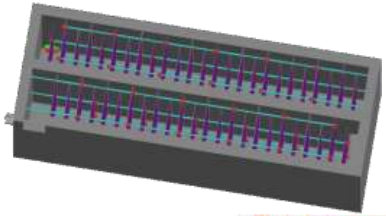
AguaClara Technologies

- Chemical dosing

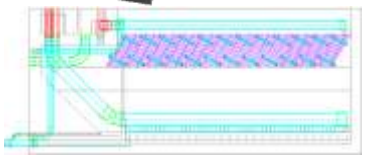
- Rapid Mix



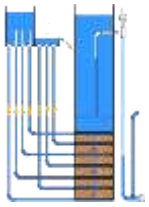
- Flocculator



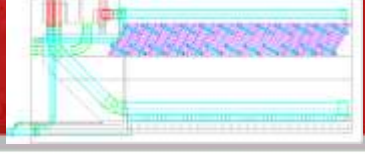
- Sedimentation



- Filtration



- Conclusions



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Sedimentation Tanks

Sedimentation Tank

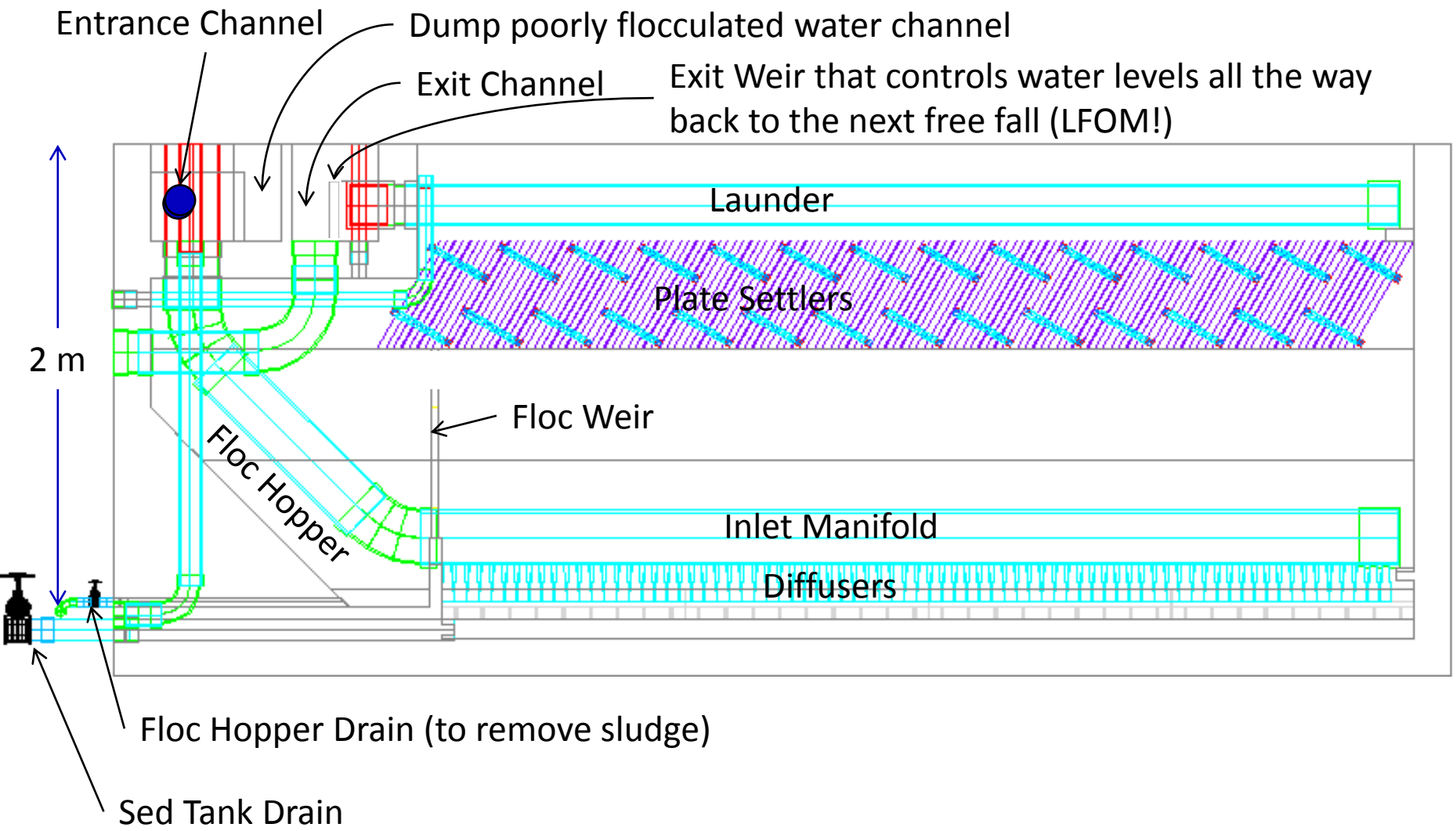
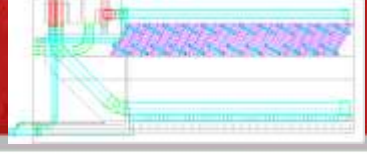


Plate Settler Spacing



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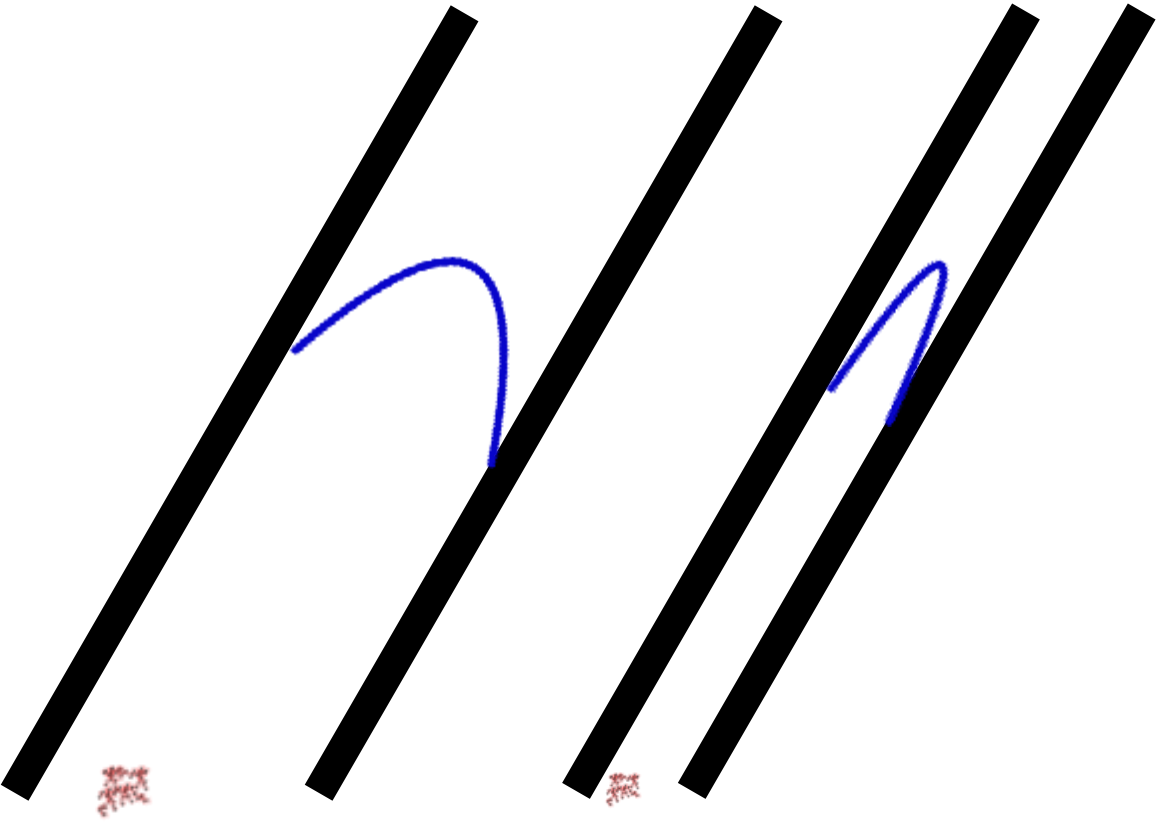
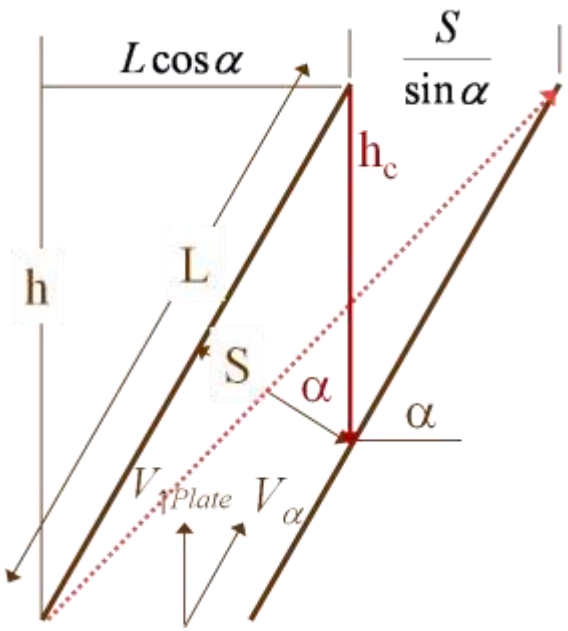
Constraints: Floc Rollup



