Water management in urban areas

Processes 2

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Content

- Stormwater runoff
- Hydraulic processes in surface water
- Water quality processes
- Exchange with the surroundings

Stormwater runoff

Source photo: http://blogs.oregonstate.edu/h2onc/ (R.M. Emanuel)

Stormwater runoff

Subprocesses

- Precipitation losses
  - Amount which doesn’t run off via the sewer system
- Retardation
  - Conversion, delay and flatting of inflow
- Discharge via groundwater
- Discharge via main drainage system

Stormwater runoff

Losses at unpaved terrain

- Interception
  - Horton: $I_i = a + b \cdot P^c$

Crop	a	b	c
Orchard	0.04	0.18	1.0
Ash (in forest)	0.02	0.18	1.0
Beech (in forest)	0.04	0.18	1.0
Oak (in forest)	0.05	0.18	1.0
Maple (in forest)	0.04	0.18	1.0
Willow (in forest)	0.02	0.40	1.0
Pine forest	0.05	0.20	0.5

Source: Kibler, 1982. Interception constants according to Horton

Stormwater runoff

Losses at unpaved terrain

- Interception
  - Horton: $I_i = a + b \cdot P^c$

- Infiltration
  - Green and Ampt: $f = K \dfrac{H_0 + H_c + L}{L} = \theta_f \dfrac{dL}{dt}$

$\theta_f = \theta_v - \theta_0$

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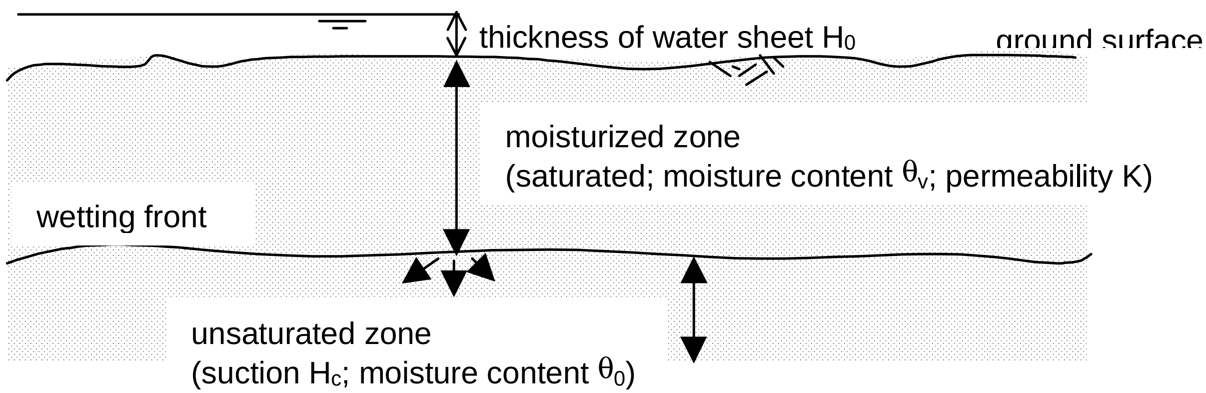
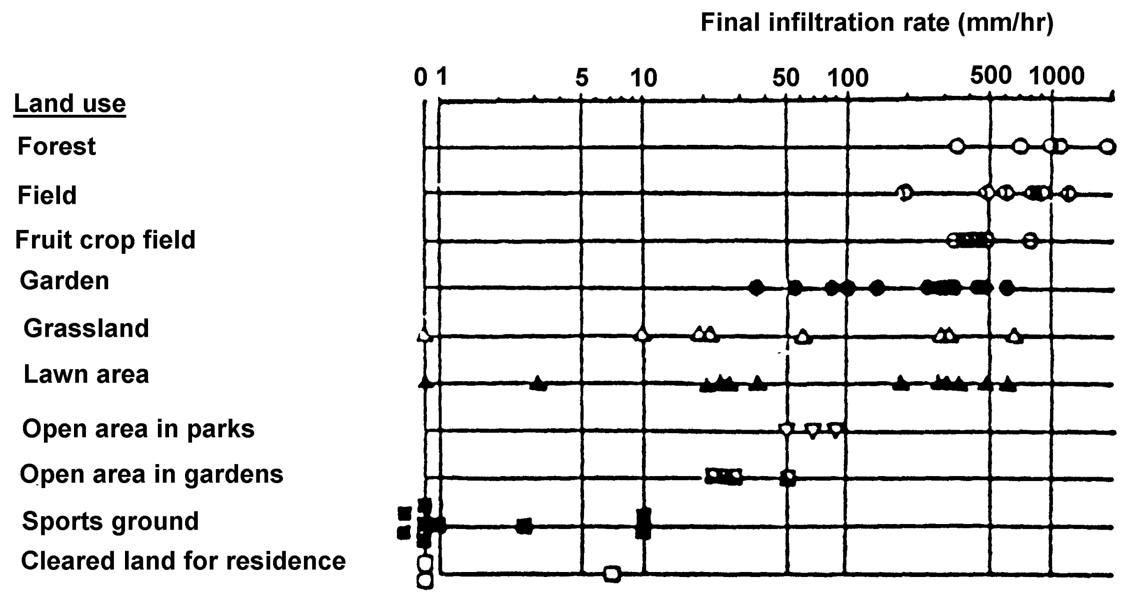


Stormwater runoff

Losses at unpaved terrain

- Infiltration intensity's
  - Horton: $f = f_e + (f_0 - f_e)e^{-kt}$

    f_e and f_0 are begin and end infiltration-intensity



Source: Ando, Takahashi, Kuan, 1984. Observed values of f_e for sandy clay soil in Tokyo

Stormwater runoff

Losses at unpaved terrain

- Depression storage

Nature of surface	Storage (mm)	Remarks	Source
Lawn	5 - 12	Recommended for design: 8 mm	Kibler, 1982
green belt, open field	5 - 15	Recommended for design: 10 mm	
general (ASCE)	6		
bare soil, mowed lawn	0.6- 2.5		Pecher, 1969
vegetated soils	2.5- 4		
General	0.645 / (I+0.084)	I = gradient of the ground (1:x)	Pfeiff, 1971

Stormwater runoff

Losses at unpaved terrain

- Depression storage

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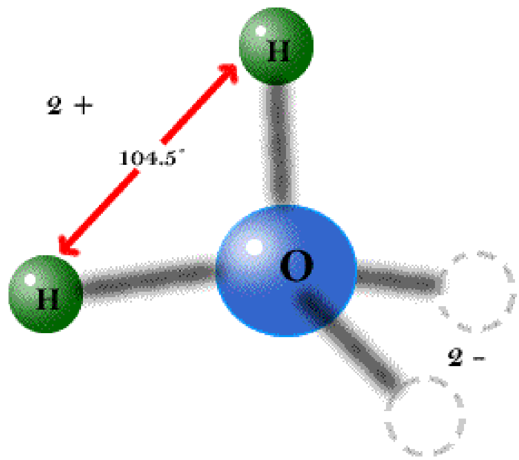
- Evapotranspiration
  - Energy balance

Stormwater runoff

Losses at paved terrain



- Moisturizing losses
  - Hygroscopic water, adhesion onto a material
  - Relative small amount;

Rough cement concrete	0.55 mm
asphalt with split	0.52 mm
cement concrete	0.35 mm
smooth asphalt	0.18 mm

- Depression storage
  - Dependent on condition of the pavement

Pavement	0.5 – 1.5 mm
Highway	2 mm
Flat roofs	4 mm
PFC	10 mm

Stormwater runoff

Losses at paved terrain

- Infiltration
  - semi impervious pavement (bricks / tiles)
  - porous pavement (asphalt with cracks)

		infiltration capacity (mm/h)				Number of experiments
Type of pavement	(dimensions in m)	Source	Median	min.	max.	
concrete brick	(0.22x0.11x0.08)	BB	32	10	352	21
concrete brick	(0.20x0.10x0.07)	DS	14	7	24	9
concrete brick	(0.20x0.09x0.065)	BB	34	8	300	13
bricks	(0.20x0.20x0.08)	DS	9	6	15	9
Tiles	(0.30x0.30x0.04)	BB	16	1	254	15
Tiles	(0.50x0.50x0.06)	DS	10	7	16	4
asphalt		DS+BB	0		0	4

