Transport of microorganisms in soil and groundwater

Tht 282 lecture 29.10.2012
Arve Heistad
Associate Professor

2111
2005

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Content

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Introduction

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Definitions

- **Microbial pathogens:**

  Microscopic organisms; *viruses, bacteria, protozoa, (algae, fungi and subviral agents)* which may infect other organisms and cause disease. This strict definition does not include microorganisms that cause disease indirectly by toxin synthesis [1)]

1) WHO 2006

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Definitions

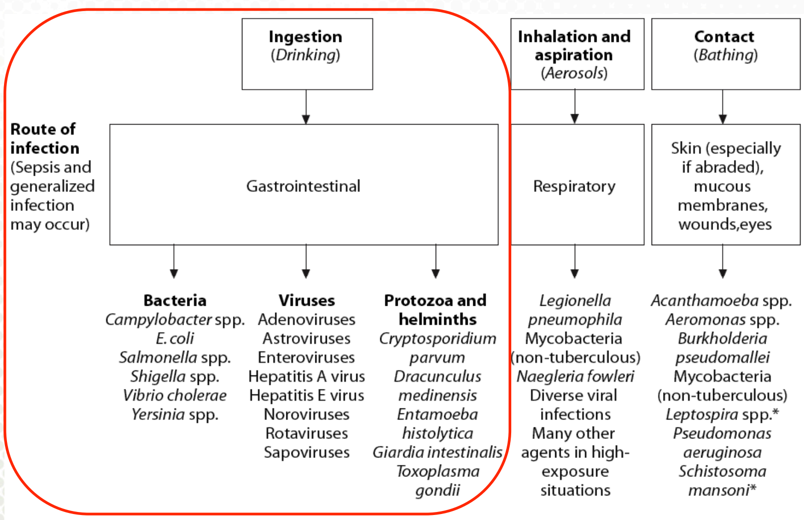
- **Migration and fate**

  Migration in this context means movement/displacement, with water as a vehicle (transport medium).

  The fate of a specific organism is here defined as the result of all factors affecting: pathogen concentration, inactivation, infectivity and virulence.

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Microbial pathogens in wastewater- faecal - oral transmission



* Primarily from contact with highly contaminated surface waters.

WHO 2004

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Microbial pathogens in wastewater - epidemiological data

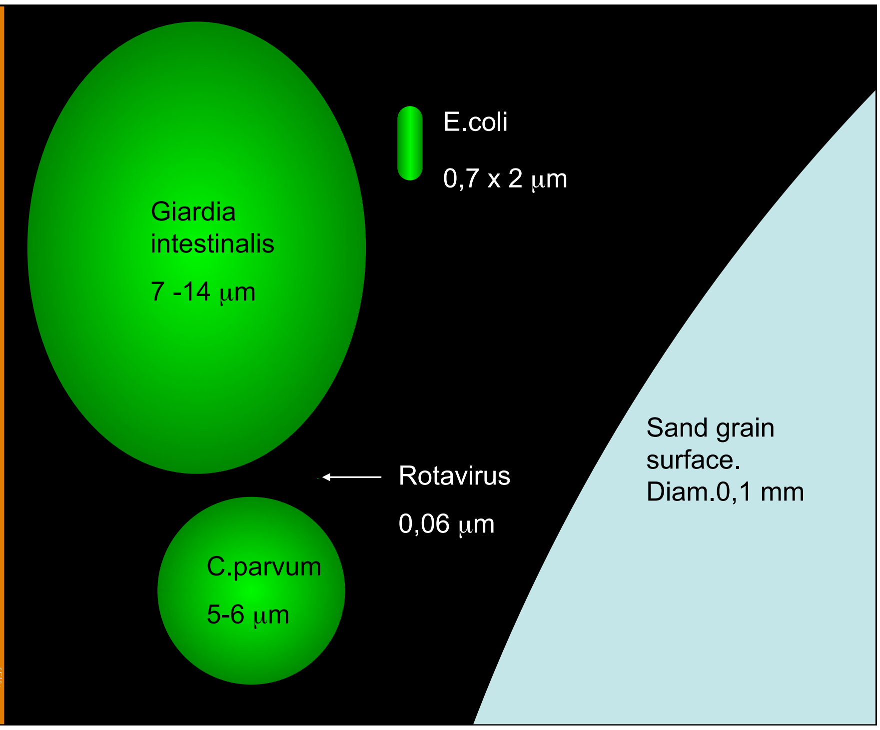
Pathogen	Incidence (per 100 000 people)	Under-reporting	Morbidity (%)	Excretion (per gram faeces)	Duration (days)	ID_{50}
Salmonella	42–58	3.2	6–80	10^{4-8}	26–51	23 600
Campylobacter	78–97	7.6	25	10^{6-9}	1–77	900
EHEC	0.8–1.4	4.5–8.3	76–89	10^{2-3}	5–12	1 120
Hepatitis A virus	0.8–7.8	3	70	10^{4-6}	13–30	30
Rotavirus	21	35	50	10^{7-11}	1–39	6
Norovirus	1.2	1562	70	10^{5-9}	5–22	10
Adenovirus	300	–	54	--	1–14	1.7
Cryptosporidium	0.3–1.6	4–19	39	10^{7-8}	2–30	165
Giardia	15–26	20	20–40	10^{5-8}	28–284	35
Ascaris	15–25	–	15	10^4	107–557	0.7