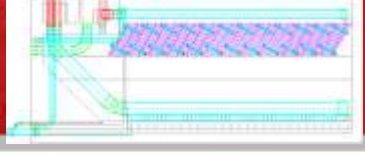


$$V_c = \frac{SV_{Plate\uparrow}}{L\sin\alpha\cos\alpha + S}$$

Capture velocity

Why can't we make plate setters that work just as well by making them short (L) and closely spaced (S)?

Plate Settler



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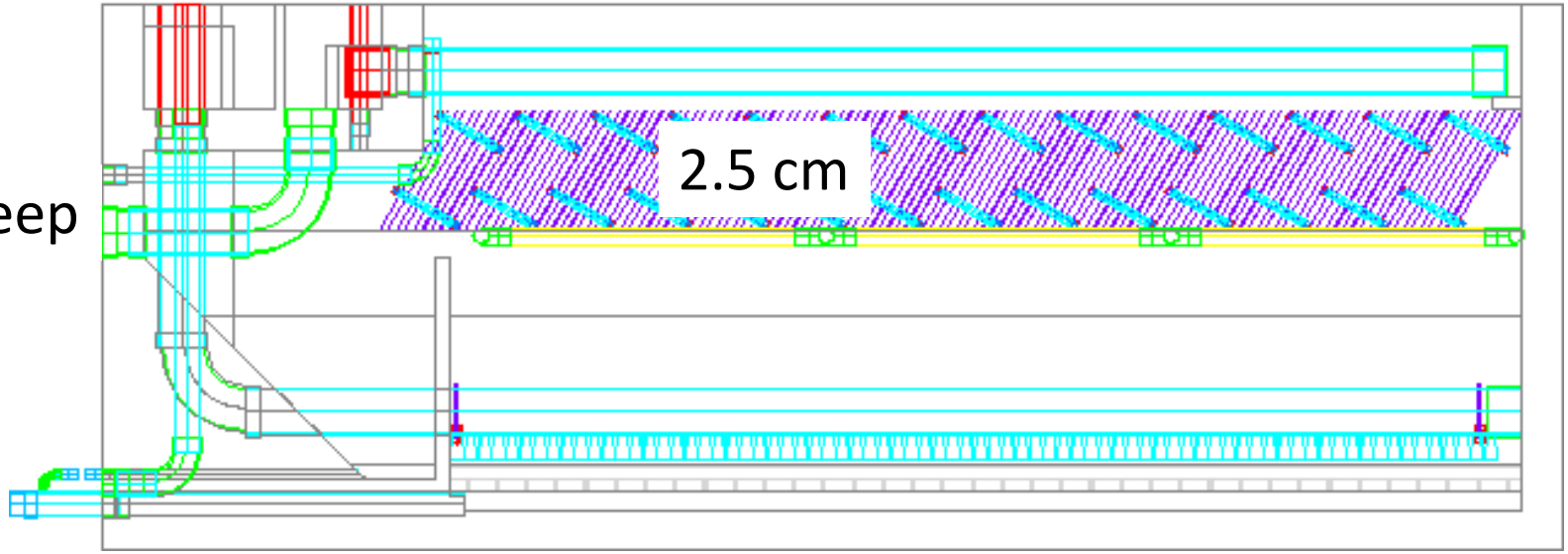
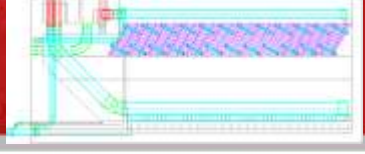
Spacing effects

- Plate settler spacing has a strong influence on sedimentation tank depth
- Diminishing effect as spacing is reduced
- AguaClara currently uses 2.5 cm spacing

1.84 m deep





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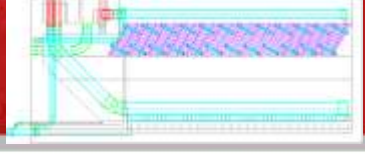
Floc Resuspension

- All surfaces in the sed tank with a horizontal component must return settled flocs to a resuspension zone. (NO FLAT BOTTOM!)
- Floc resuspension geometry works by having a flocculated water jet with a high vertical velocity component that returns settled flocs to the floc blanket



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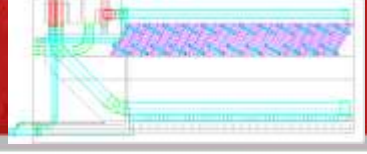
Research Goals

- Use a floc blanket to improve performance and reduce the required coagulant dose
- Reduce mean circulation currents
- Minimize performance degradation caused by temperature gradients
- Design a sedimentation tank that has no sediment! (all sediment goes to floc hopper)
- Simplify operation



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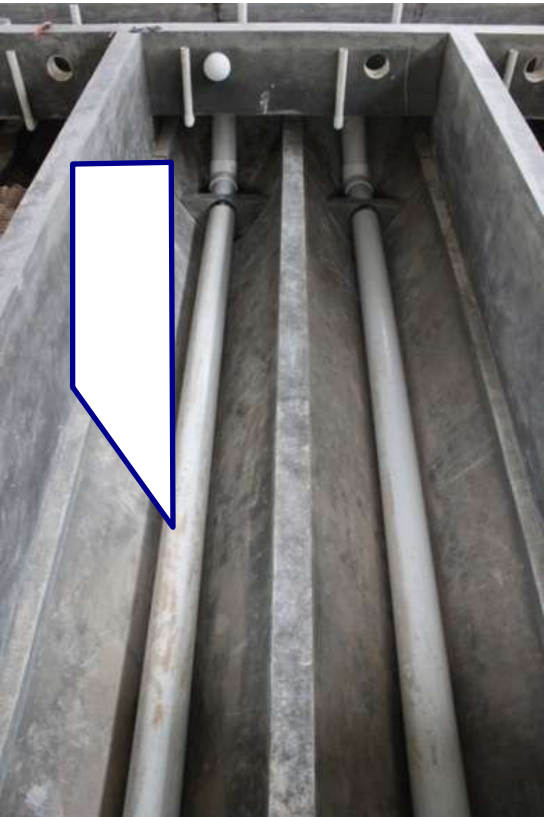
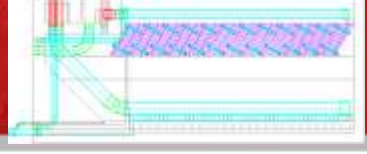
Sedimentation Research



