control of chlorine disinfection in off-grid rainwater tanks for potable use

ce 291 final project
may 2016
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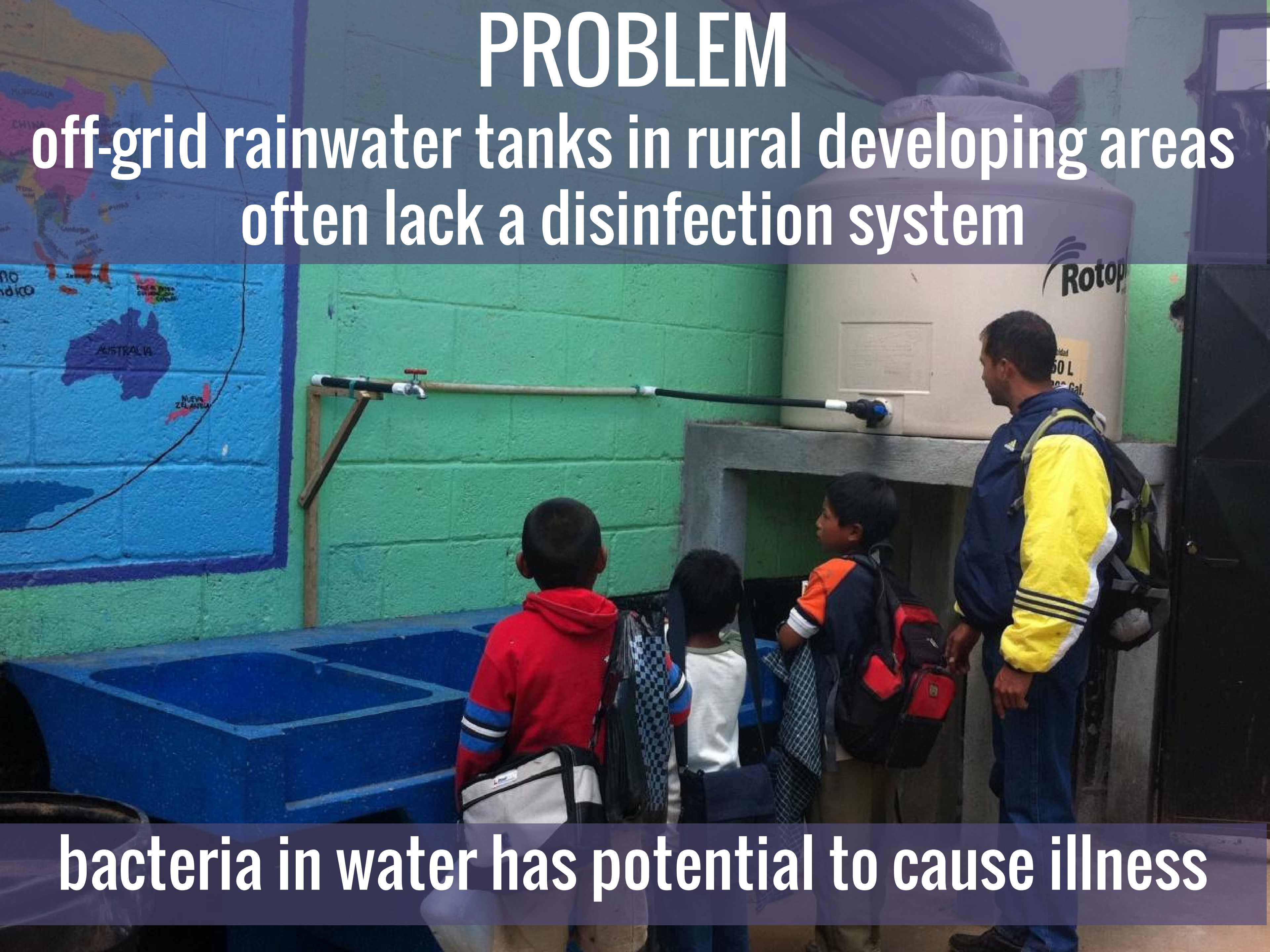
PROBLEM

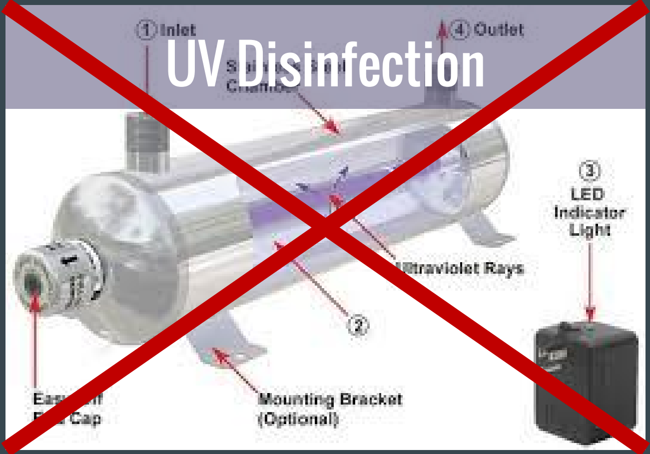
off-grid rainwater tanks in rural developing areas often lack a disinfection system



bacteria in water has potential to cause illness

OBJECTIVE

investigate modeling and control options for chlorine disinfection



concentration should stay in range:

0.5 - 5 ppm

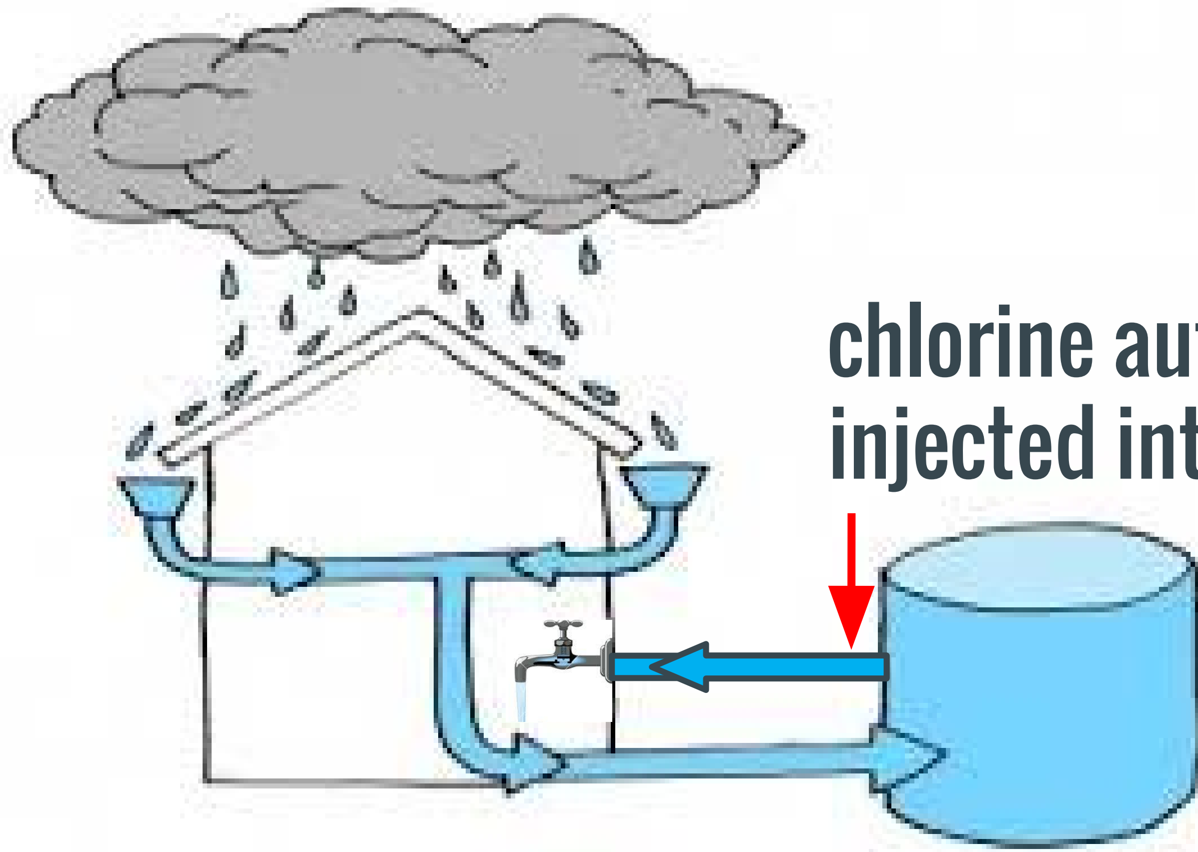
PDE

diffusion - convection - reaction

$$u_t = \underbrace{[D * u_{xx}]}_{\text{diffusion / dispersion}} - \underbrace{[c * u_x]}_{\text{convection / advection}} - \underbrace{[r * \mathrm{u}]}_{\text{reaction}}$$

generally cannot be solved by pen and paper

Option #1:
inject into pipeline



chlorine automatically injected into pipe

completely automated, yet more expensive

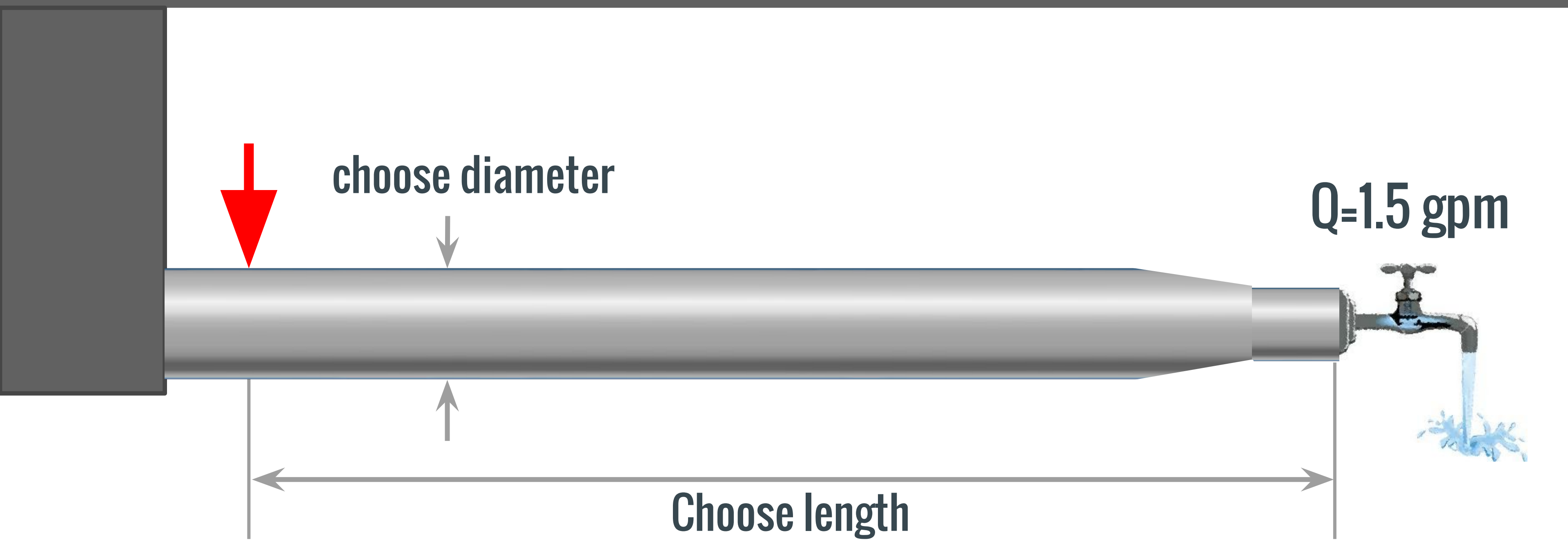
how much contact time is needed?

To achieve this level of Inactivation		This much contact time (minutes) is required for this Pathogen		
Log	**Percent**	***Cryptosporidium***	***Giardia***	**Virus**
0.5	67 %	Ineffective	9	0.25 (15 sec)
1.0	90	Ineffective	19	0.5 (30 sec)
1.5	96.7	Ineffective	28	0.75 (45 sec)
2.0	99	Ineffective	37	1
2.5	99.67	Ineffective	47	1.5
3.0	99.9	Ineffective	56	2
3.5	99.97	Ineffective	65	2.5
4.0	99.99	Ineffective	75	3

some say 2-minutes, others 30-minutes

sizing pipe to ensure contact time

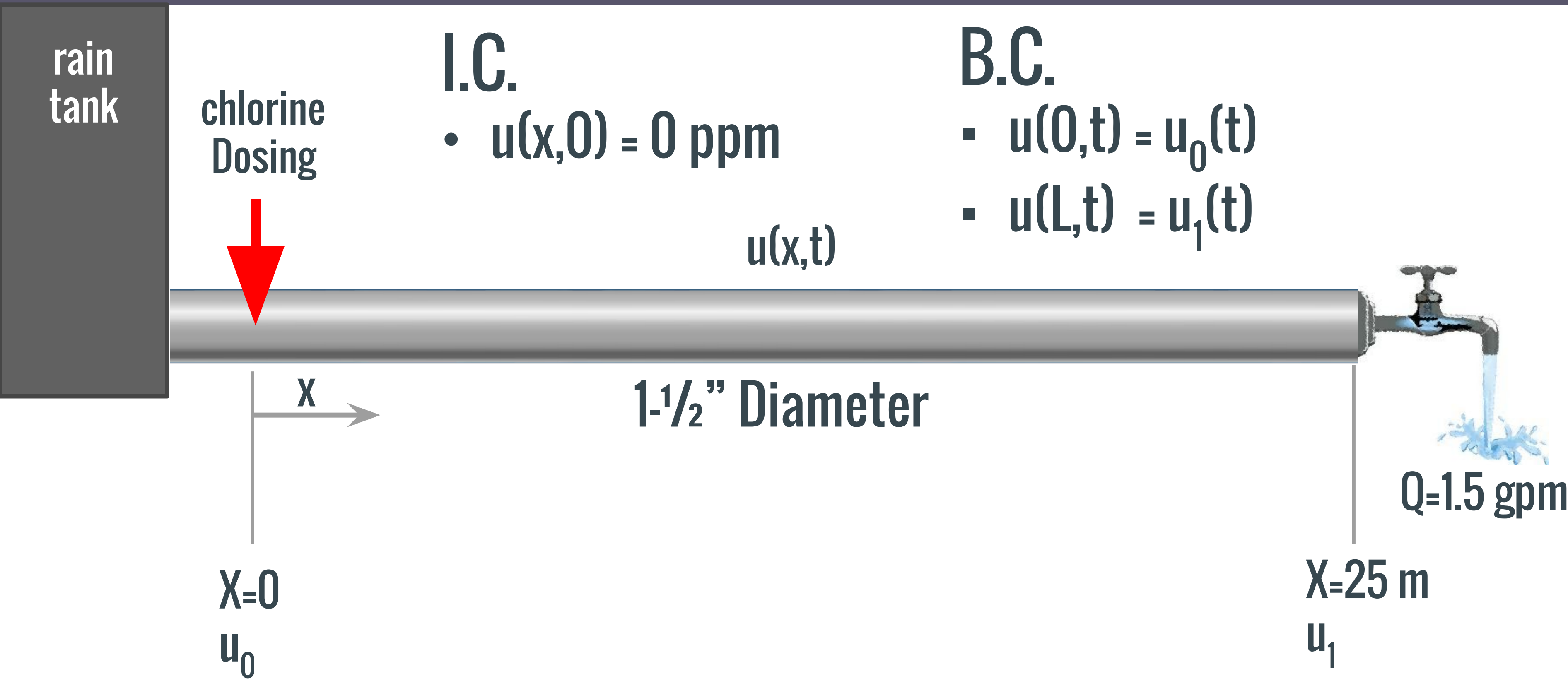
- 40-mm diam → 5 minutes → 25-m long → Volume = 7.5 gal
- 30-min: (depends on usage rate)