Source: Van de Ven, 1985. Average infiltration capacity according to Bebelaar and Bakker (BB) and Van Dam and Schotkamp (DS)

Stormwater runoff

Losses at paved terrain

- Cumulative infiltration
  - Hillel and Gardner: $I_{cum} = \sqrt{at + b} - c$
    - $a = 2 \cdot K \cdot H_c \cdot \theta_f$
    - $b = (K \cdot R_b \cdot \theta_f)^2$
    - R_b= resistance to the crust [T]

Stormwater runoff

Losses at paved terrain

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    - $a = 2 \cdot K \cdot H_c \cdot \theta_f$
    - $b = (K \cdot R_b \cdot \theta_f)^2$
    - R_b= resistance to the crust [T]
- Evaporation
  - Energy balance

Stormwater runoff

Runoff coefficients

- $C = \dfrac{\text{total runoff via the sewerage (excluding the base flow)}}{\text{total precipitation on directly connected paved area (DCPA)}}$

Stormwater runoff

Runoff coefficients

- $$C = \frac{\text{total runoff via the sewerage (excluding the base flow)}}{\text{total precipitation on directly connected paved area (DCPA)}}$$

- $$C_p = \frac{\text{maximum runoff intensity}}{\text{maximum precipitation intensity}} \text{ during a rainstorm}$$

Stormwater runoff

Runoff coefficients

- $$C = \frac{\text{total runoff via the sewerage (excluding the base flow)}}{\text{total precipitation on directly connected paved area (DCPA)}}$$

- $$C_p = \frac{\text{maximum runoff intensity}}{\text{maximum precipitation intensity}} \text{during a rainstorm}$$

- $$C_t = \frac{\text{total runoff via the sewerage (excluding the base flow)}}{\text{total precipitation on entire drainage basin}}$$

Stormwater runoff

Runoff coefficients

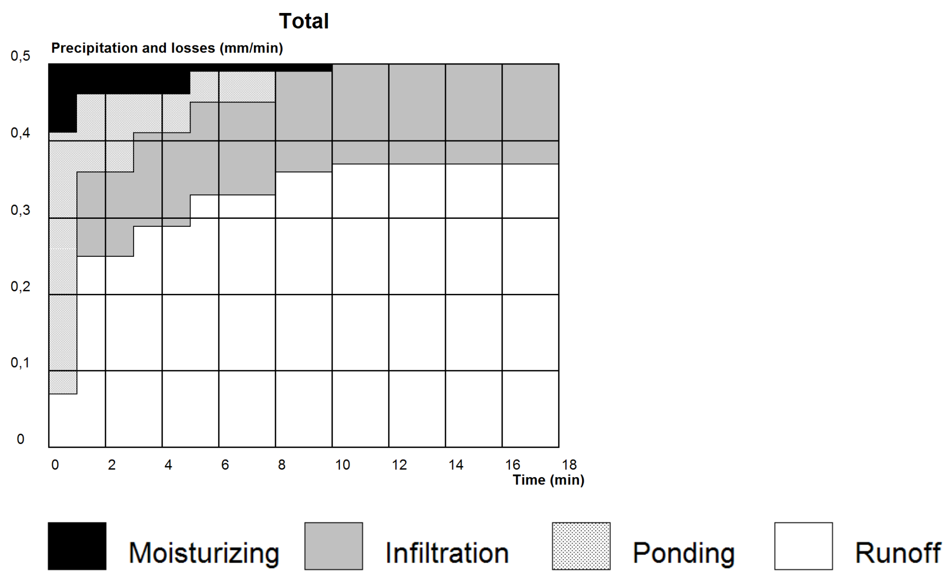
- C depends on losses:
  - Evaporation
  - Infiltration
  - Storage
  - Inflow from/ discharge to unpaved surface (C > 1 !!)
- Variable characteristics (each rainstorm):
  - Degree of filling of the initial storage
  - Moisture content of the soil
  - Temperature of the pavement
  - Etc…
- (semi-)Consistent characteristics:
  - Percentage of pavement
  - Type of pavement
  - Vegetation of unpaved area
  - Etc…

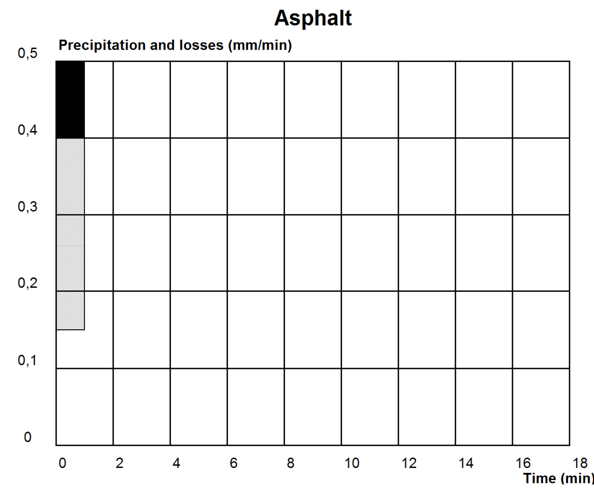
Stormwater runoff

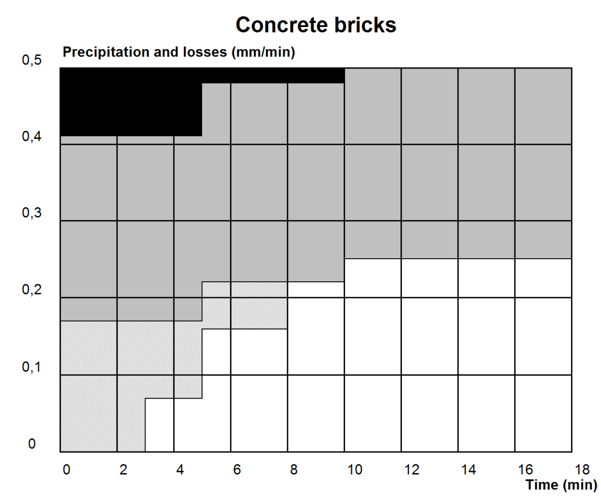
Runoff coefficients

Source: Pecher, 1969.

Course of precipitation losses and runoff on a imaginary surface. 50% paved with asphalt and 50% concrete bricks during 0.5 mm/min rainfall.