Source: Westrell 2004

7

www.umb.no

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

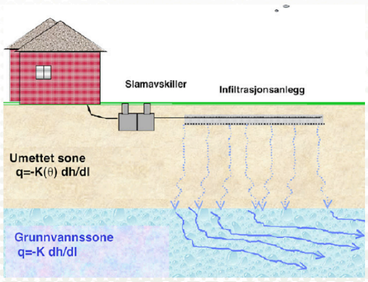


8

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Contamination pathways

- Onsite sanitation systems
  - Leaking joints and septic tanks
  - Clogged infiltration systems
  - Package treatment plants without polishing step
  - Improper site investigation
  - Inproperly designed systems
  - Limitations in treatment efficiency
  - Lack of management



9

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Contamination pathways

- Conventional systems
  - Leaking sewers
  - Overflows from pump stations during peak flows
  - Connection failures

10

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Contamination pathways

- Sludge utilization
  - Treated sludge used in agriculture, on golf courses, landscaping and as top cover on landfills.
  - Energy forest

11

www.umb.no

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Pathogen fate and transport in soil and groundwater

12

www.umb.no

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Advection - dispersion

- Advection is the transport of pathogens with the average water velocity, through the porous medium.
- Dispersion is the spreading of microbes
  - Mechanical dispersion
  - Diffusion
- The overall equation describing advection, dispersion and removal of microbial pathogens in a saturated medium is given by:

$$\frac{\partial C}{\partial t} + \frac{\rho_b}{n}\frac{\partial S}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x}$$

Removal — Dispersion — Advection

13

www.umb.no

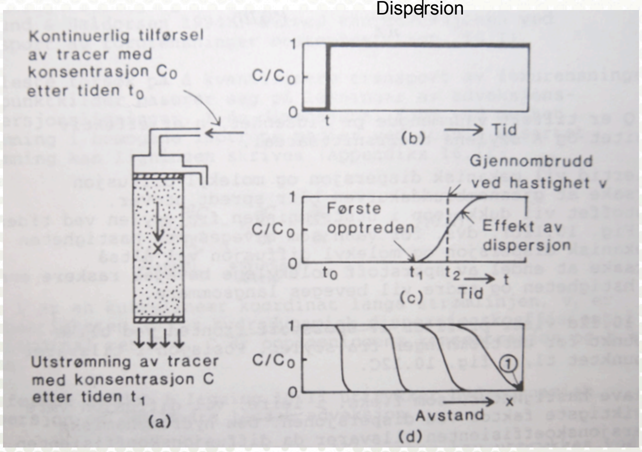
Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Advection - dispersion

- Effect of dispersion

$$\frac{\partial C}{\partial t} + \frac{\rho_b}{n}\frac{\partial S}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x}$$

Dispersion



14

www.umb.no

J.- O. Englund

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Advection - dispersion - removal

- Removal of pathogens

$$\frac{\partial C}{\partial t} + \frac{\rho_b}{n}\frac{\partial S}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x}$$

Removal

Irreversible sorption: $\frac{\rho_b}{n}\frac{\partial S}{\partial t} = k_{att}C \longrightarrow C(x) = C_0 exp\left(-k_{att}\frac{x}{v}\right)$

Reversible sorption: $\frac{\rho_b}{n}\frac{\partial S}{\partial t} = k_{att}C - \frac{\rho_b}{n}k_{det}S$