Sedimentation Tank



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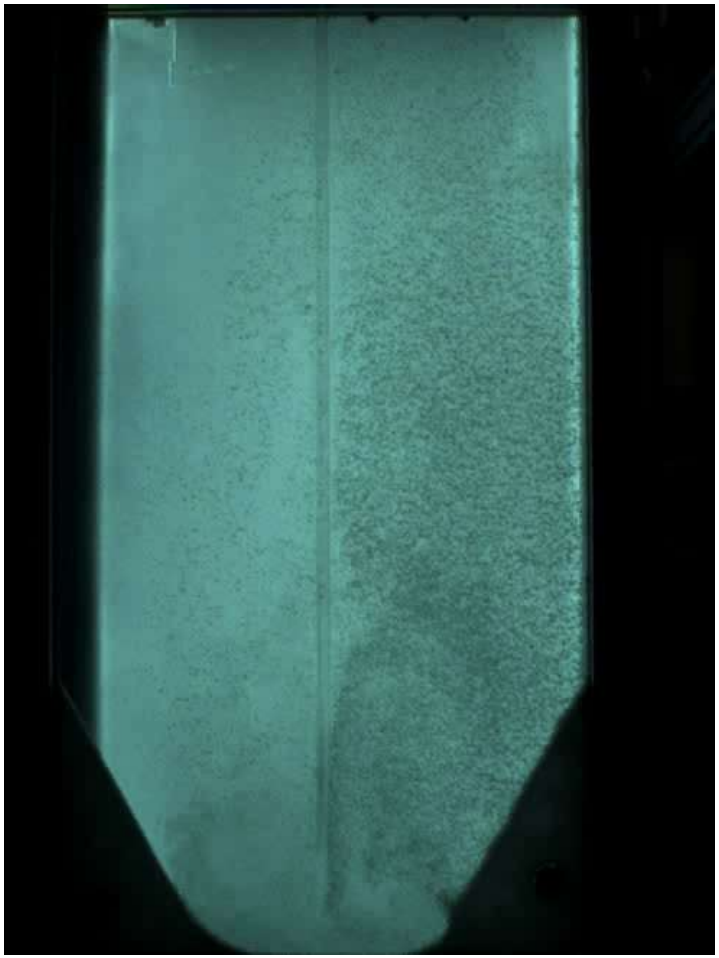
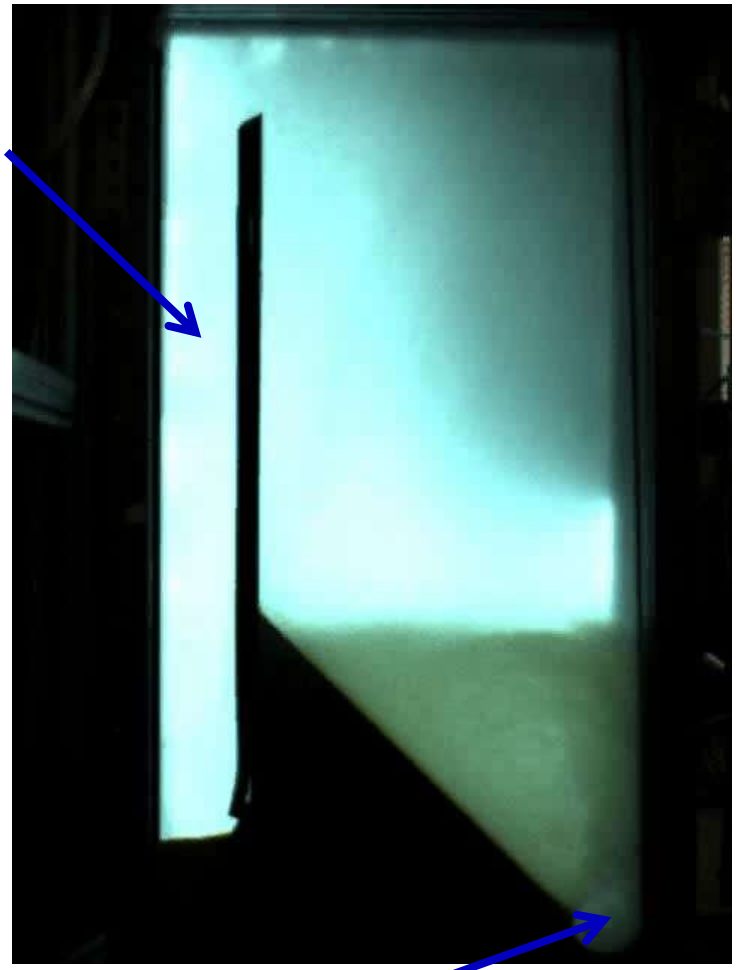
Bottom Geometry