Stormwater runoff

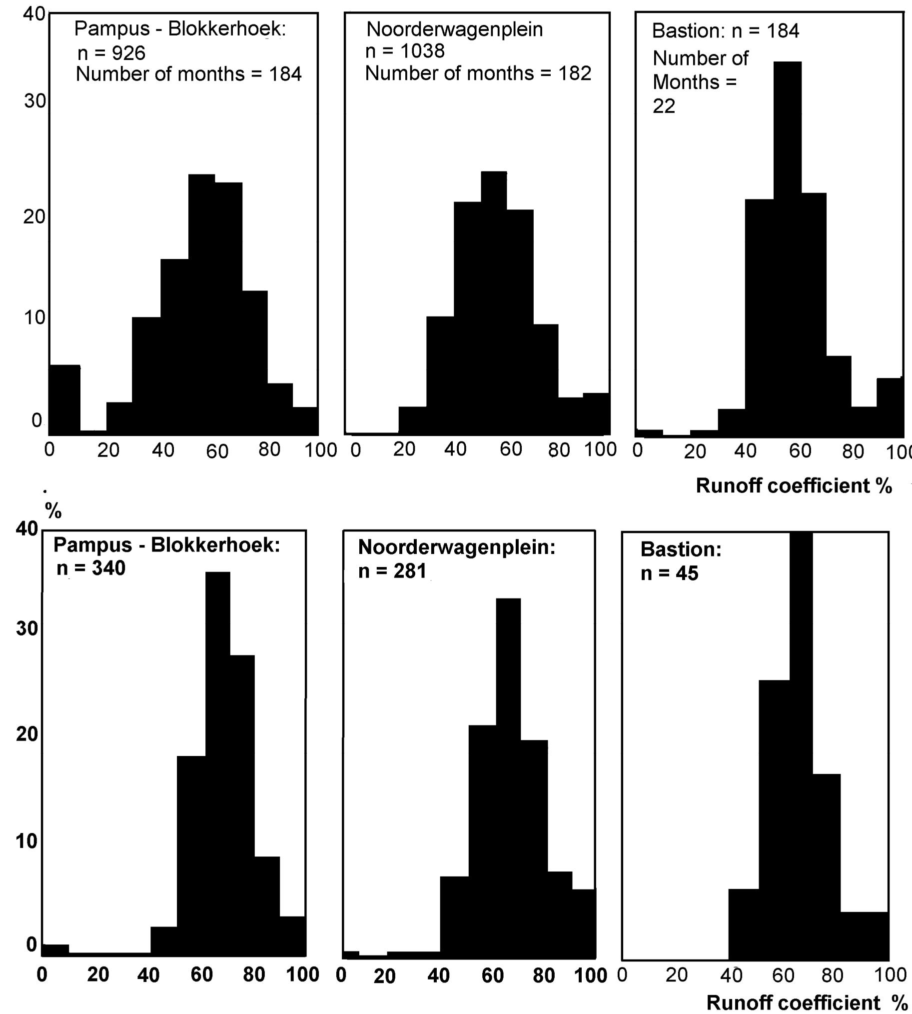
Runoff coefficients

Source: Van de Ven, 1985.

Probability density of C
for three areas in Lelystad;

- Rainstorms with runoff > 1 mm

- Rainstorms with runoff > 5 mm

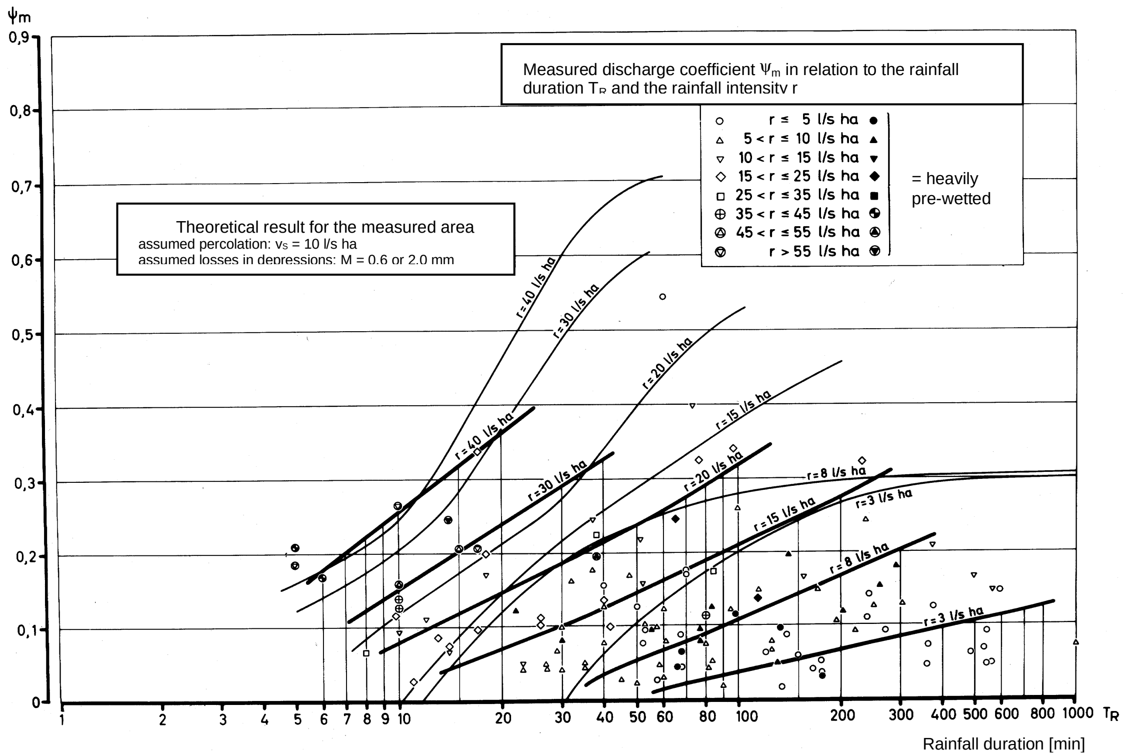


Stormwater runoff

Runoff coefficients

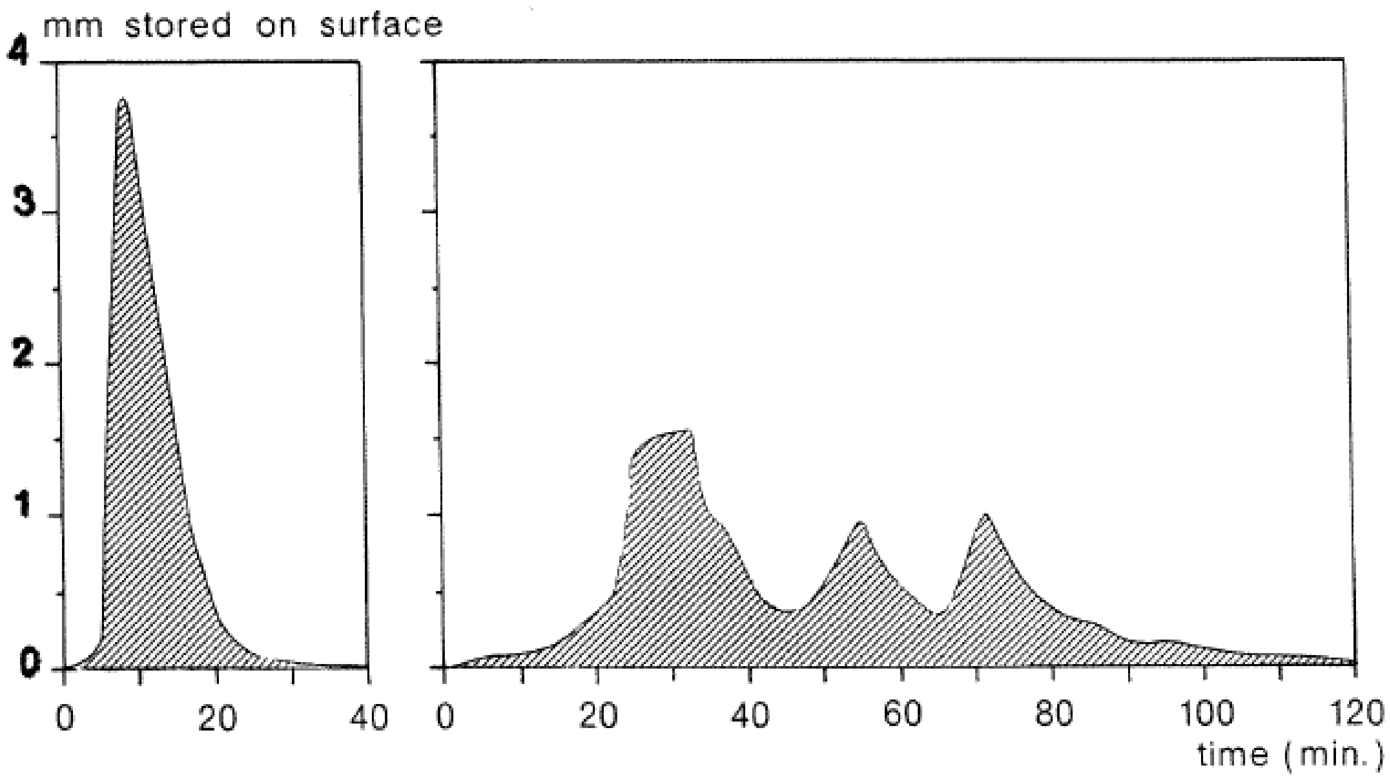
Source: Pecher, 1969.