Inactivation (1st order): $C(t)=C_o e^{-\gamma t}$

15

www.umb.no

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Advection - dispersion - filtration

- Removal of pathogens

$$\frac{\partial C}{\partial t} + \frac{\rho_b}{n}\frac{\partial S}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x}$$

Removal

Irreversible sorption: $\frac{\rho_b}{n}\frac{\partial S}{\partial t} = k_{att}C \longrightarrow C(x) = C_0 exp\left(-k_{att}\frac{x}{v}\right)$

Classical colloid filtration theory

$$k_{att} = \frac{3(1-n)v}{2d_c}\eta_o\alpha$$

n is porocity, d_c is the filter medium grain size (collector diameter) and η_o is the single collector contact efficiency. α (attachment efficiency) represent the surface attachment step, the fraction of collisions that ends with attachment.

16

www.umb.no

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Colloid filtration

$$k_{att} = \frac{3(1-n)v}{2d_c}\eta_o\alpha$$

$$\eta_o = \eta_D + \eta_G + \eta_I$$

$$\eta_I = 0.55 A_S N_R^{1.675} N_A^{0.125}$$

$$\eta_G = 0.22 N_R^{-0.24} N_G^{1.11} N_{vdW}^{0.053}$$

$$\eta_D = 2.4 A_S^{1/3} N_R^{-0.081} N_{Pe}^{-0.715} N_{vdW}^{0.052}$$

17

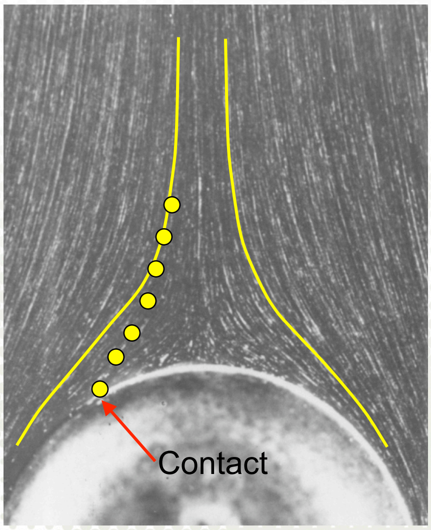
www.umb.no

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Colloid filtration

Sedimentation:

Particles leaving the streamline. Size and density dependent.



18

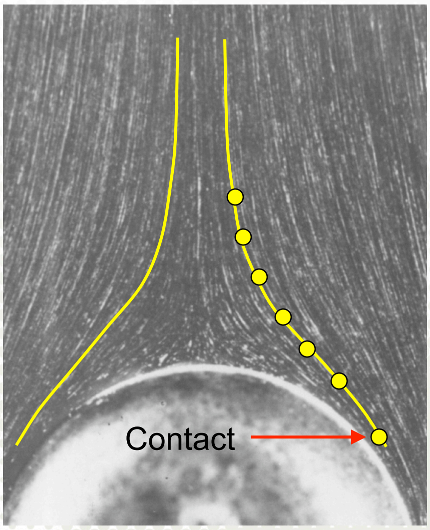
www.umb.no

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Colloid filtration

Interception:

Particles striking the collector just by following the streamline.