Option #1:
inject into pipeline

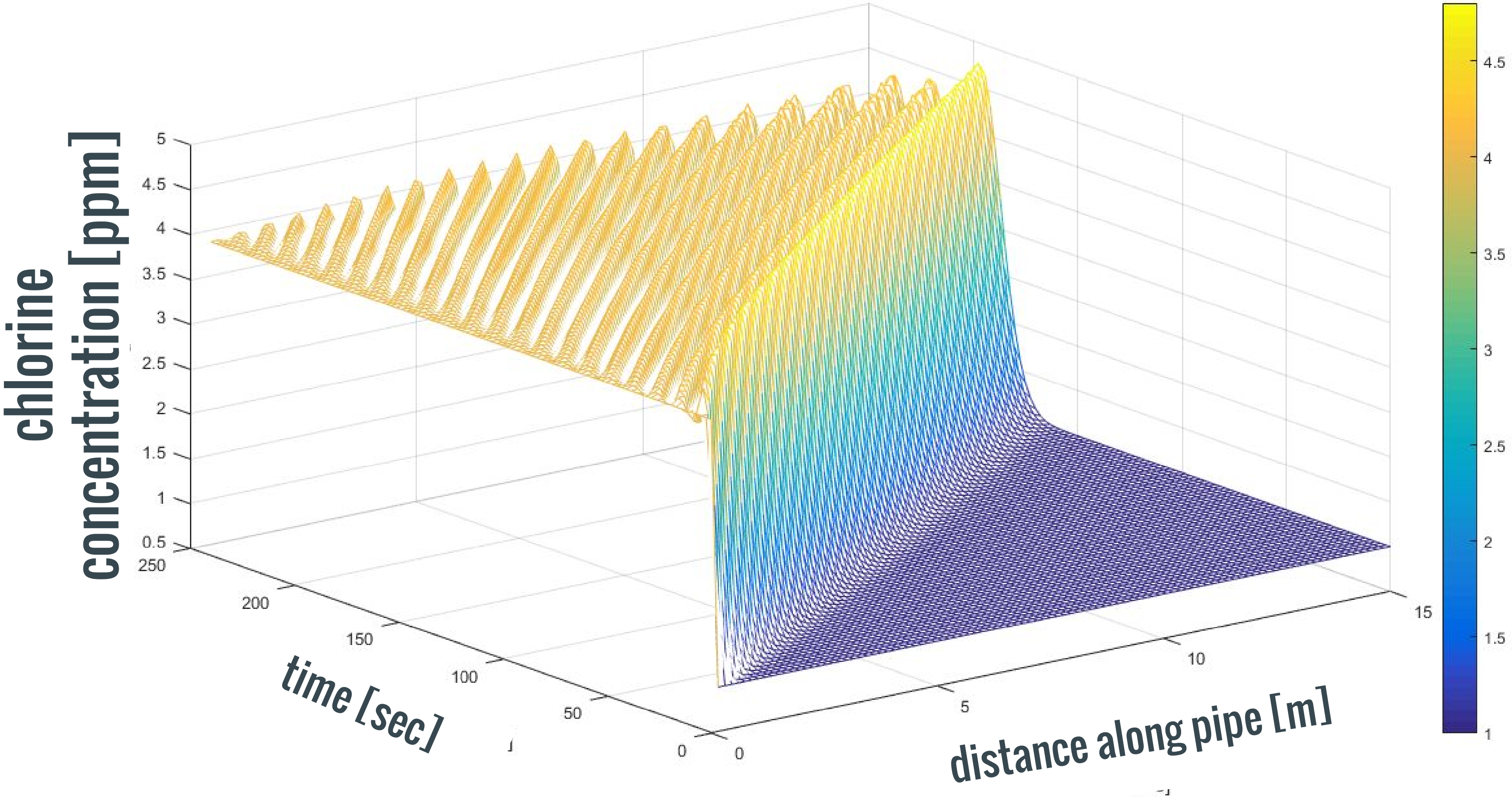
I.C.
- $u(x,0) = 0$ ppm

B.C.
- $u(0,t) = u_0(t)$
- $u(L,t) = u_1(t)$

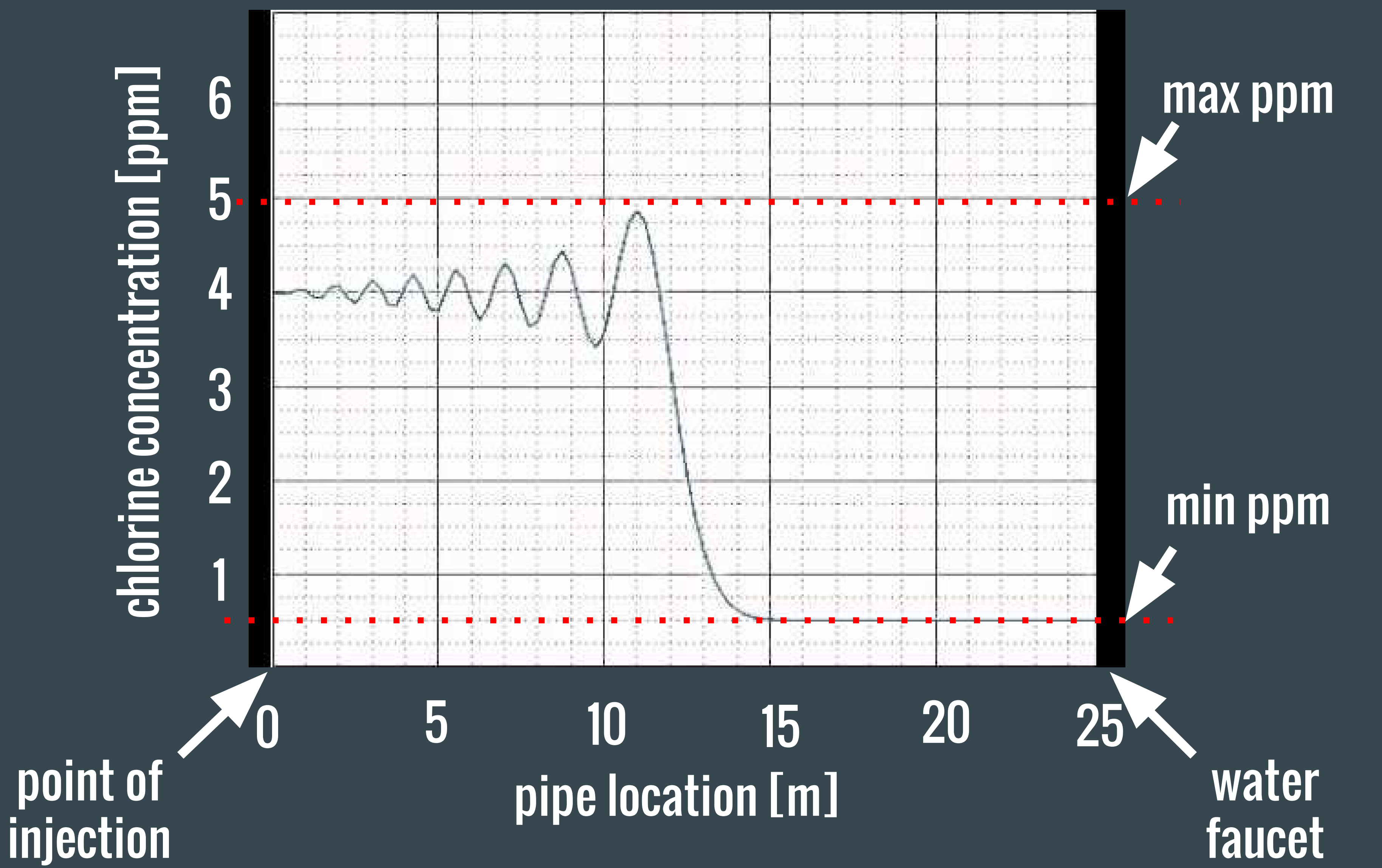