C_t vs T_r (rainstorm duration)
for different average precipitation intensity's (r)



Stormwater runoff

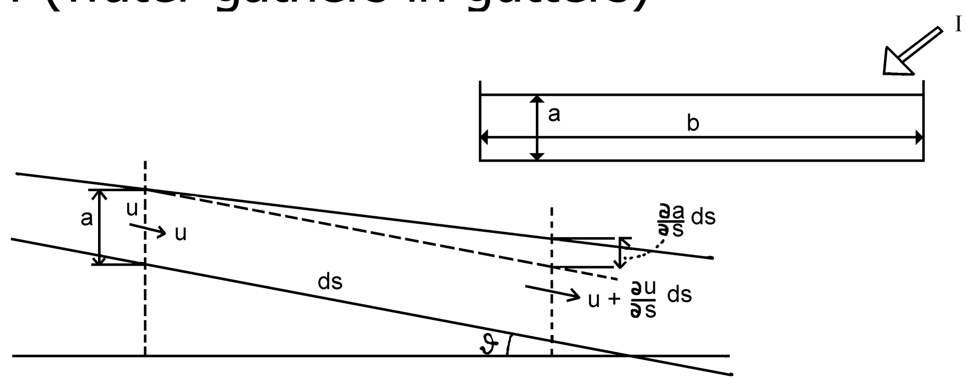
Surface storage during a rainstorm



Stormwater runoff

The runoff process theory

- Thin layer surface flow (directly fed by precipitation)
- Gully flow (water gathers in gutters)



- Long wave with peripheral inflow
  - Mass balance:
  - Momentum balance:

$$\frac{\partial a}{\partial t}+u\frac{\partial a}{\partial s}+a\frac{\partial u}{\partial s}=\frac{I}{b}$$

$$a\frac{\partial u}{\partial t}+u\frac{\partial a}{\partial t}+2au\frac{\partial u}{\partial s}+\left(ga+u^{2}\right)\frac{\partial a}{\partial s}=v\frac{I}{b}-\frac{\tau_{b}}{\rho}+ga\theta$$

Stormwater runoff

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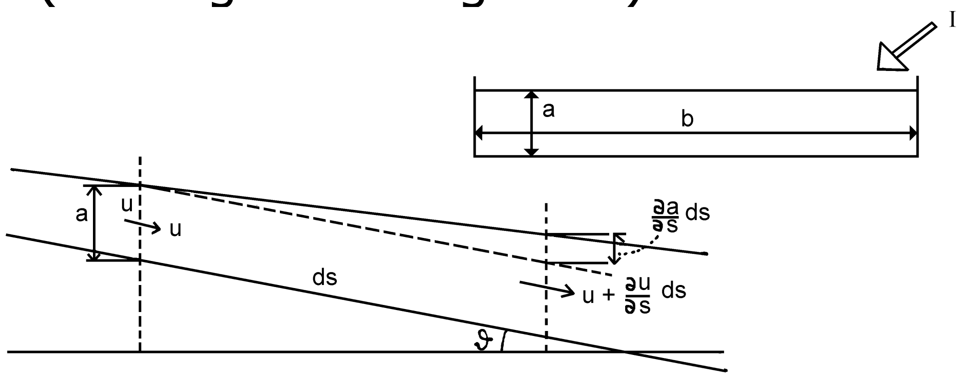


- Long wave with peripheral inflow
  - Mass balance:
  - Momentum balance:
  - Modified into:

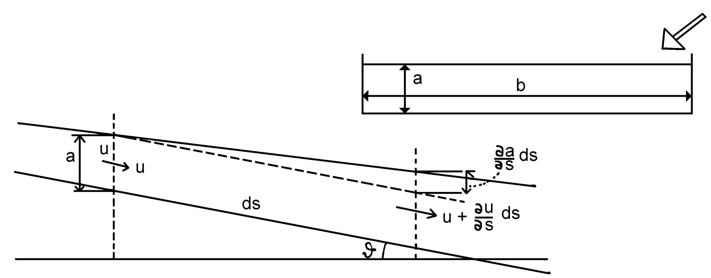
$$\frac{\partial a}{\partial t}+u\frac{\partial a}{\partial s}+a\frac{\partial u}{\partial s}=\frac{I}{b}$$

$$a\frac{\partial u}{\partial t}+u\frac{\partial a}{\partial t}+2au\frac{\partial u}{\partial s}+\left(ga+u^2\right)\frac{\partial a}{\partial s}=v\frac{I}{b}-\frac{\tau_b}{\rho}+ga\theta$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial s}+g\frac{\partial a}{\partial s}=\frac{v-u}{a}\frac{I}{b}-\frac{\tau_b}{\rho a}+g\theta$$

Stormwater runoff

The runoff process theory

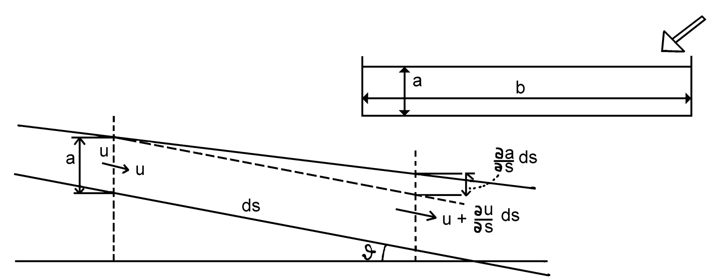


$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial s} + g\frac{\partial a}{\partial s} = \frac{v-u}{a}\frac{I}{b} - \frac{\tau_b}{\rho a} + g\theta$$

- Laminar surface flow
  - friction: $\frac{\tau_b}{\rho a} = 3\nu\frac{u}{a^2}$

Stormwater runoff

The runoff process theory



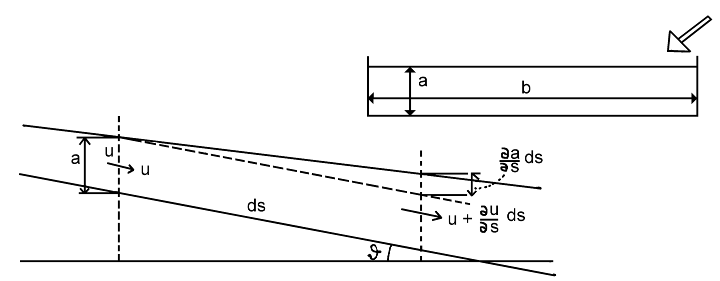
$$\cancel{\frac{\partial u}{\partial t}} + \cancel{u\frac{\partial u}{\partial s}} + \cancel{g\frac{\partial a}{\partial s}} = \cancel{\frac{v-u}{a}}\frac{I}{b} - \frac{\tau_b}{\rho a} + g\theta$$

- Laminar surface flow
  - friction: $\frac{\tau_b}{\rho a} = 3\nu\frac{u}{a^2}$
- Steady state and neglecting lower order terms

$$q = u.a = \frac{1}{3}\frac{g}{\nu}a^3\theta$$

Stormwater runoff

The runoff process theory



- Laminar surface flow

$$\cancel{\frac{\partial u}{\partial t}} + u\cancel{\frac{\partial u}{\partial s}} + g\cancel{\frac{\partial a}{\partial s}} = \frac{v-u}{\cancel{a}}\frac{\cancel{I}}{b} - \frac{\tau_b}{\rho a} + g\theta$$

  - friction: $\frac{\tau_b}{\rho a} = 3\nu\frac{u}{a^2}$

- Steady state and neglecting lower order terms

$$q = u.a = \frac{1}{3}\frac{g}{\nu}a^3\theta$$

$$\frac{\partial a}{\partial t} + \frac{q_L}{L} = \frac{I}{b}$$

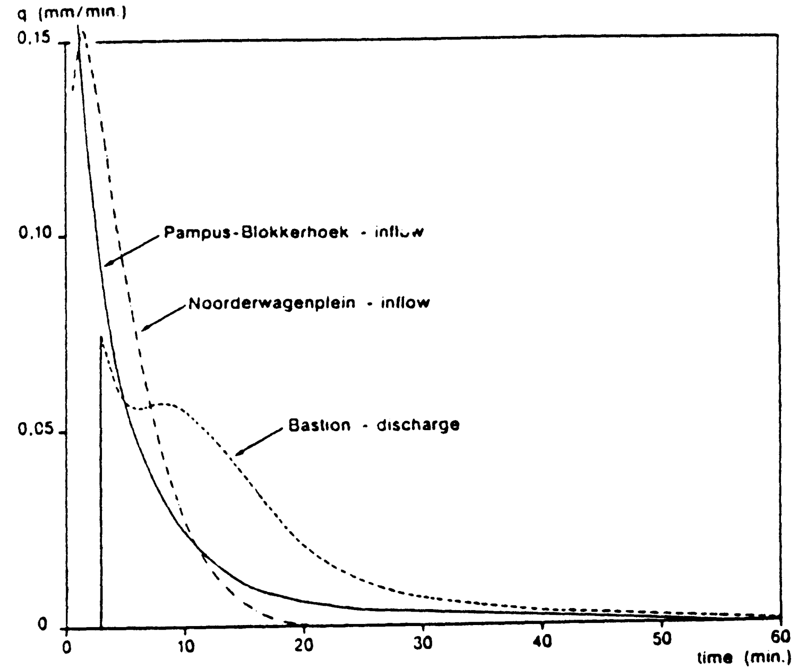
- Integrated over rainstorm duration (L)
  - $\frac{q_L}{L} = \alpha a^3 \left[LT^{-1}\right]$ with $\alpha = \frac{1}{3}\frac{g}{\nu}\frac{\theta}{L}$