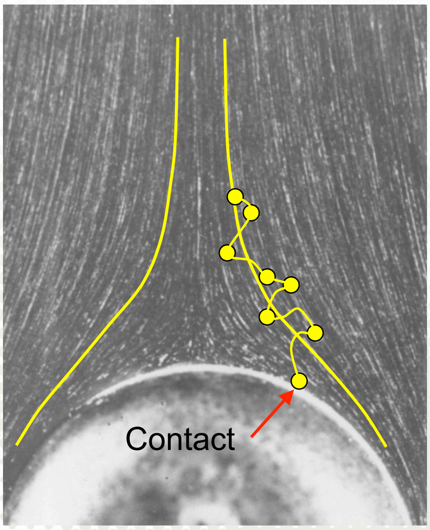


Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Colloid filtration

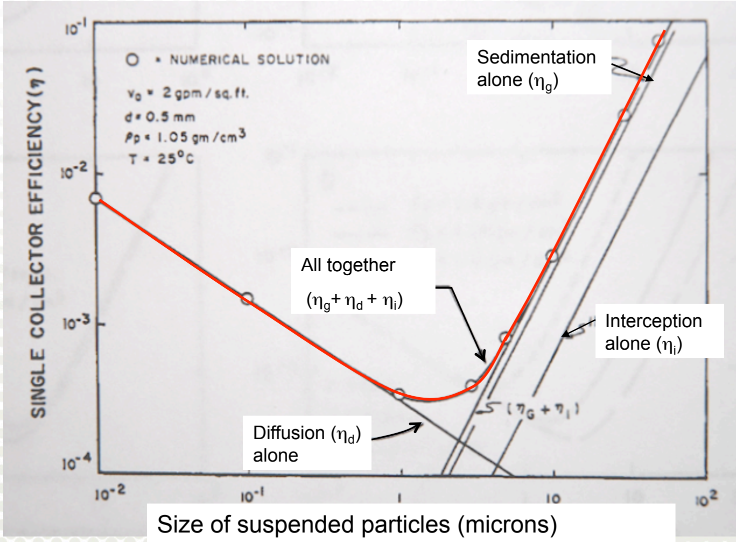
Diffusion:

Contact because of random Brownian movement



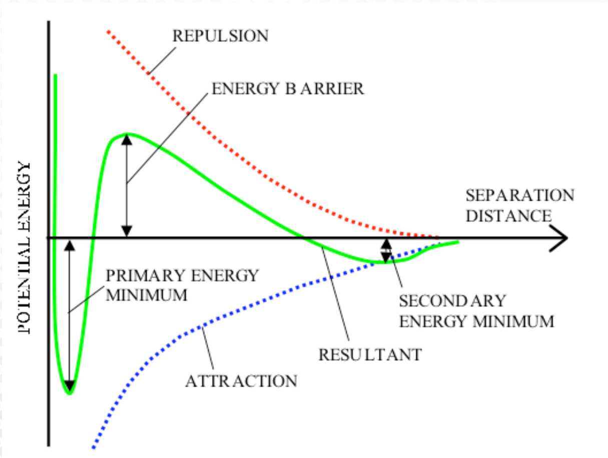
Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Colloid filtration - size effects



Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Colloid filtration theory breaks down under unfavorable deposition conditions

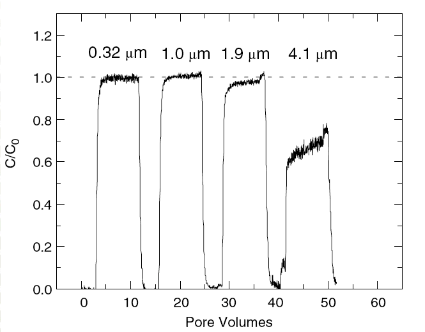


Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Physical straining

- Important for removal of the largest microorganisms (protozoa and helminths)

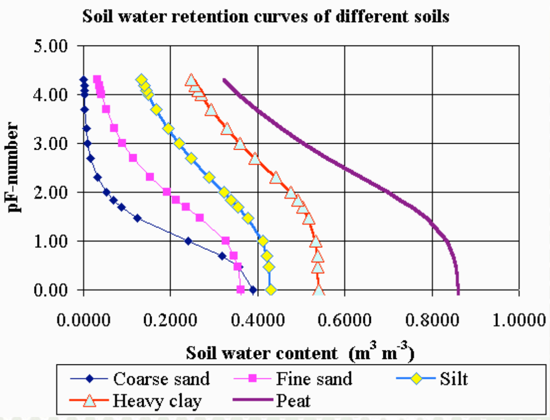
When the ratio of the particle diameter to the median grain diameter, $d_p/d_c > 0.05$

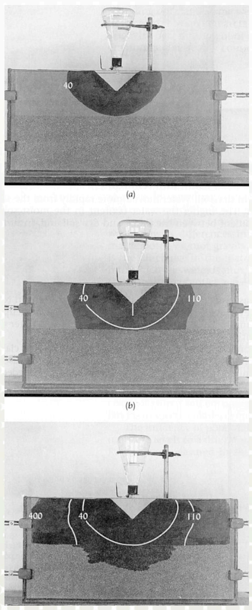


Example: Breakthrough curves for latex particles in DI water, filtered through quartz sand (d=0.21 mm), approach velocity 0.042 cm/s (**Tufenkji et al. 2004**)