Eulerian Frame

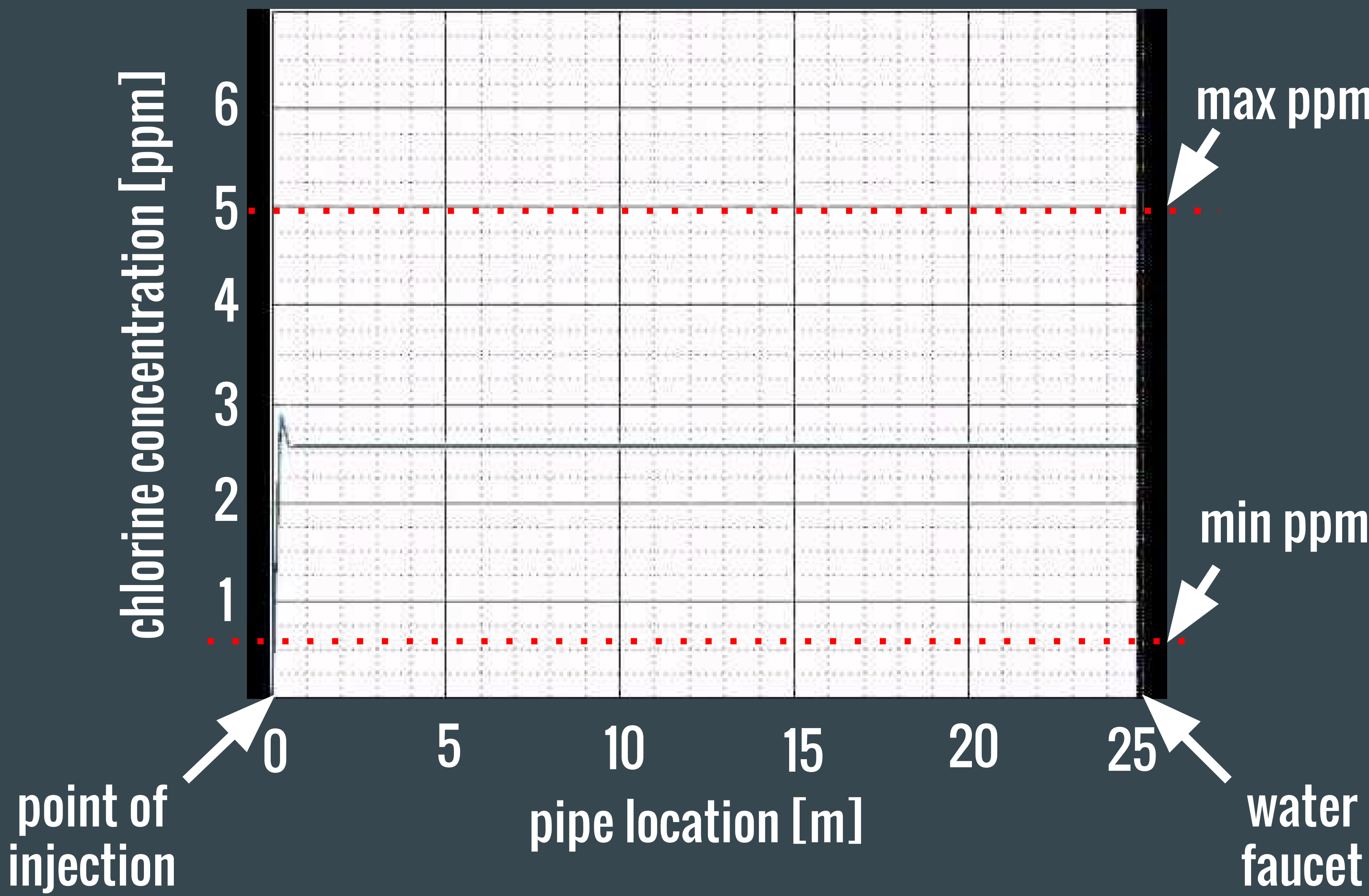
simulation of concentration in pipe



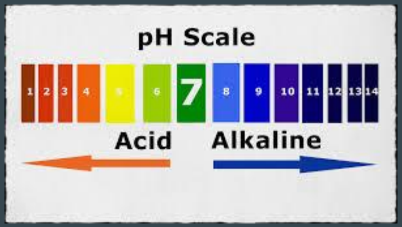
modeling concentration in pipe from 0 to 5 min