Temperature [°C]	Kinematic viscosity (ν) [m2.s^{-1}]
0	1.79
5	1.52
10	1.31
15	1.15
20	1.01
25	0.90

Stormwater runoff

The runoff process in practice

- Unit hydrograph
  - linearized runoff process based on observations



Source: Van de Ven, 1985. Unit hydrographs of inflows and discharge for different basins in Lelystad.

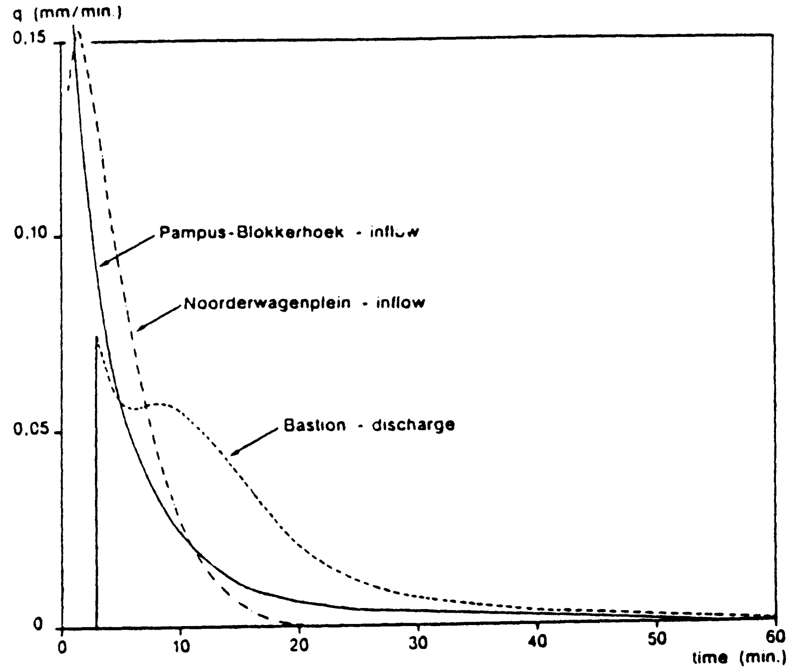
Stormwater runoff

The runoff process in practice

- Unit hydrograph
  - linearized runoff process based on observations

- Total runoff
  - convolution integral of precipitation times unit hydrograph

$$q(t) = \int_0^t p(t) \cdot h(t-\tau) d\tau$$



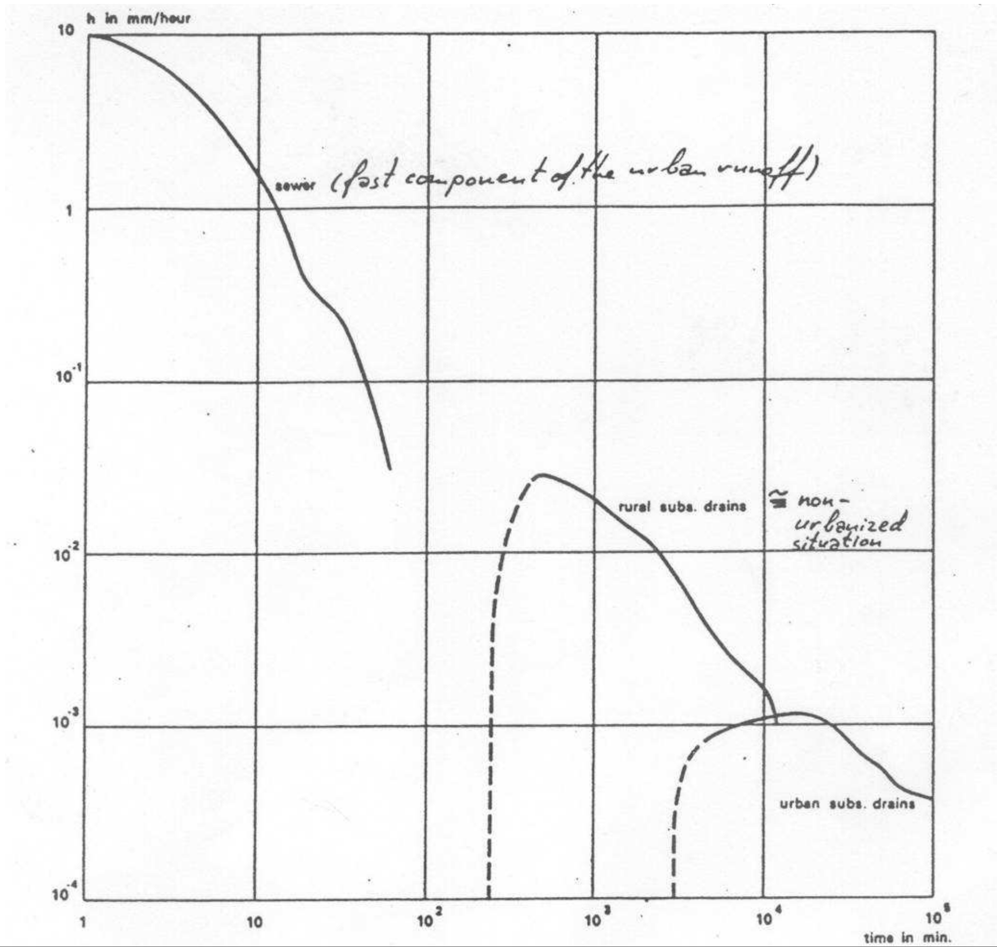
Source: Van de Ven, 1985. Unit hydrographs of inflows and discharge for different basins in Lelystad.

Stormwater runoff

The runoff process in practice

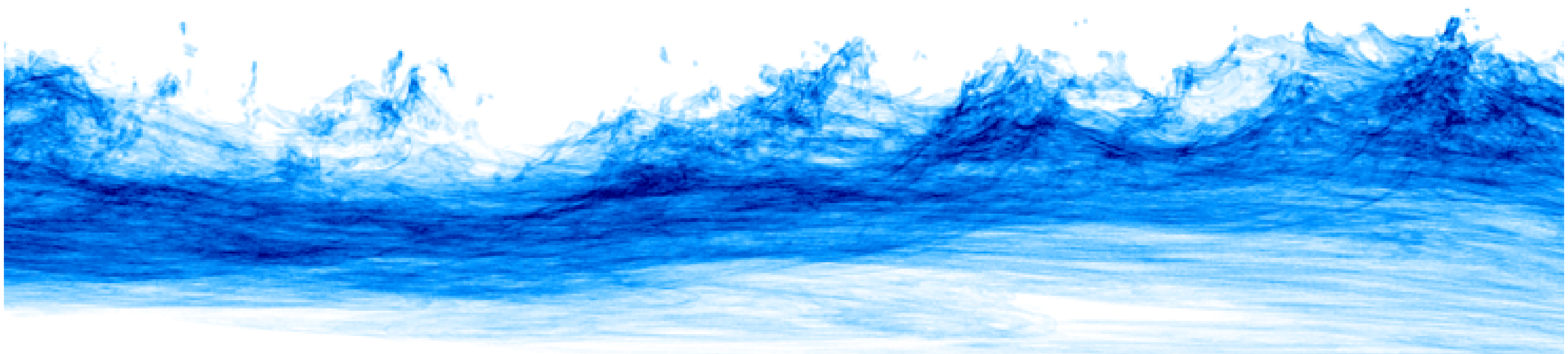
Source: Van de Ven, 1982.