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Unsaturated flow

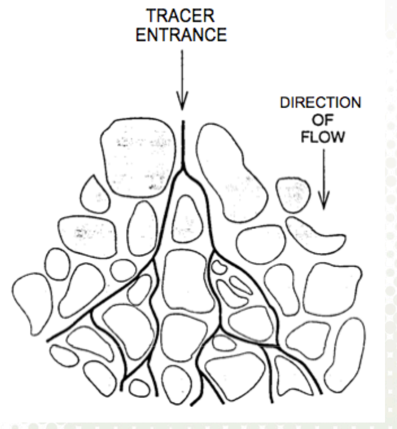




www.water.tkk.fi/.../ www_book/sgh_7pf.htm

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Unsaturated flow



Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Inactivation

- **Highest inactivation and removal in top soil (unsaturated flow)**
  - Biological activity (biofilm), predation and competition
  - Fluctuating soil moisture content and rapid temperature changes
  - Exposure to air-water interface
  - Thin film flow facilitates contact (attachment)

Die-off rates in source separated urine

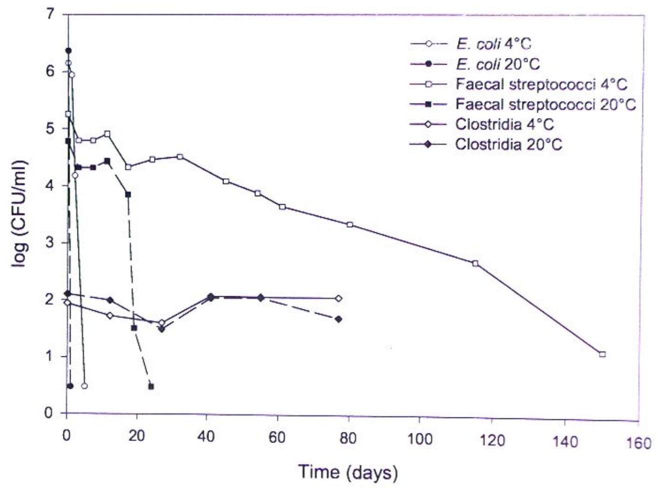


Figure 11. Inactivation of *E. coli*, faecal streptococci and *C. perfringens* spores (c source-separated human urine (pH 9) at 4°C and 20°C.

C.Høglund

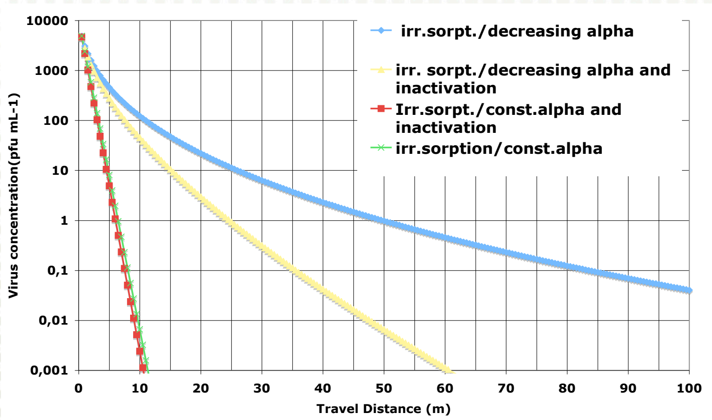
Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Constant vs. decreasing attachment efficiency, α

Example: d_p=60 nm, v_d=0.2 m d^{-1}, n=0.35, d_c=0.9 mm, T=277.15 K, λ=0.02 day^{-1}

Attachment efficiency, α=**0.0035 (constant)**

Attachment efficiency, **α(x)=0.0023 X $^{-0.6234}$ (decreasing with distance X)**



28

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

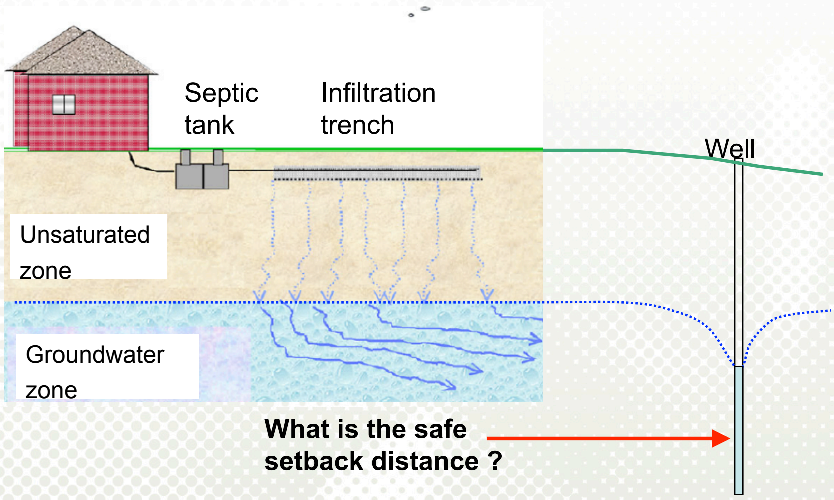
Practical application

29

www.umb.no

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Safe setback distance



Modified from Siegrist et al. 2000

30

www.umb.no

Arve Heistad, IMT
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Example Discharge from two different onsite treatment plants.