water stagnant for 24 hours



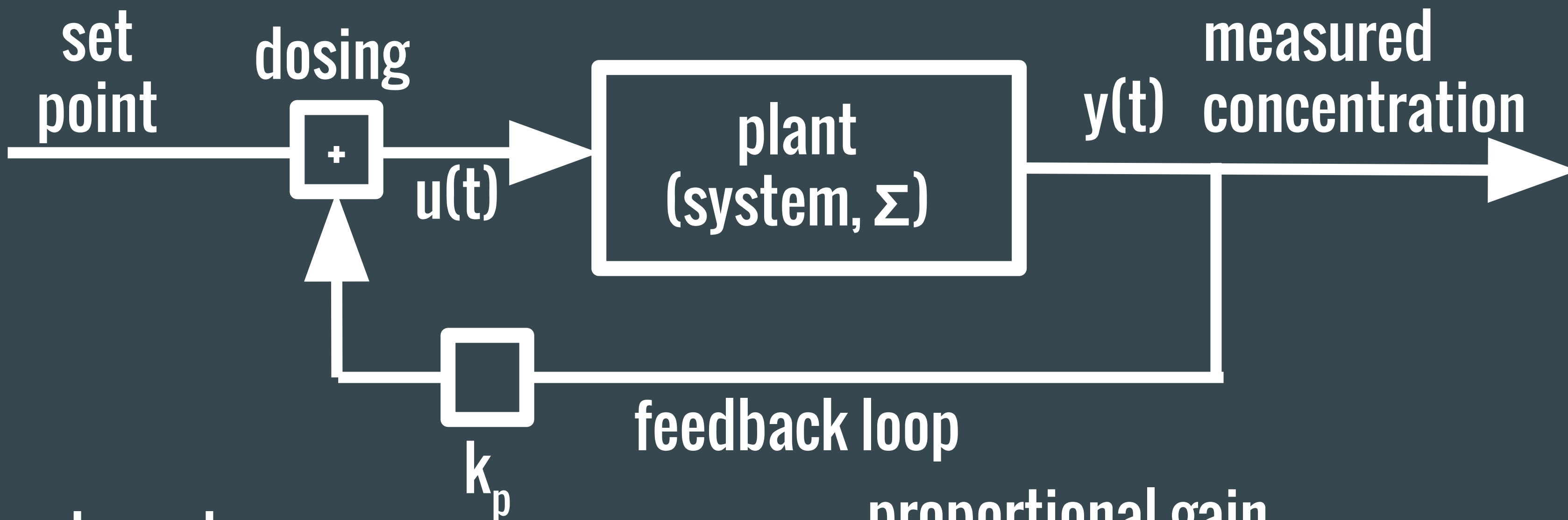
factors influencing concentration / decay

+ water temperature 
+ pH 

+ bacteria levels 
+ desired contact time 
+ flow continuity (daily usage) 