- Retardation
  - Sewer
  - Rural drainage
  - Urban drainage



Hydraulic processes in surface water

Source photo: www.flickr.com/creativecommons



Hydraulic processes in surface water

Classification

- Time dependence
  - Steady (Stationary)
  - Non-steady (Non-stationary)
- Location dependence
  - Uniform
  - Non-uniform
- Turbulence (Reynold's number $Re = \frac{u \, . R}{\nu}$)
  - Laminar (Re < 400)
  - Turbulent (Re > 2000)

Hydraulic processes in surface water

Shallow water equations (De Saint Venant)

- Continuity $$B\frac{\partial a}{\partial t}+\frac{\partial Q}{\partial x}=0$$
- Momentum $$\frac{\partial Q}{\partial t}-\frac{2QB}{A_s}\frac{\partial a}{\partial t}+gA_s\left(1-\frac{Q^2B}{gA_s^3}\right)\frac{\partial a}{\partial x}+gA_s\frac{\partial Z_0}{\partial x}+\frac{gQ|Q|}{C^2A_sR}-\frac{B\beta W|Wx|}{\rho}=0$$

Q = Flow
x = location
A_s = cross section of the flow
B = surface width
a = water depth
R = hydraulic radius
Z_0 = level of the flow bed
t = time
g = acceleration of gravity
W = wind velocity
β = factor
ρ = fluid density

Hydraulic processes in surface water

Simplified shallow water equations

- Momentum equation: $$\cancel{\frac{\partial Q}{\partial t}} - \cancel{\frac{2QB}{A_s}\frac{\partial a}{\partial t}} + gA_s\left(1-\cancel{\frac{Q^2 B}{gA_s^3}}\right)\frac{\partial a}{\partial x} + gA_s\frac{\partial Z_0}{\partial x} + \frac{gQ|Q|}{C^2 A_s R} - \cancel{\frac{B\beta W|Wx|}{\rho}} = 0$$
  - Steady $\frac{\partial v}{\partial t} = 0$
  - Uniform $\frac{\partial v}{\partial x} = 0$
  - Parallel water level and flow bed
  - No wind effects

Hydraulic processes in surface water

Simplified shallow water equations

- Momentum equation: $$\cancel{\frac{\partial Q}{\partial t}} - \cancel{\frac{2QB}{A_s}\frac{\partial a}{\partial t}} + gA_s\left(1 - \cancel{\frac{Q^2 B}{gA_s^3}}\right)\frac{\partial a}{\partial x} + gA_s\frac{\partial Z_0}{\partial x} + \frac{gQ|Q|}{C^2 A_s R} - \cancel{\frac{B\beta W|Wx|}{\rho}} = 0$$
  - Steady $\frac{\partial v}{\partial t} = 0$
  - Uniform $\frac{\partial v}{\partial x} = 0$
  - Parallel water level and flow bed
  - No wind effects

Transformed momentum equation: $$gA_s\frac{\partial Z_0}{\partial x} + \frac{gQ|Q|}{C^2 A_s R} = 0$$

- with $\frac{\partial Z_0}{\partial x} = I$

Chezy

$Q = A_s C\sqrt{RI}$

Manning

$Q = A_s K_m R^{2/3} I^{1/2}$

Hydraulic processes in surface water

Friction dominated shallow water equations

- Momentum equation: $\cancel{\frac{\partial Q}{\partial t}} - \cancel{\frac{2QB}{A_s}\frac{\partial a}{\partial t}} + gA_s\left(1 - \frac{Q^2 B}{gA_s^3}\right)\frac{\partial a}{\partial x} + gA_s\frac{\partial Z_0}{\partial x} + \frac{gQ|Q|}{C^2 A_s R} - \cancel{\frac{B\beta W|Wx|}{\rho}} = 0$
  - Steady $\frac{\partial v}{\partial t} = 0$
  - Non-uniform $\frac{\partial v}{\partial x} \neq 0$ ($\frac{v}{x} \cong 0$ back water curve)
  - No wind effects

Hydraulic processes in surface water

Friction dominated shallow water equations

- Momentum equation: $$\cancel{\frac{\partial Q}{\partial t}} - \cancel{\frac{2QB}{A_s}\frac{\partial a}{\partial t}} + gA_s\left(1-\frac{Q^2 B}{gA_s^3}\right)\frac{\partial a}{\partial x} + gA_s\frac{\partial Z_0}{\partial x} + \frac{gQ|Q|}{C^2 A_s R} - \cancel{\frac{B\beta W|Wx|}{\rho}} = 0$$
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Transformed momentum equation: $$gA_s\left(1-\frac{Q^2 B_s}{gA_s^3}\right)\frac{\partial a}{\partial x} + gA_s\frac{\partial Z_0}{\partial x} + \frac{gQ|Q|}{C^2 A_s R} = 0$$

- with $\frac{\partial Z_0}{\partial x} = I_b$ hydraulic gradient: $$\frac{da}{dx} = I_b \frac{1-\frac{Q^2}{C^2 . A_s^2 . R . I_b}}{1-\frac{v^2}{ga}}$$

Hydraulic processes in surface water

Friction dominated shallow water equations

- Momentum equation: $$\cancel{\frac{\partial Q}{\partial t}} - \cancel{\frac{2QB}{A_s}\frac{\partial a}{\partial t}} + gA_s\left(1-\frac{Q^2B}{gA_s^3}\right)\frac{\partial a}{\partial x} + gA_s\frac{\partial Z_0}{\partial x} + \frac{gQ|Q|}{C^2A_sR} - \cancel{\frac{B\beta W|Wx|}{\rho}} = 0$$
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Transformed momentum equation: $$gA_s\left(1-\frac{Q^2B_s}{gA_s^3}\right)\frac{\partial a}{\partial x} + gA_s\frac{\partial Z_0}{\partial x} + \frac{gQ|Q|}{C^2A_sR} = 0$$

- with $\frac{\partial Z_0}{\partial x} = I_b$ hydraulic gradient: $$\frac{da}{dx} = I_b\frac{1-\frac{Q^2}{C^2.A_s^2.R.I_b}}{1-\frac{v^2}{ga}}$$
- with $Fr = \frac{v}{\sqrt{ga}}$ (Froude number) $$\frac{da}{dx} = \frac{I_b - I_c}{1-Fr^2}$$

  I_b = bottom gradient

  I_c = friction gradient

Hydraulic processes in surface water

Shallow water equations for tranquil flow

- Momentum equation: $$\frac{\partial Q}{\partial t}-\frac{2QB}{A_s}\frac{\partial a}{\partial t}+gA_s\left(1-\cancel{\frac{Q^2B}{gA_s^3}}\right)\frac{\partial a}{\partial x}+gA_s\frac{\partial Z_0}{\partial x}+\frac{gQ|Q|}{C^2A_sR}-\cancel{\frac{B\beta W|W|x}{\rho}}=0$$
  - Non-steady $\frac{\partial v}{\partial t}\neq 0$
  - Non-uniform $\frac{\partial v}{\partial x}\neq 0$
  - No wind effects
  - Tranquil flow $Fr^2=\frac{v^2}{ga}\approx 0 \quad\Rightarrow\quad 1-\frac{v^2}{ga}=1-\frac{Q^2B}{gA_s^3}\approx 1$

Hydraulic processes in surface water

Shallow water equations for tranquil flow

- Momentum equation: $$\frac{\partial Q}{\partial t} - \frac{2QB}{A_s}\frac{\partial a}{\partial t} + gA_s\left(1 - \cancel{\frac{Q^2 B}{gA_s^3}}\right)\frac{\partial a}{\partial x} + gA_s\frac{\partial Z_0}{\partial x} + \frac{gQ|Q|}{C^2 A_s R} - \cancel{\frac{B\beta W|Wx|}{\rho}} = 0$$
  - Non-steady $\frac{\partial v}{\partial t} \neq 0$
  - Non-uniform $\frac{\partial v}{\partial x} \neq 0$
  - No wind effects
  - Tranquil flow $Fr^2 = \frac{v^2}{ga} \approx 0 \Rightarrow 1 - \frac{v^2}{ga} = 1 - \frac{Q^2 B}{gA_s^3} \approx 1$