- Assessing risk of Adenovirus infection when consuming well water
  - Biological/chemical package teatment plant without polishing step
  - Compakt filterbed

Hazard Assessment

- One family member is infected by Adenovirus and is sick.
- The patient excrete 150g faeces with 10^{11} Adenoviruses/g faeces (Wadell, 1984), In a period of 14 days (Van et al. 1992) during one year.
- The daily discharge from the house is 600L .

Treatment efficiency

- Reduction of Adenovirus in the package plant was 1log (assumption) and in the filterbed 4log (Heistad et al. 2009).
- Further reduction of Adenovirus after discharge (sorption and inactivation)

Arve Heistad, IMT
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Package treatment plant without polishing

Assumed virus reduction: 90 % (1 log)

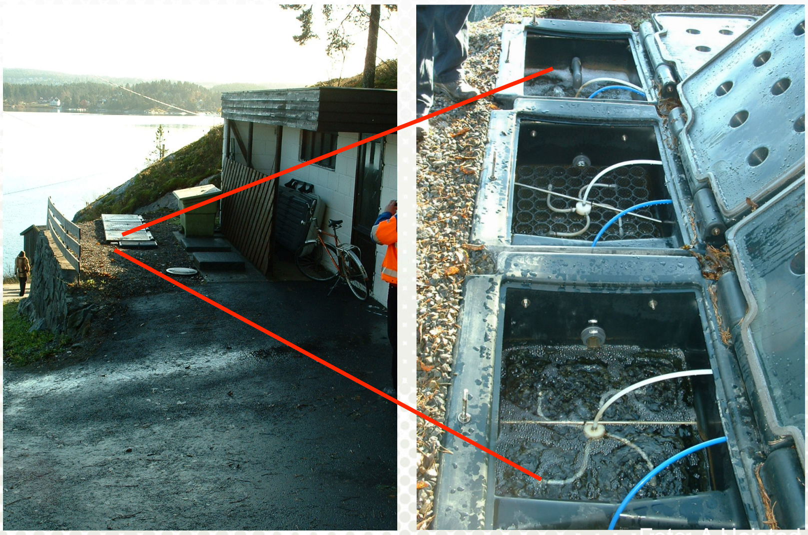
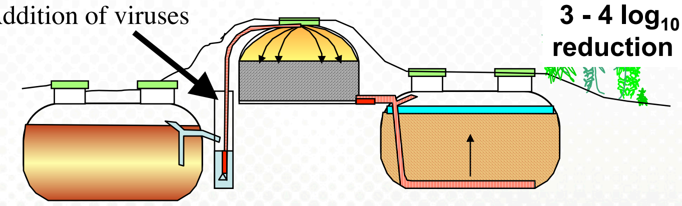


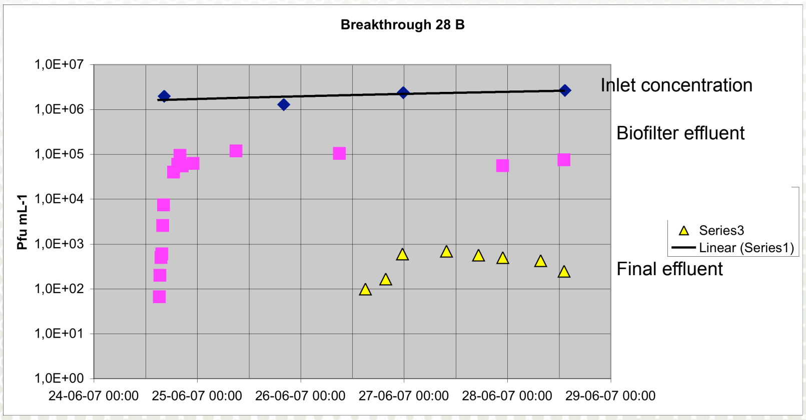
Foto: A.Heistad

Arve Heistad, IMT
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Compak tfilter