In future could update model based on a usage pattern

proportional controller



boundary control

proportional gain

error

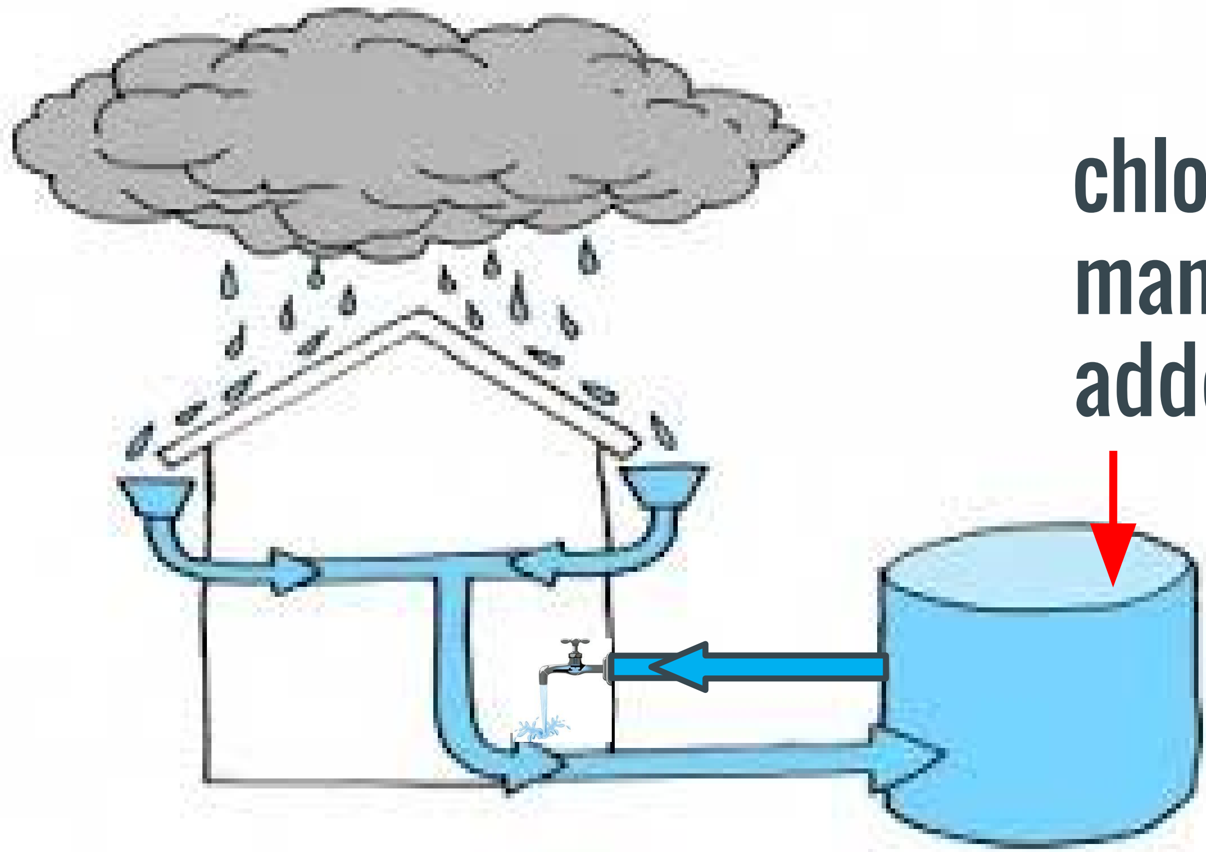
$$u(t) = k_p * e(t)$$

measured output

$$u(t) = k_p * [SP - y(t)]$$

set point = 0.5 ppm

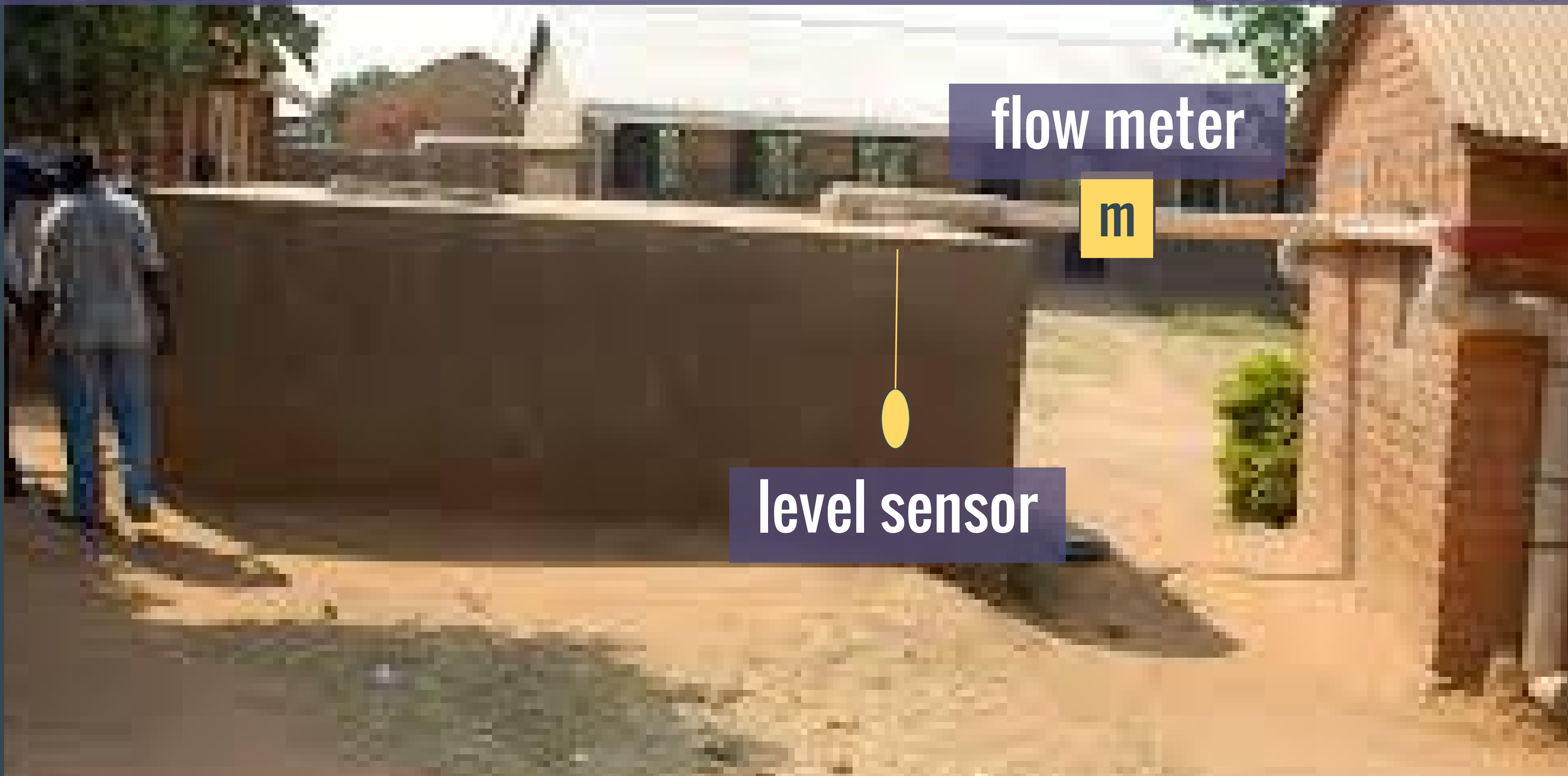
Option #2:
add to tank



chlorine manually added to tank

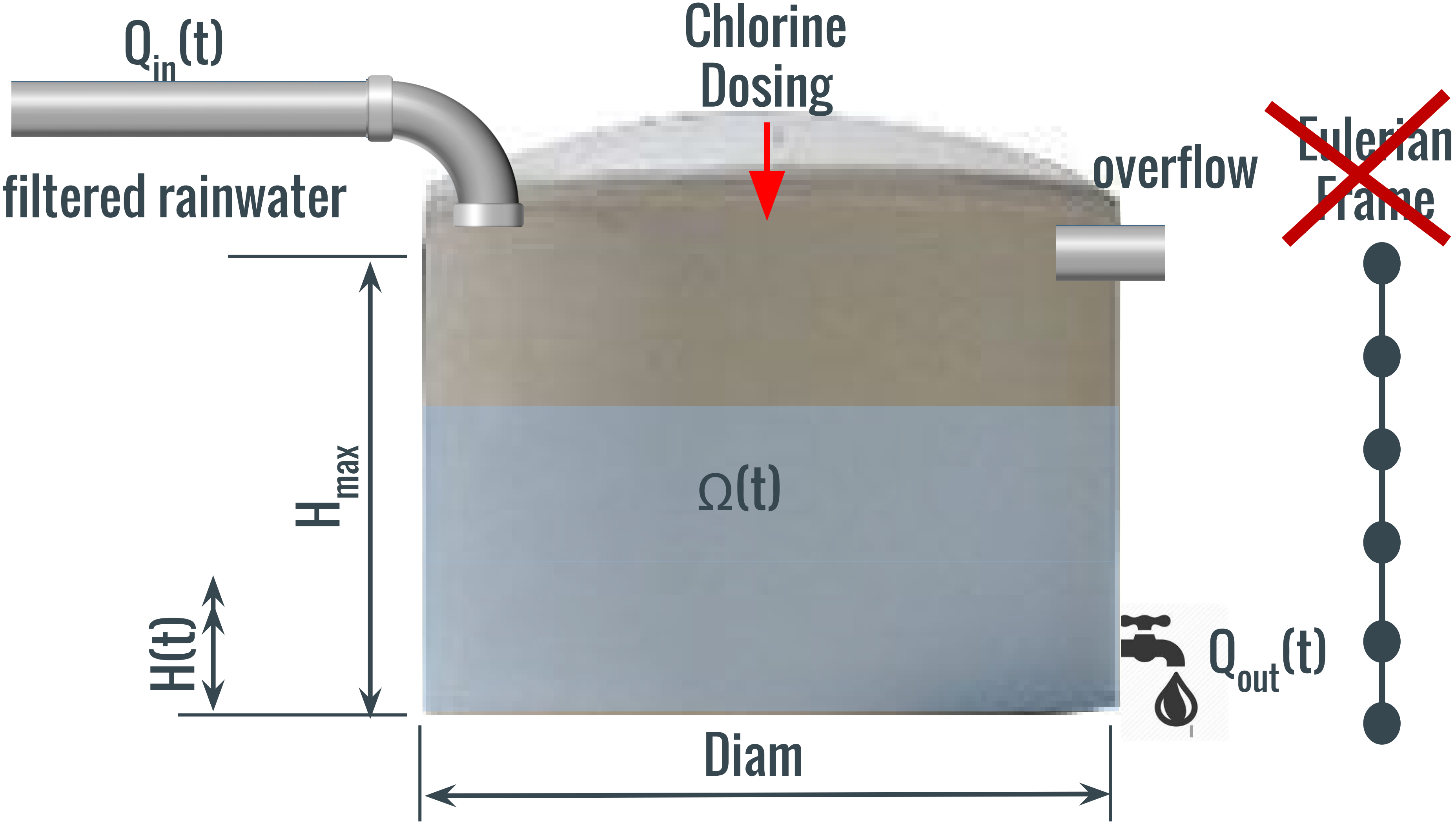
less expensive, but harder to control