Transformed momentum equation: $$\frac{\partial Q}{\partial t} - 2\frac{QB}{A_s}\frac{\partial a}{\partial t} + gA_s\frac{\partial a}{\partial x} + gA_s\frac{\partial Z_0}{\partial x} + \frac{gQ|Q|}{C^2 A_s R} = 0$$

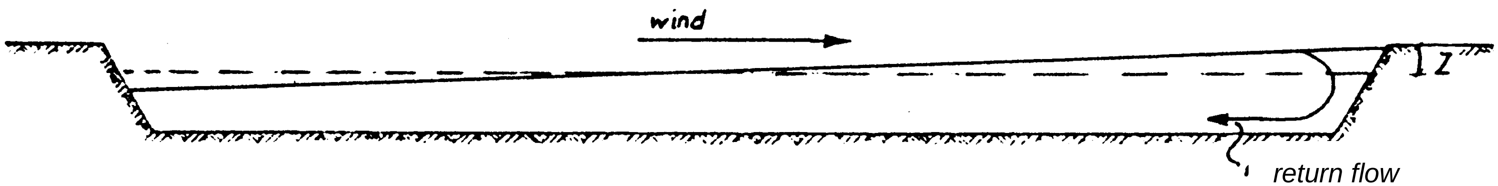
Hydraulic processes in surface water

Large water bodies

- Wind setup

$$z = \alpha \frac{W^2}{h} \cdot l \cdot \cos\phi$$

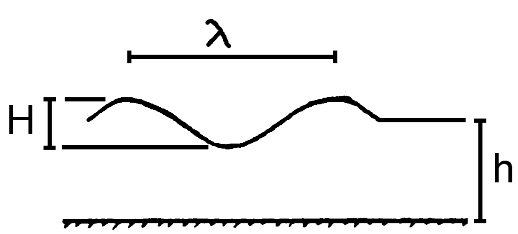
z = wind setup
α = constant (0.2 – 0.4 · 10^{-6}) [-]
W = wind velocity [m·s^{-1}]
ϕ = angle between wind direction and fetch length
l = fetch length [m]
h = water depth [m]



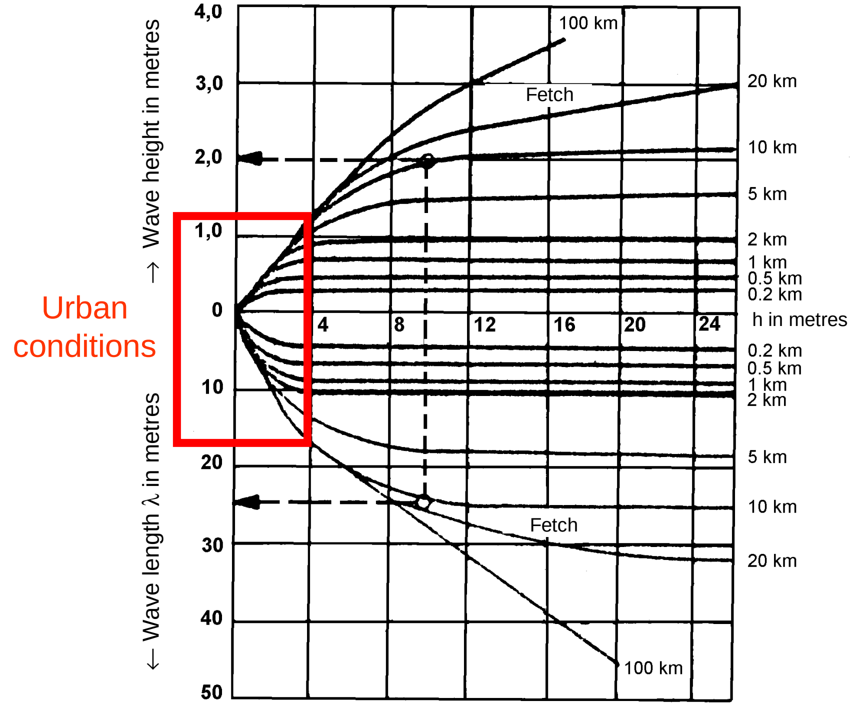
Hydraulic processes in surface water

Large water bodies

- Waves (empirical)
  - h average water depth [m]
  - l fetch length [km]
  - H wave height [m]
  - λ wave length [m]
- Wave breaking
  - breaking at h = 1.3 H – 2 H
  - proper bank structure design



Wave characteristics for
h = 10m & l = 10km



Source:Groen and Dorrestein, 1976. Wave characteristics for W = 22 m/s

Water quality processes

Source photo: www.rijnland.net (Hoogheemraadschap Rijnland, 2008. Maarten van der Weijden swimming in the canals of Leiden)

Water quality processes

Sources of pollution

Source photo's: www.flickr.com/creativecommons

Water quality processes

Wet deposition

- Precipitation quality
- National monitoring network
  - monthly data
  - sensitive to errors
- Unknown urbanization effects

Parameter	mol.l^{-1}	DEPOSITION CONCENTRATION mol. m^{-2}/ 24hrs	mol.ha^{-1}/year	molecular weight
Acid	4.57*	60.0 x 10^{-6}	220	
Calcium	37.5 x 10^{-6}	50.1 x 10^{-6}	183	40.1
Magnesium	18.9 x 10^{-6}	30.7 x 10^{-6}	112	24.3
Sodium	121 x 10-6	219 x 10^{-6}	800	23.0
Ammonium	171 x 10-6	256 x 10^{-6}	934	14.0
Chloride	128 x 10-6	260 x 10^{-6}	950	35.5
Fluoride	3.7 x 10-6	8.0 x 10^{-6}	30	19.0
Nitrate	89 x 10-6	126 x 10^{-6}	14	
Orthophosphate	4.9 x 10-6	6.7 x 10^{-6}	24	30.9
Sulphate	100 x 10^{-6}	126 x 10^{-6}	460	96.1
Arsenic	13 x 10^{-9}	21 x 10^{-9}	77 x 10-3	74.9
Cadmium	3.97 x 10^{-9}	6.54 x 10^{-9}	23.9 x 10-	112.4
Chrome	10 x 10^{-9}	20 x 10^{-9}	75 x 10-	52.0
Copper	200 x 10^{-9}	240 x 10^{-9}	0.88	63.5
Iron	1.05 x 10^{-6}	1.36 x 10^{-6}	4.96	55.8
Manganese	0.60 x 10^{-6}	1.12 x 10^{-6}	4.09	54.9
Nickel	33 x 10-9	50 x 10^{-9}	180 x 10-3	58.7
Lead	87 x 10^{-9}	129 x 10^{-9}	471 x 10-3	207.2
Zinc	1.30 x 10^{-6}	1.65 x 10^{-6}	6.02	65.4

* pH-units

Source:Van der Meent, 1984. Average quality of precipitation in the Netherlands. Medians of the 27 local average concentrations and depositions of matter; data July 1978 – December 1982.

Water quality processes

Wet deposition

Source: Van der Meent, 1984. Deposition of various matter from observed precipitation quality.