Flat bottom

Floc Hopper

Upflow velocity is 1 mm/s



Jet Reverser

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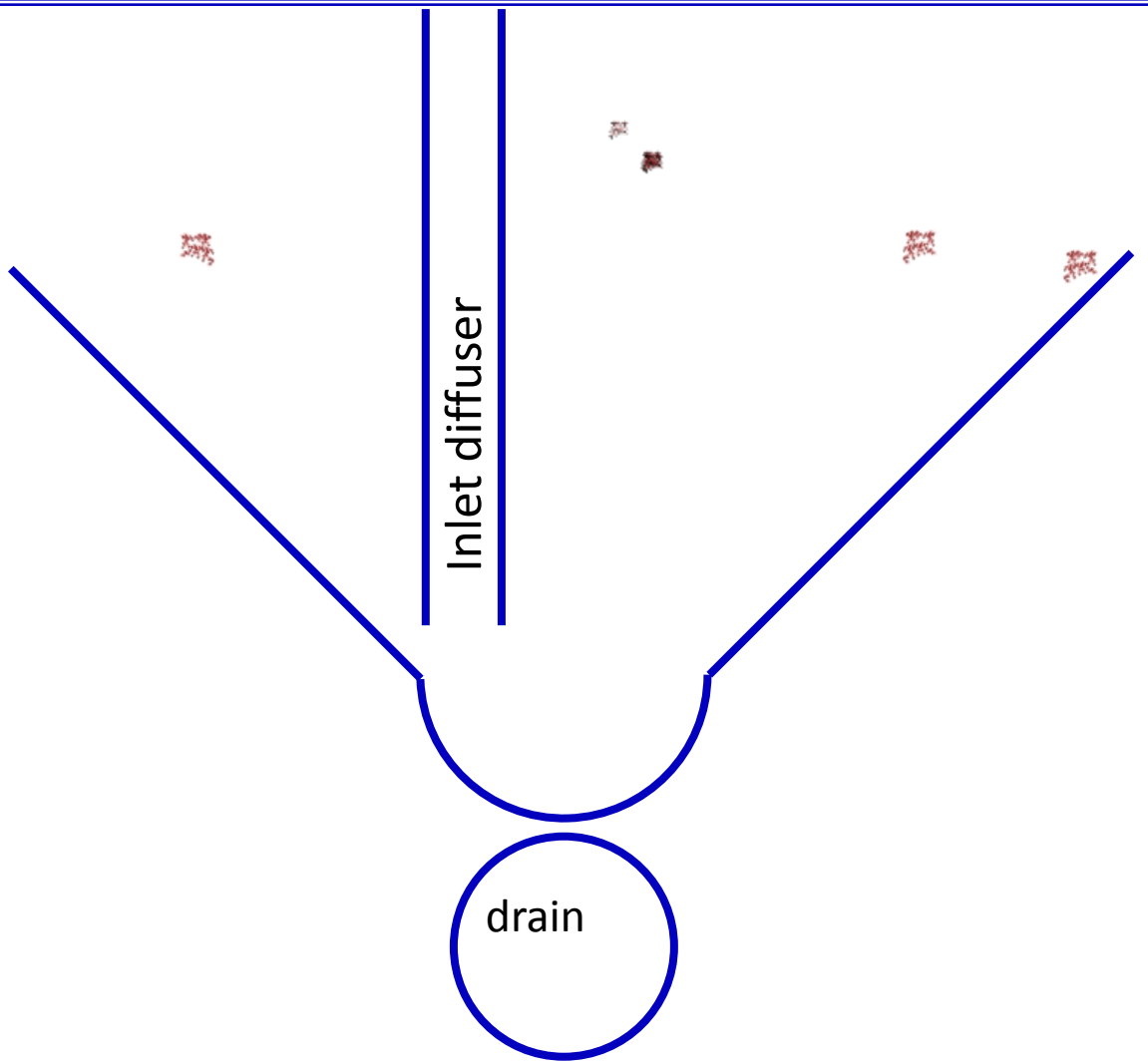
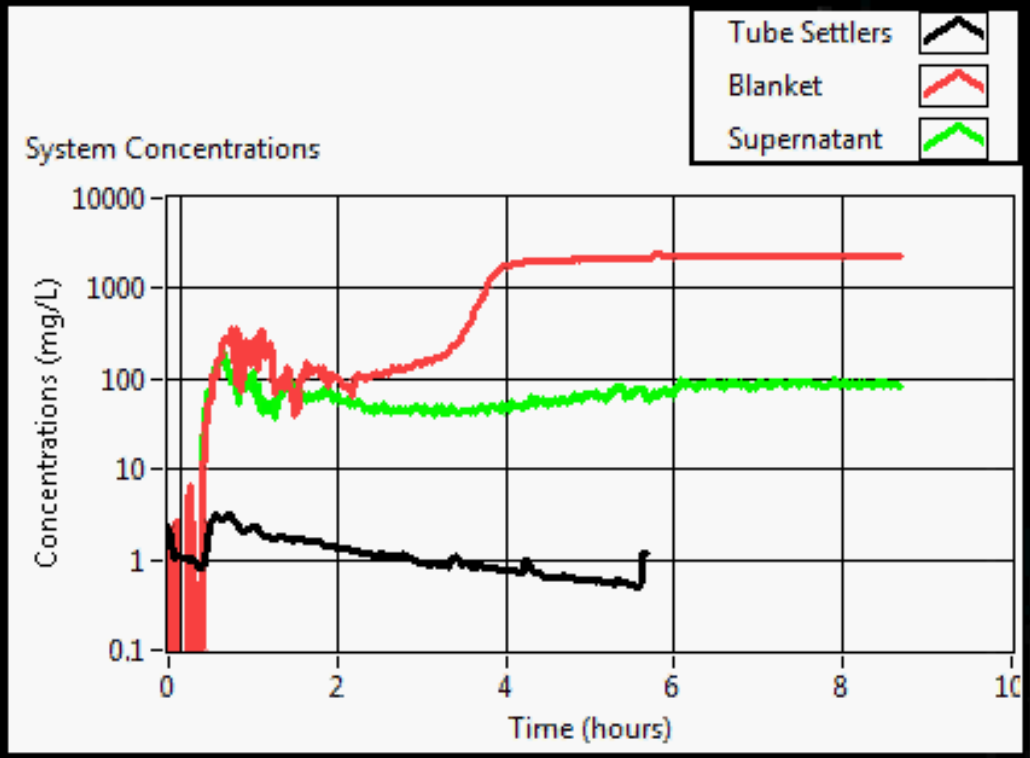
Floc Blanket Resuspender



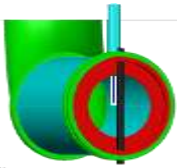
Time (hours) 0.13
Jet Diameter 7.9 mm
PACl Dose 2.5 mg/L



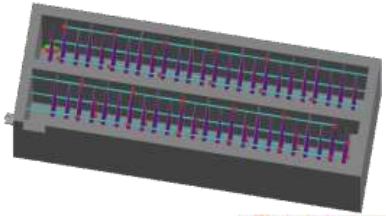
AguaClara Technologies

- Chemical dosing

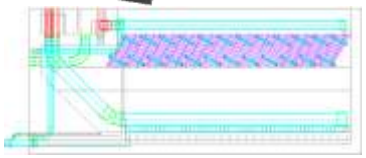
- Rapid Mix



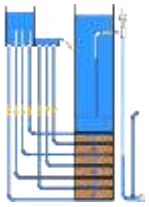
- Flocculator



- Sedimentation



- Filtration



- Conclusions

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Filter range of applicability

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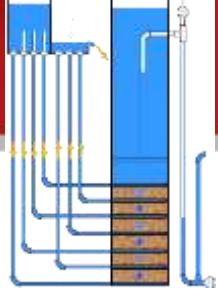
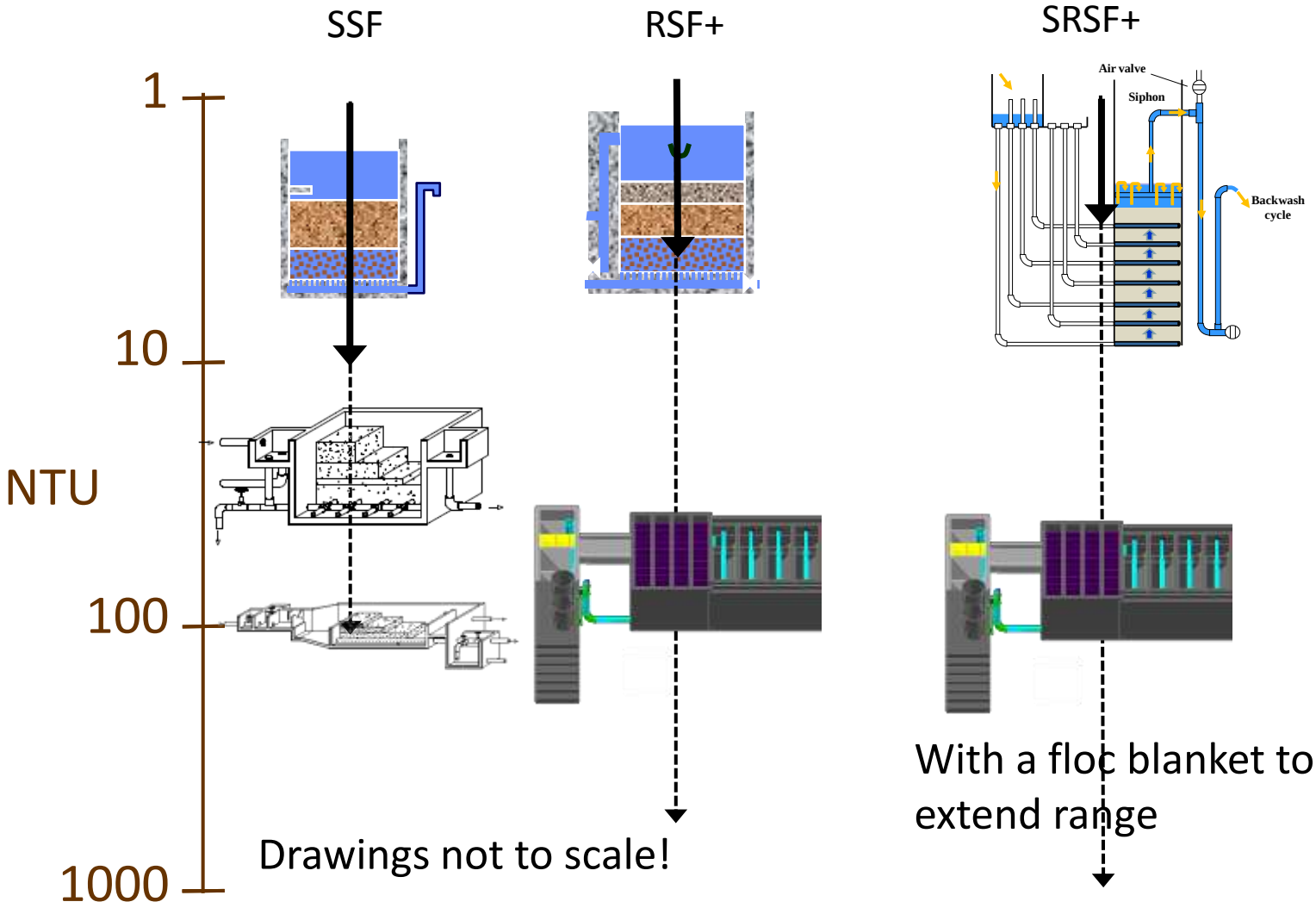
The "if it is dirty, filter it" Myth