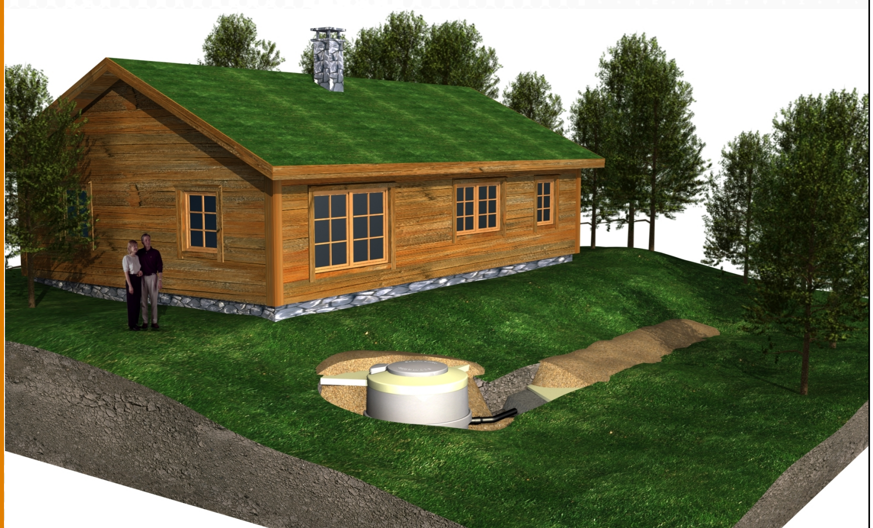


3 - 4 $\log_{10}$ virus reduction



Arve Heistad, IMT
Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Greywater treatment



Arve Heistad, IMT
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

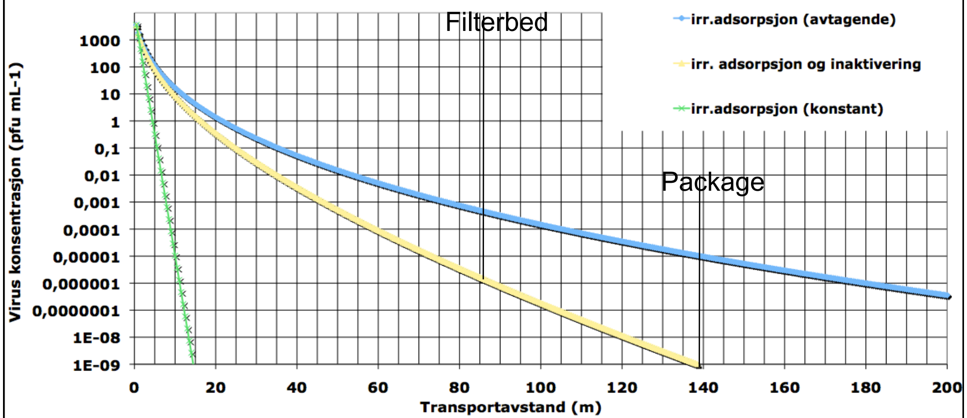
- **Exposure and dose-response assessments**
  - Every person consume driking water from a well: 1.2L/d (Westrell et al. 2004) containing Adenovirus from the wastewater plant.
  - An exponential dose-response model was used to describe the relation between the dose ingested and the probability of infection (Haas et al. 1999). ***r*** was set as 0.417 (Haas et al. 1999).
- **Preliminary results**
  - To exceed the acceptable risik (WHO, annual acceptable infection risk=10^{-4}) for Adenovirus, we must consume 1.9 x 10^{-4} Adenovirus. This is equivalent to 1.58 x 10^{-7} Adenoviruses per mL well water (assuming daily water consumption 1.2L per person per dag.
  - The following concentrations of virus are discharged from the two treatment plants: Package plant: 2.5 x 10^{6} Adenoviruses per mL
  - Filterbed: 2.5 x 10^{3} Adenovirus per mL.