rainwater system guidelines give vague tank disinfection instructions

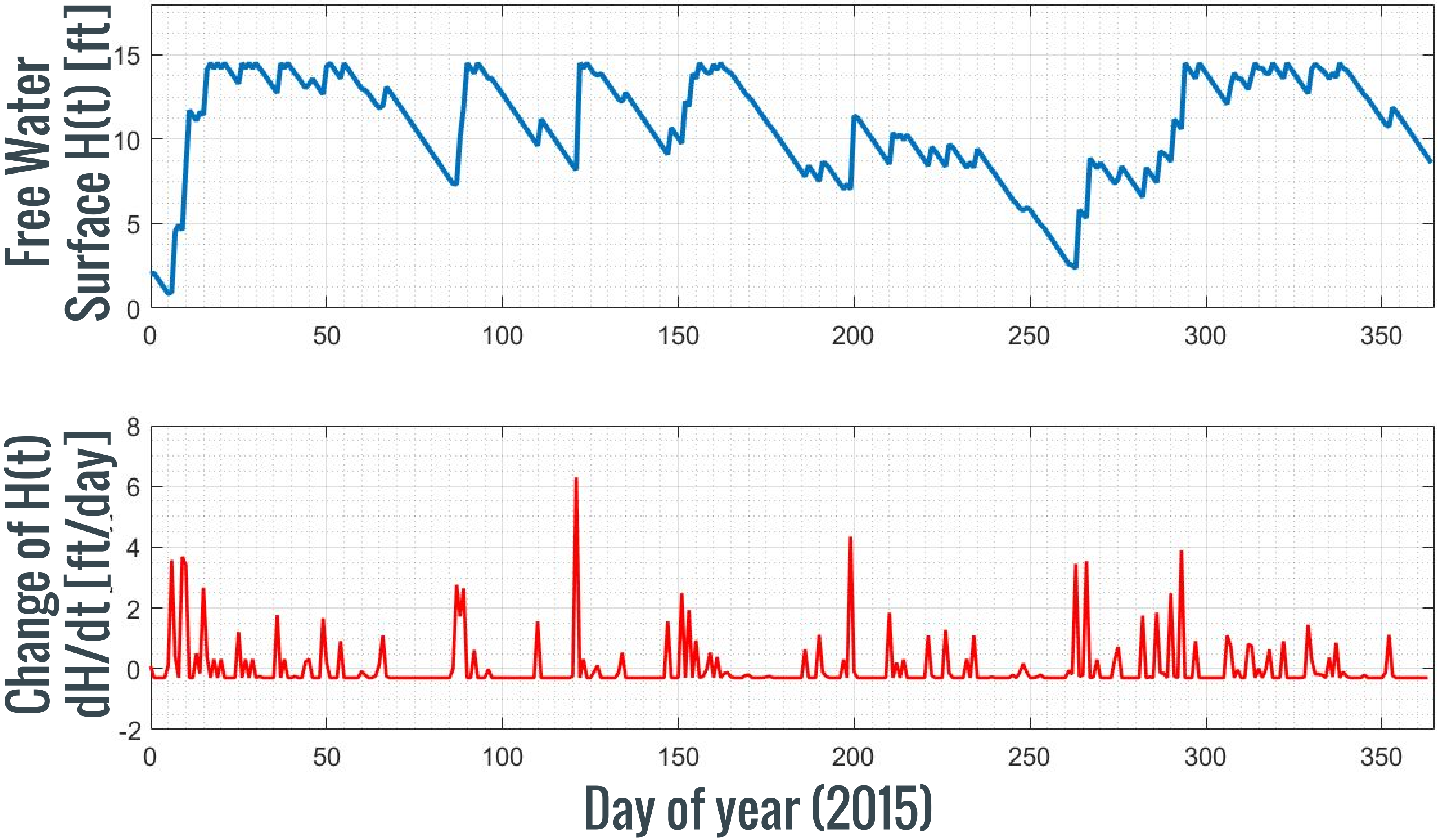


maybe we can precisely predict when to add chlorine

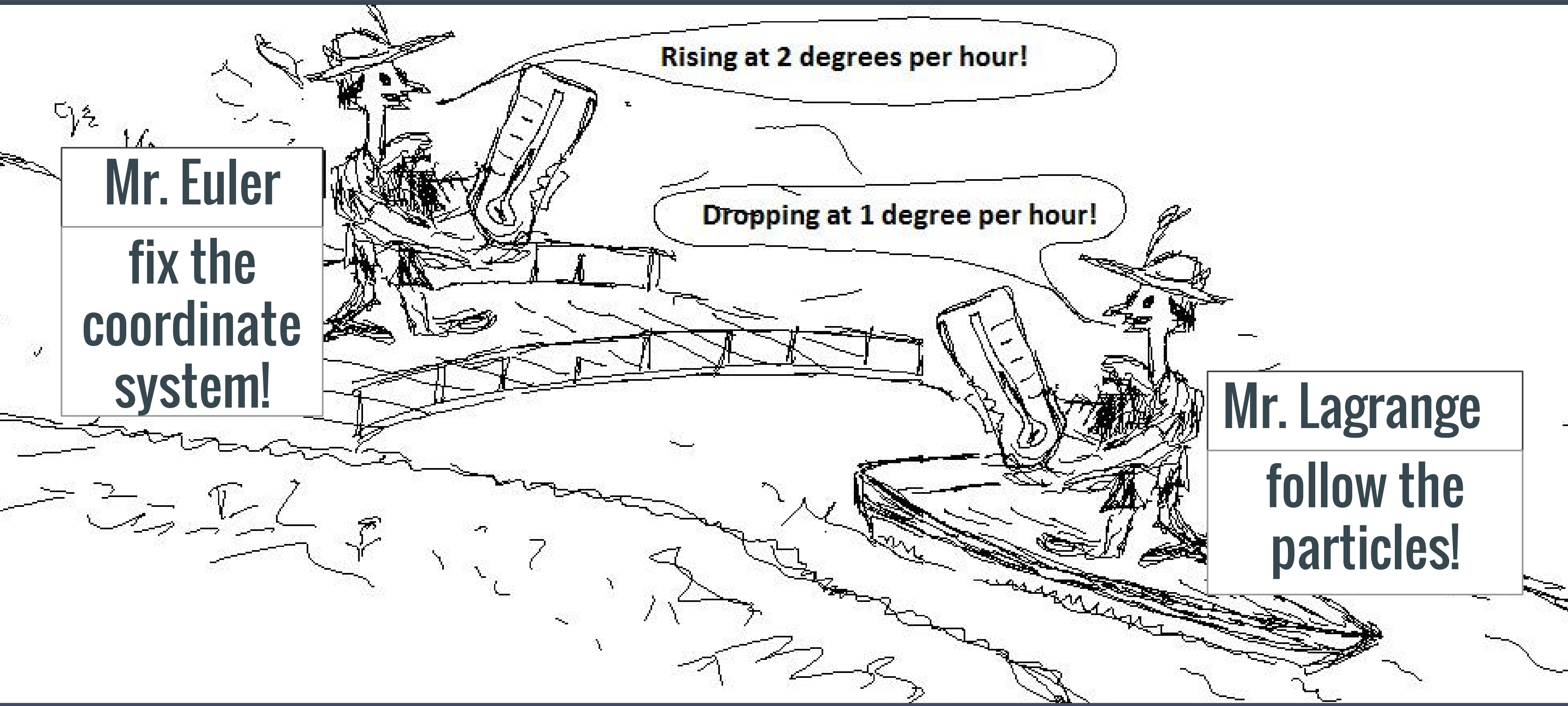
Option #2:
adding to tank



free water height changes
→ domain of problem, Ω, is time dependent



Domain Formulations: Eulerian is fixed, Lagrangian is moving



both methods have difficulties when boundary conditions need updating!