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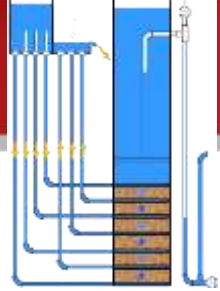
Filtration: The Backwash Dilemma



- Backwash velocity >> filtration velocity
- Backwash water must be clean water
- Backwash water sources?
  - Pump it from clearwell
  - Set of filters working in parallel to backwash one filter
  - Filtered water stored at adequate elevation

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Rapid Sand Filtration

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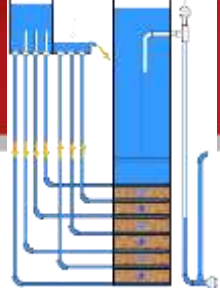
Backwash without pumps



https://confluence.cornell.edu/display/AGUACLARA/Santa+Rosa+de+Copan

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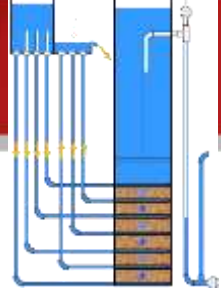
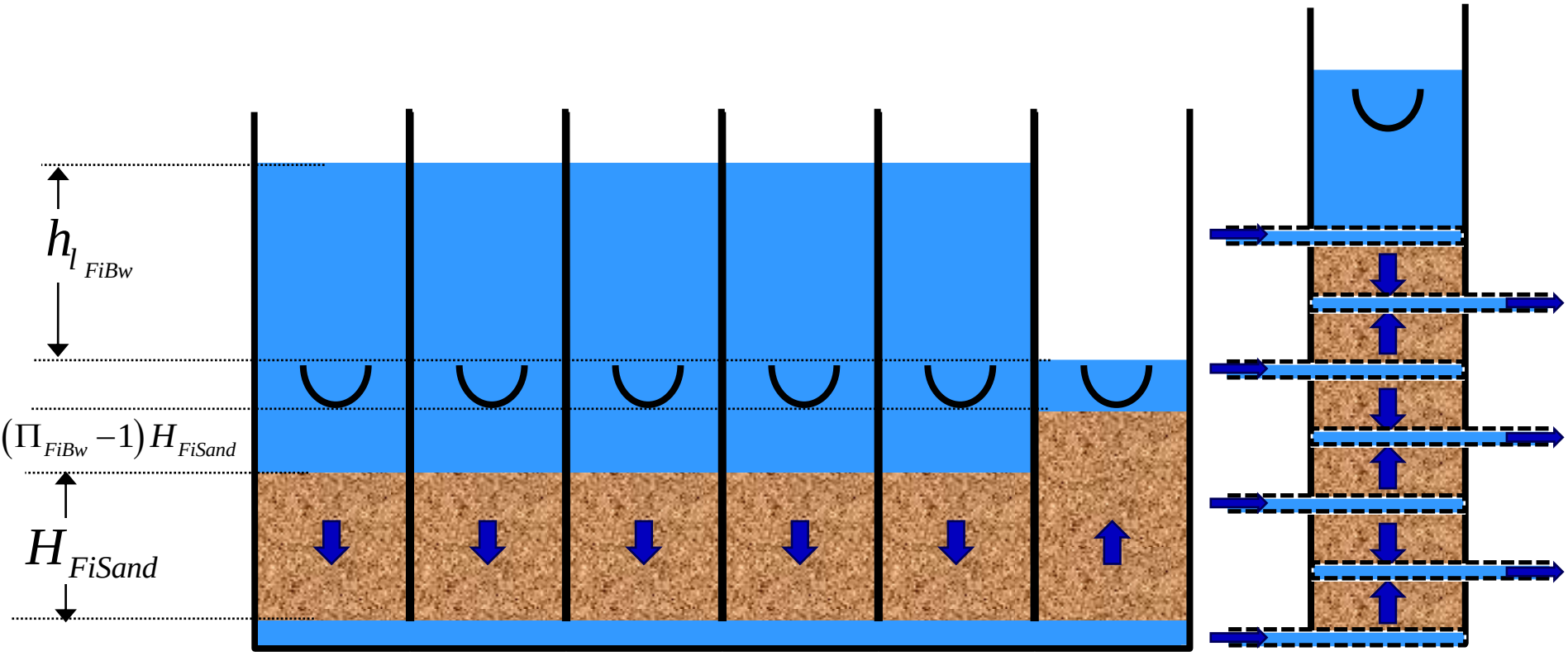
Stacked Rapid Sand Filter (SRSF)



Instead of 6 filters side by side, stack them up!



Reduce backwash water volume by factor of number of layers

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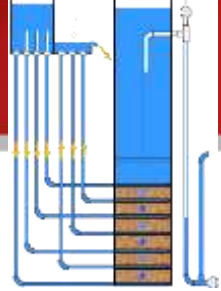
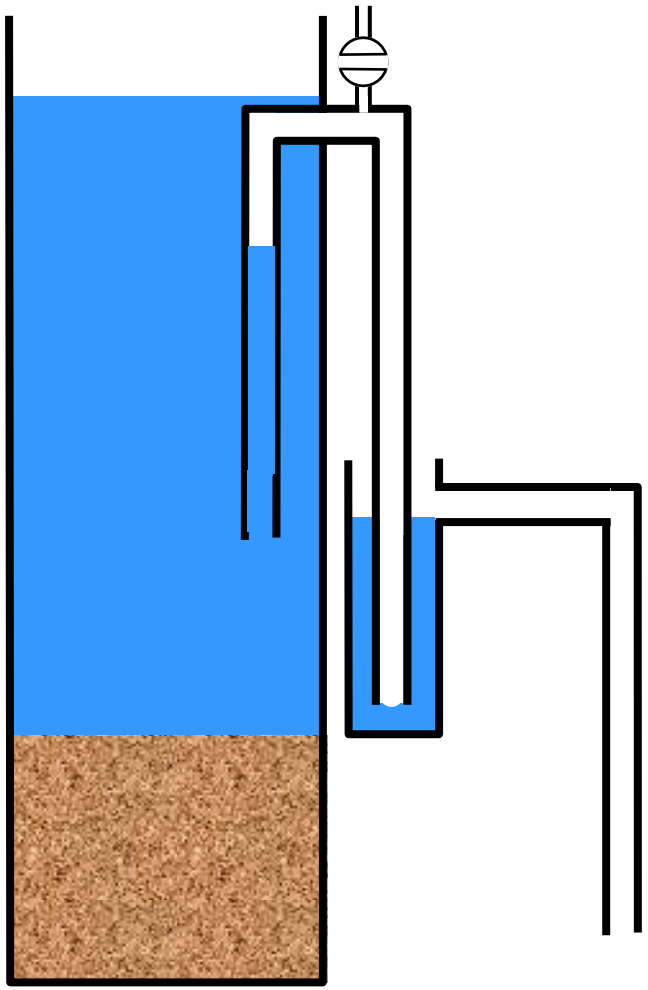
Begin Filtration