Arve Heistad, IMT
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

- To fulfill the goals (WHO) we must add further reductionsmålene for akseptabel helserisiko (WHO) må videre reduksjonen av virus etter rensing være:
-
  - Minirenseanlegg = 13 log (99,99999999999 %)
  - Filteranlegg =10 log (99,99999999 %)

Arve Heistad, IMT
NORWEGIAN UNI

Additional reduction in the saturated zone

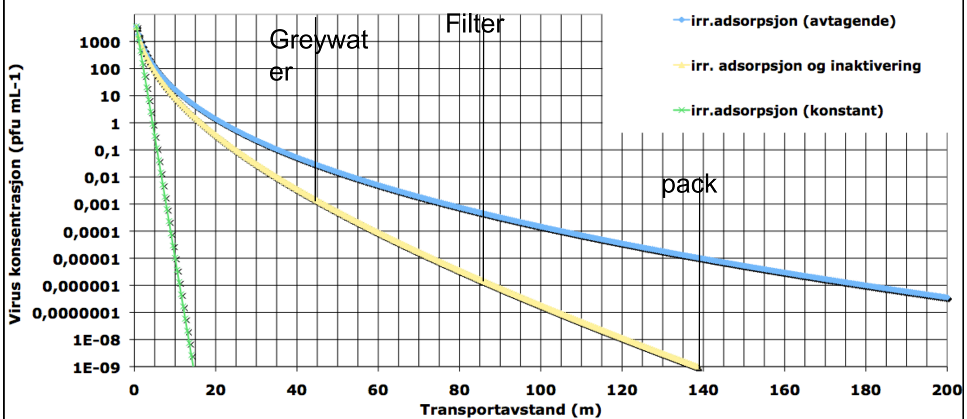


Package: 13 log .
Filterbed: 10 log .

www.umb.no

Arve Heistad, IMT
NORWEGIAN UNI

Greywater treatment



Package: 13 log .
Filterbed: 10 log
Greywater: 7 log .

www.umb.no

Arve Heistad, IMT
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

GUIDELINES FOR DRINKING-WATER QUALITY

Figure 7.2 Performance targets for selected bacterial, viral and protozoan pathogens in relation to raw water quality (to achieve 10^{-6} DALYs per person per year)

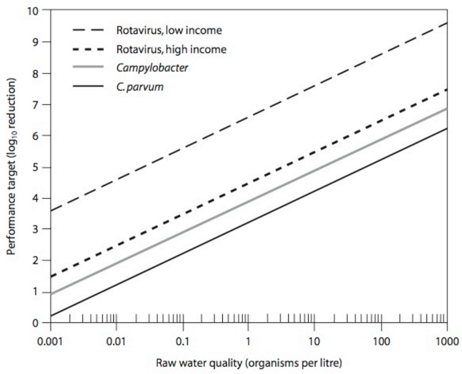


Table 7.4 Health-based targets derived from example calculation in Table 7.3

	Cryptosporidium	*Campylobacter*	Rotavirus[a]
Organisms per litre in source water	10	100	10
Health outcome target	10^{-6} DALYs per person per year	10^{-6} DALYs per person per year	10^{-6} DALYs per person per year
Risk of diarrhoeal illness[b]	1 per 1600 per year	1 per 4000 per year	1 per 11 000 per year
Drinking-water quality	1 per 1600 litres	1 per 8000 litres	1 per 32 000 litres
Performance target[c]	4.2 log_{10} units	5.9 log_{10} units	5.5 log_{10} units

[a] Data from high-income regions. In low-income regions, severity is typically higher, but drinking-water transmission is unlikely to dominate.
[b] For the susceptible population.
[c] Performance target is a measure of log reduction of pathogens based on source water quality.

WHO:

Drinking water treatment targets depending on the raw water quality

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Summary

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Summary

1. Large range of inactivation- and deposition rates among pathogenic microorganisms.

Viruses, parasitic protozoa more persistent than *E.coli.*

E.coli as the only faecal indicator is not recommended.

Viruses are the group of pathogens of major concern in relation to wastewater contamination of soil and groundwater.

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Summary

2. Unsaturated zone important for removal of microbial pathogens.

Predation, competition, inactivation and sorption are more efficient in the unsaturated zone, than in the groundwater zone.

Summary

3. Microbial pathogens are not only attached irreversibly, to one type of sorption sites.

Detachment may occur during heavy rainfall caused by a decrease in the ionic strength and an increase in soil water content.

The attachment rate coefficient is not constant with travel distance, but rather decline in a power-law fashion.

Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES

Summary

4. Risk reduction the ultimate goal

Risk assessment based on precise transport estimates.

- Deposition parameters
- Dose-response relations
- Realistic health targets

Risk reduction by optimization of technical and natural barriers, as well as management


Department of Mathematical Sciences and Technology
NORWEGIAN UNIVERSITY OF LIFE SCIENCES
Thank you for the attention !
45
www.umb.no