A HYBRID METHOD: Arbitrary Lagrangian-Eulerian (ALE) formulation

free surface velocity

$$v^f = \frac{d}{dt} H(t)\; e_3 = \frac{1}{A(t)} \left[Q_{in}(t) - Q_{out}(t) \right]$$

domain velocity

$$v^d(x,t) = v^f(t)$$

convective velocity

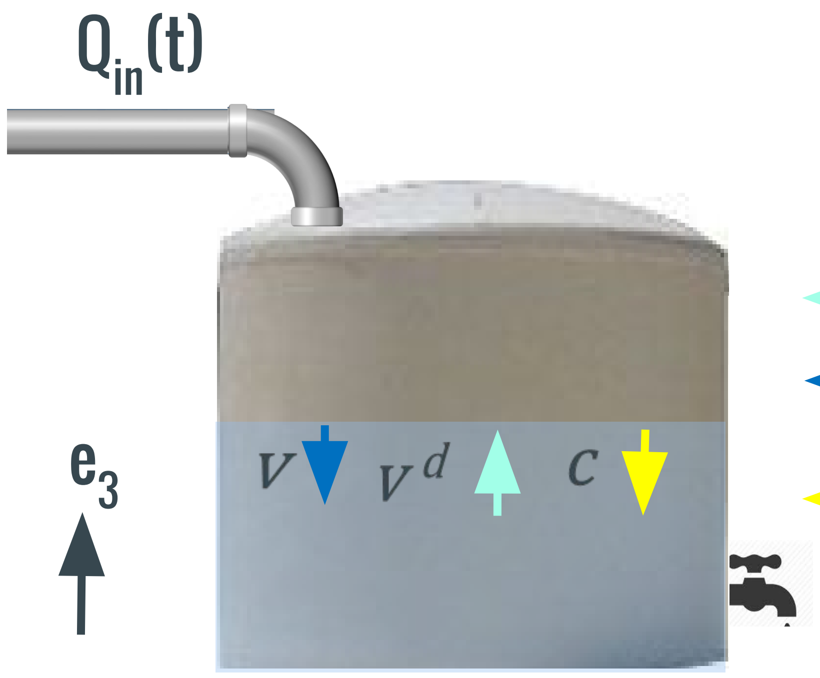
$$\underbrace{c = v - \mathrm{v}^d}$$

D-C-A

$$u_t = [\nabla \cdot (D\; \nabla u)\;] - [c * \nabla u] - [r * \mathrm{u}]$$

motion equations written w.r.t a reference

Equations coupled:
Diffusion-Convection-Reaction & Navier-Stokes



v^d - *domain velocity (in e_3)*

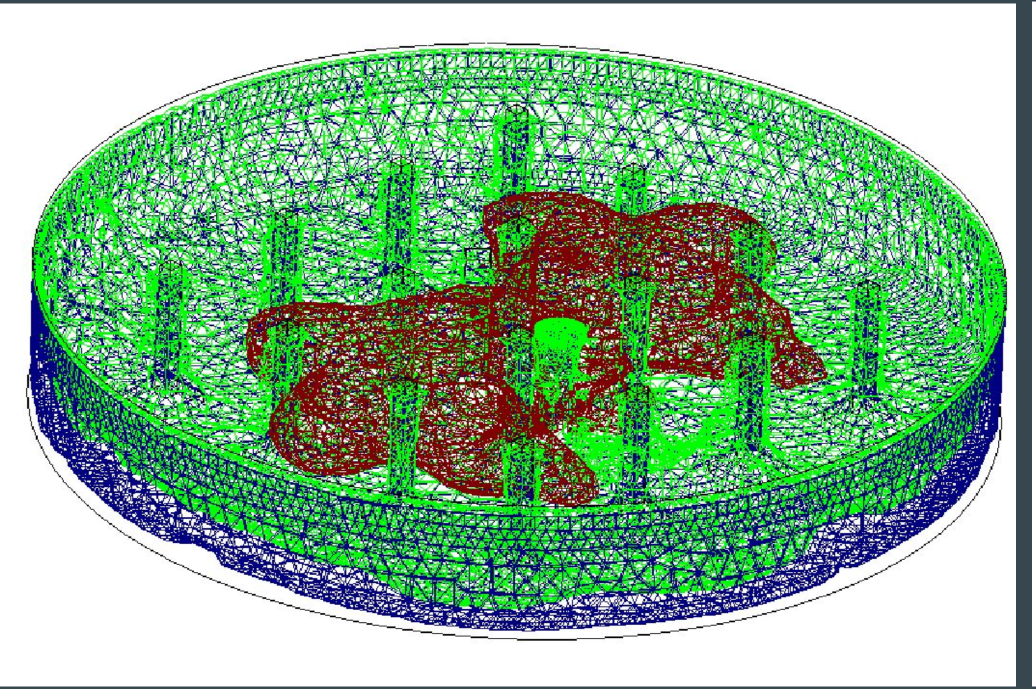
v - *velocity per navier-stokes*

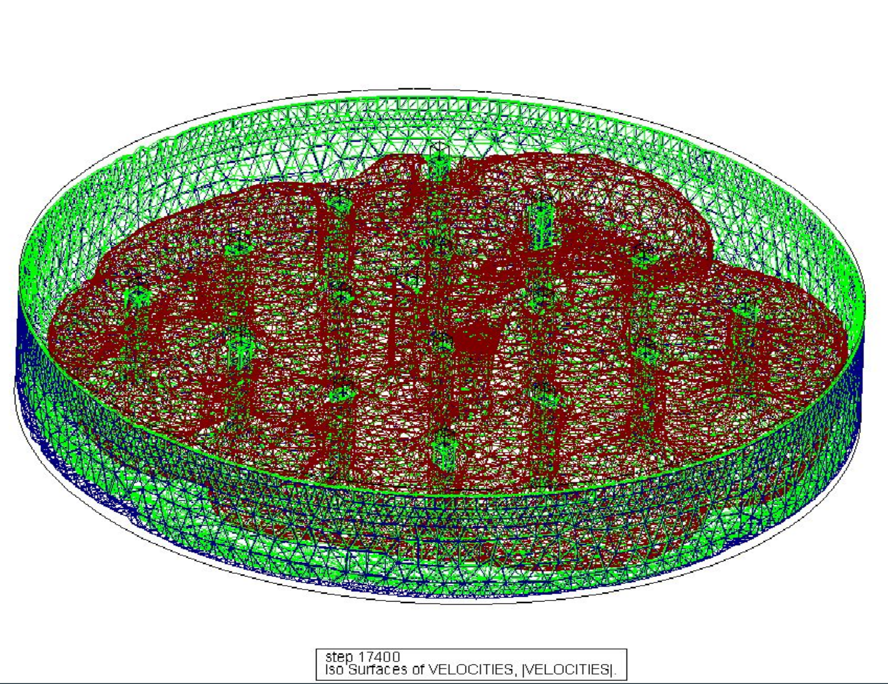
c - *convective velocity* ($c = v - v^d$)

Navier-Stokes

$$\frac{1}{r} * \frac{\partial(r v_r)}{\partial r} + \frac{1}{r} * \frac{\partial(v_\theta)}{\partial \theta} + \frac{\partial(v_z)}{\partial z} = 0$$

this modeling approach has been used by others on larger scale – may work for rain tanks too





chlorine disinfection simulation
(Codina, 2014)

SUMMARY

+ chlorine can be modeled with diffusion-convection-reaction eqn

+ a model prepared for 5-minute min contact time in pipe

+ pipe dosing becomes complex for 30-min contact time in pipe, and irregular, low-volume flow

+ proportional controller can be used to tune dosage

+ chlorine dosing in the tank can be modeled using ALE method

+ with a tank model and sensor data, precise chlorine requirement could be displayed or automated