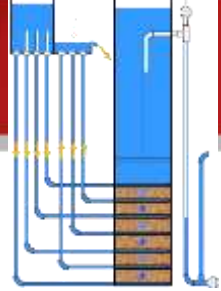


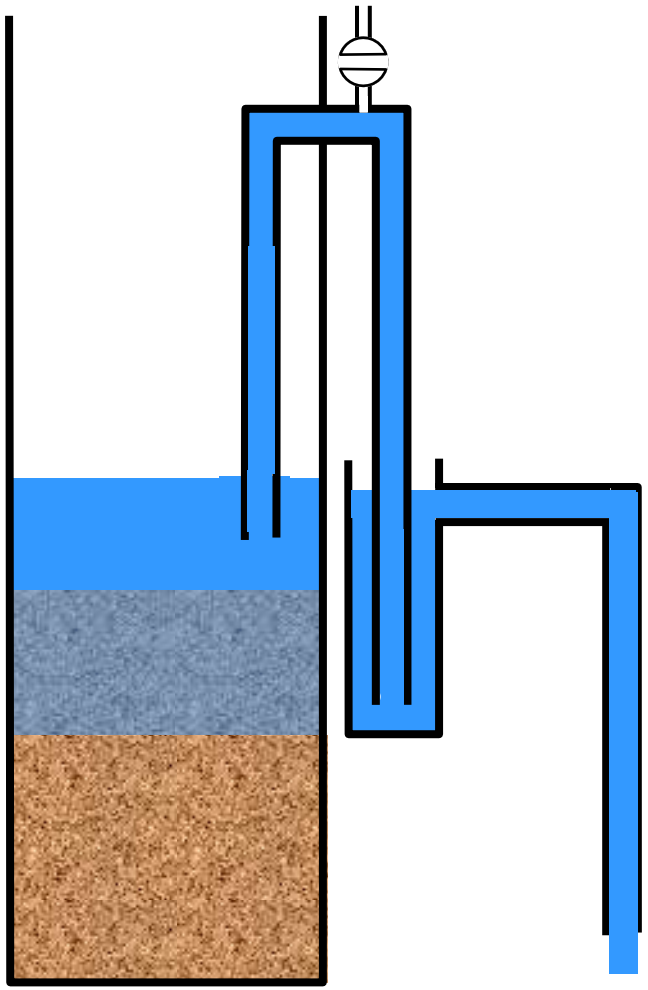


One valve operation. Using hydraulics to control the transition from backwash to filtration mode and back again.

A small air release valve controls the entire process!

Begin Backwash





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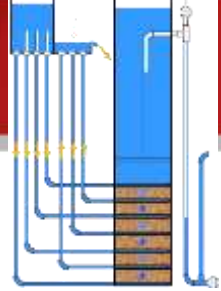
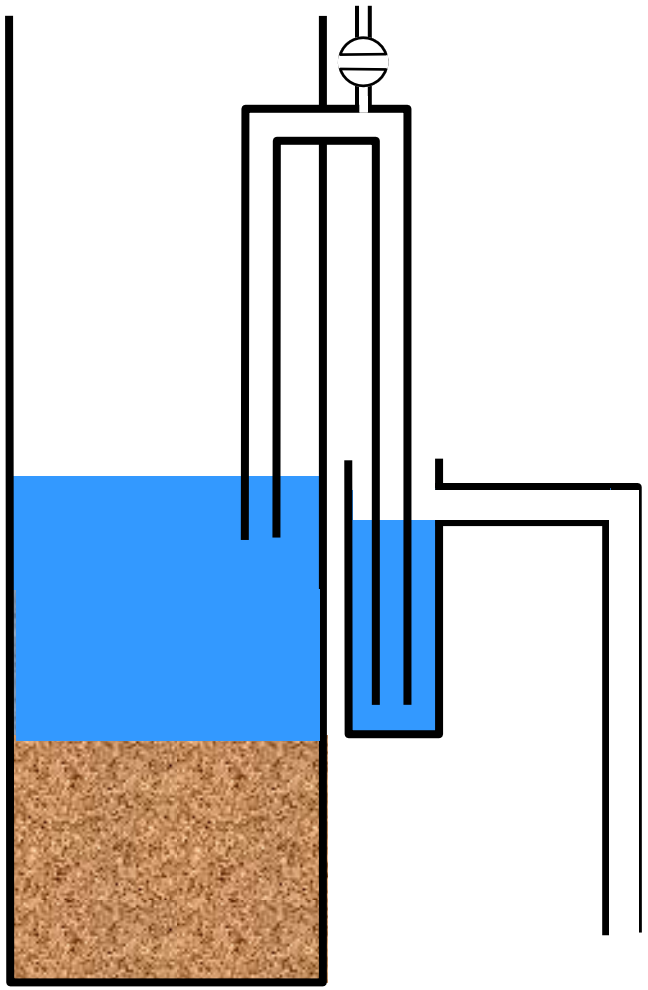
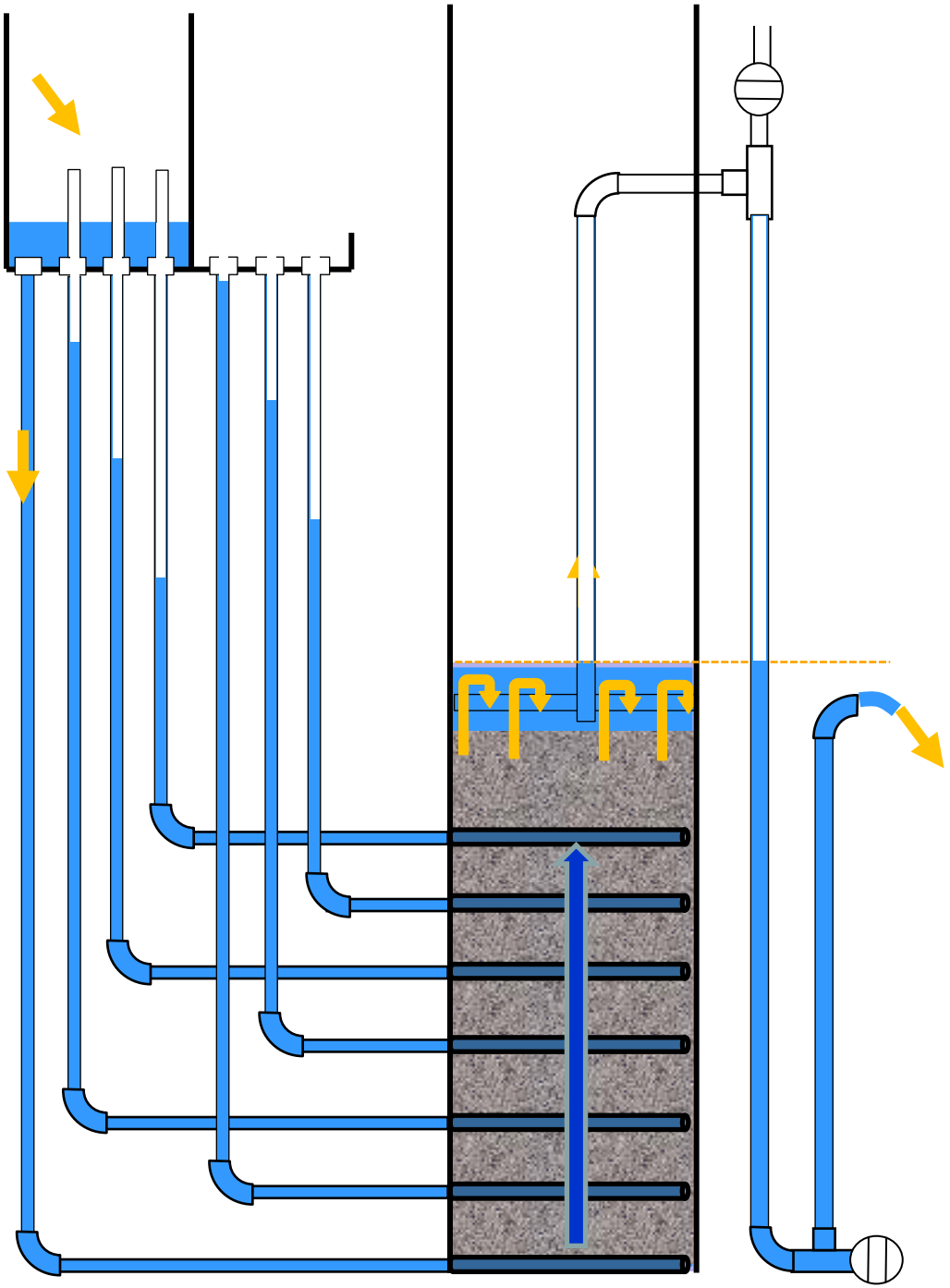
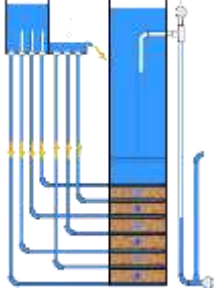
End Backwash



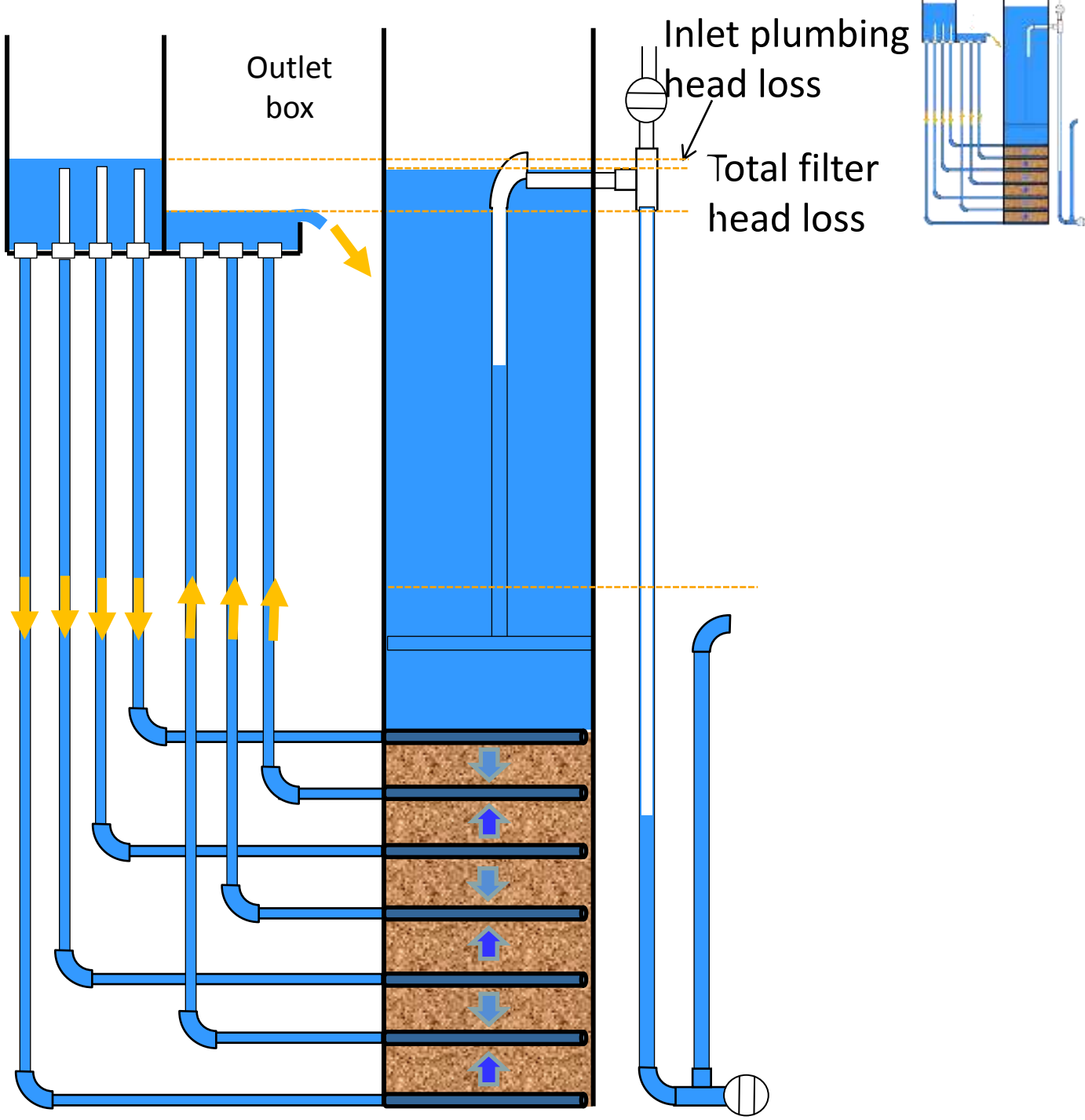


End Backwash cycle

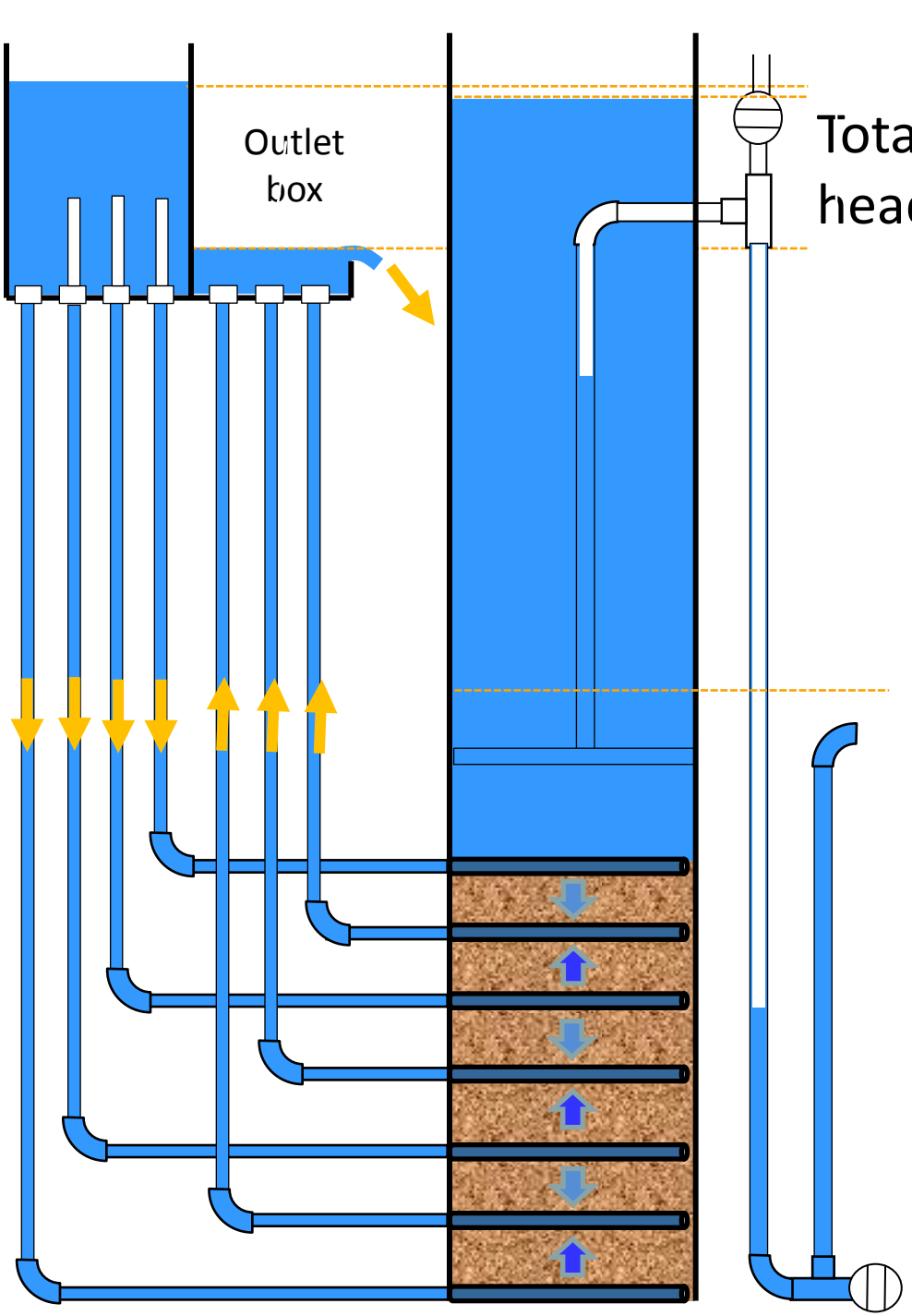


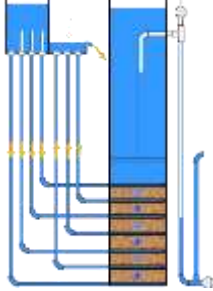


Begin Filtration cycle

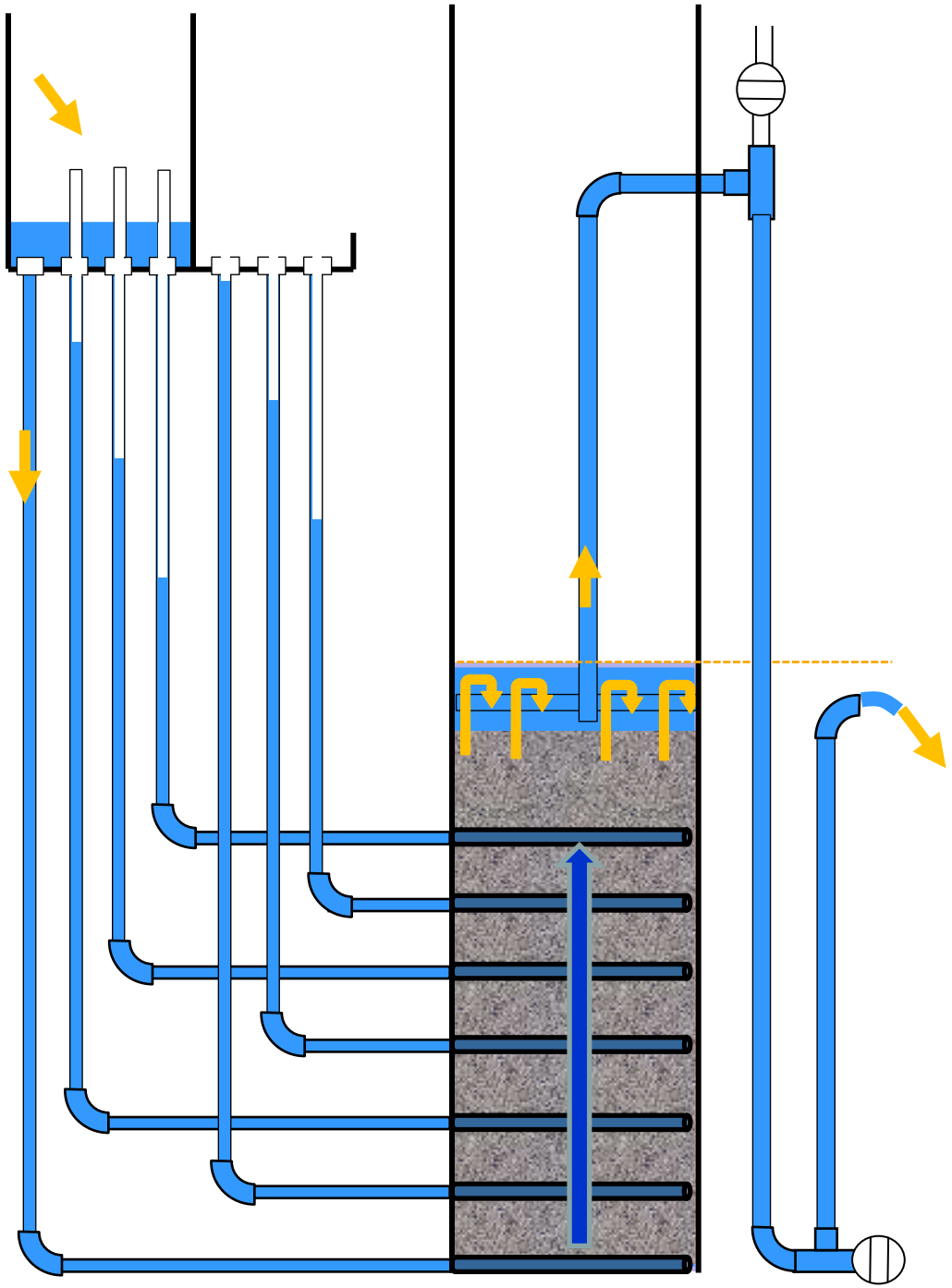


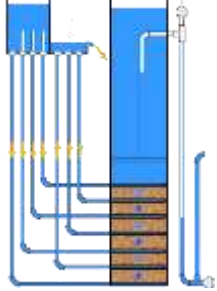
End Filtration cycle



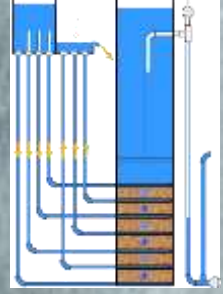


Backwash cycle





SRSF without sand showing slotted pipe system



SRSF during backwash

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Stacked Rapid Sand Filter

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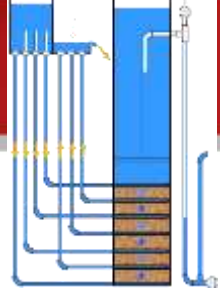
1/6 the size, no electricity



Inlet Box - Water arriving from sedimentation tanks

Outlet Box – Filtered water leaving for distribution tank

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SRSF Controls: Electro-Mechanical or Fluidics

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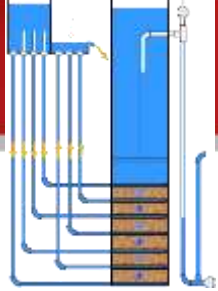
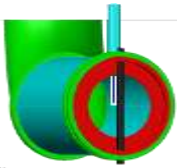


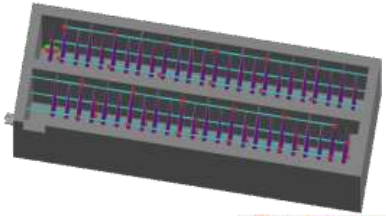
AguaClara Technologies

- Chemical dosing

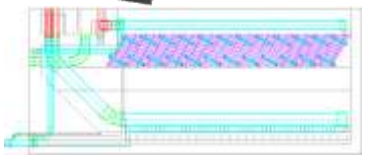
- Rapid Mix



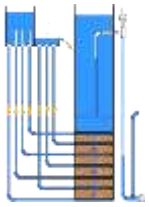
- Flocculator



- Sedimentation



- Filtration



- Conclusions

AguaClara in Honduras

San Nicolas 2014

Atima 2012

Under construction

Agalteca 2010

“Cuatro Comunidades ” 2009

Marcala 2008/2011

Tamara 2008

Under construction

Ojojona 2007

Alauca 2011

AguaClara

Three Key Innovations

- AguaClara is open source engineering:
  - Many inventions, continuous R&D, **ZERO patents**
  - Our technologies are described on our website and published in the literature.
  - Our example designs are available on the web! http://aguaclara.cornell.edu/design/
- Our technologies **use ZERO electricity** (except for batteries in the turbidimeters)
- Our plant **performance data is online** http://aguaclara.cornell.edu/projects/data

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How Much Does it Cost?

CAPITAL COST

Less than *half* of package plants

$10,000 per L/s of capacity

or $30 per person

OPERATING COST

$5 per person per year

or $50 per **million** liters

ELECTRICITY COST

ZERO

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Reflections

- Technology and Engineering Philosophy matter!
- Infrastructure failures often have multiple causes and many of them are linked to design choices
- We design for Simplicity on the other side of Complexity

AguaClara

Thank you!

- Questions
- Connections between AguaClara and AMEC
- Potential applications of AguaClara technologies
- Next steps

- Contact Info
- mw24@cornell.edu