Water quality processes

Atmospheric deposition

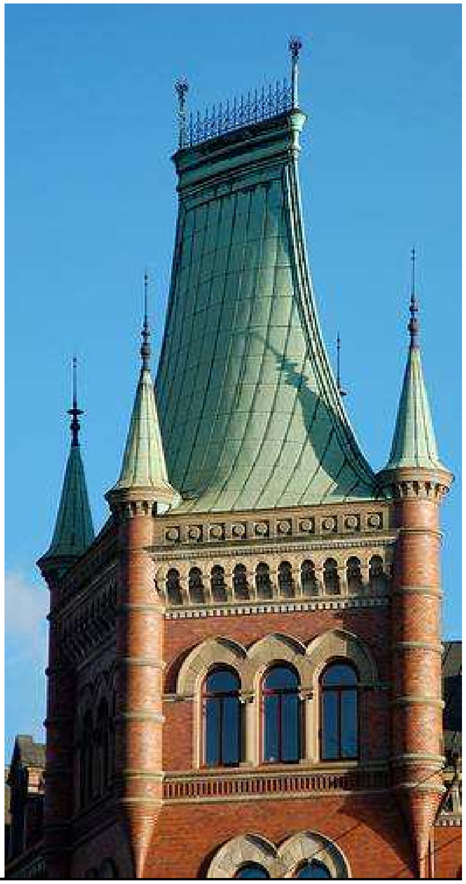
Source: Ellis, 1985. Average concentrations of atmospheric depositions in urban areas

- Urban imports

variable	total deposition ($gm^{-2}y^{-1}$)	wet deposition (mgL^{-1})	melt water (mgL^{-1})	% contribution to import
Suspended matter	8.4-36.2	5-70	263 - 690	10 -25
COD	0.44-31.6	8-27	15 - 25	15 -30
SO_4	6-15	4.8-46.1		31 -100
P-tot	0.021-0.024	0.02-0.37		17-140
NO_3-N	1.8-8.2	0.5-4.4	4.1 - 5.7	30-94
Pb	0.04-4.0	0.03-0.12	0.3 - 0.4	15-54
Zn	0.1-1.3	0.05-0.38	0.35- 0.41	20-62

Water quality processes

Corrosion leaching



- Corrosion of extensively used building material
- Major heavy metal source

Metal	leaching intensity ($g.m^{-2}.yr^{-1}$)	concentration in runoff ($\mu g.l^{-1}$)
Zinc	0.6 – 7	17,790; 2,135-4,981; 2,900
Copper	0.7 – 1.7	11,000; 6,700; 1,198
Lead	5	310*; 200*

* roof with parts of lead

Source: Teunisse, Wagemaker, 2000.

- Toxic levels (industrial waste water)
- Environmental protection versus cultural heritage

TU Delft

Water quality processes

Traffic pollution

- Exhaust
- Wearing of tires
- Wearing of clutch plates
- Leakage of oil

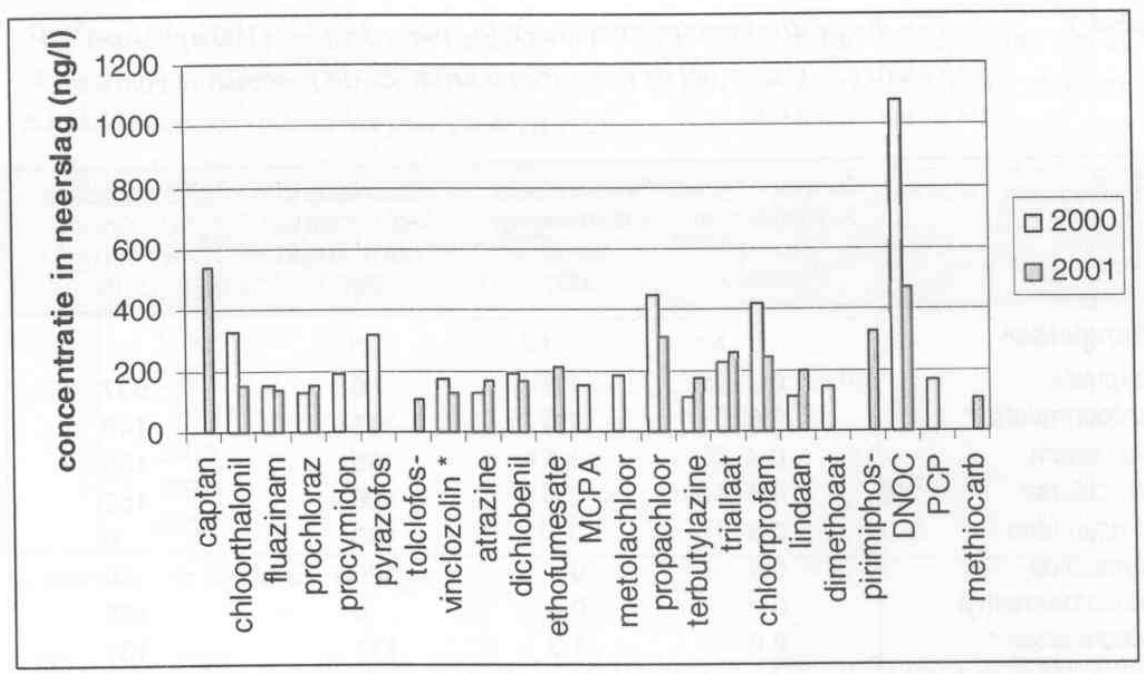
Variable	**mg.axle^{-1}.km^{-1}**		**kg.km^{-1}.yr^{-1}**
	RIZA	*v.d. Ven*	*v.d. Ven*
Solid material < 3.35 mm	671	350	408
Org. solid mat. < 3.35 mm	34.1	118	137
Oil and grease	4.3	14.1	16.4
Rubber	3.5	-	-
Pb	7.9	1.22	1.41
Cr	0.052	0.036	0.042
Cu	0.080	0.174	0.203
Ni	0.12	0.036	0.041
Zn	0.99	0.88	1.02
Cd	0.0087	0.006	0.007
COD	36.1	276	321
BOD_5^{20}	1.5	18	21

Source: RIZA, 1980; Van de Ven, Oldenkamp, 1987

Water quality processes

Pesticides

Source: TNO, 2002.



Water quality processes

Stormwater runoff quality

1. Accumulated waste washed into sewer during a shower

Water quality processes

Stormwater runoff quality

Source: Ellis, 1985.

	Average concentration (mg.1)								Average load ($kg.ha^{-1}.yr^{-1}$)					
Variable	Tot. susp	org. susp	BOD	COD	NH_4	Pb	PAH[1] B(a)P	E.Coli[2]	tot. susp	org. susp	BOD	COD	NH_4	Pb
Sewerage type														
Rainwater sewerage	21 - 582	26 - 149	7 - 22	33 - 265	0.2 - 4.6	0.03 - 3.1	29 - 200	10^2 - 10^4	347 - 2340	90 - 127	35 - 172	22 - 703	1.2 - 25.1	0.09 - 1.91
Discharge from highway	28 - 1278	18 - 86	12 - 32	128 - 171	0.02 - 2.1	0.15 - 2.9	365 - 60000	10 - 10^3	121 - 6289	45 - 851	90 - 172	181 - 3865	0.8 - 6.1	0.65 - 13.0
Roof discharge	12.3 - 216	40 - 88	2.8 - 8.1	57.9 - 80.6	0.4 - 3.8	0.001 - 0.030	10^2							
Water in inlet	15 - 840	-	6.8 - 241	25 - 109	0.7 - 1.39	0.06 - 0.85	-	10 - 10^2						
r.w.a. Residential area	112 - 1104	28 - 124	7 - 56	37 - 120	0.3 - 3.3	0.09 - 0.44	-	10 - 10^3	620 - 2300	-	5 - 76.8	22 - 761	-	0.06 - 1.91
r.w.a. Residential area	230 - 1894	75 - 85	5 - 7	74 - 160	0.03 - 5.1	0.1 - 0.4		10^2 - 10^4	50 - 840		43 - 87	1000 - 1029		0.17 - 6.84
r.w.a light Industrial areas	45 - 375	35 - 72	8 - 12	40 - 70	0.2 - 1.1	0.6 - 1.2		400 - 1700						2.2 - 7.0

Water quality processes

Stormwater runoff quality

1. Accumulated waste washed into sewer during a shower
2. Characteristics of the location determine the runoff quality

Variable	Units	General residential areas	Individual houses [5]	commercial areas [1]	Roads[3]	Main road[4]	Two residential areas[6]
Faecal coli	MPN/100 ml	1530-132500[2]	360-13000	19.000	2400		
Faecal Streptococci	MPN/100 ml	20,000		20,000	2900	1000-4000	
BOD_5^{20}	mg/l	7-13	6- 39	19	9	2-19	2.5/6.1
COD	mg/l	37-99	45-229	73-123	59	19-119	35.9/58.6
DOC	mg/l	5-21		31			
$N\text{-}NH_4$	mg/l	0.15-2.5	0.16-0.75	0.03	0.13	0.51-2.5	
$N\text{-}N0_3$	mg/l	0.1-1.7	0.5 -1.4	0.2 -0.5	0.28	0.6-1.4	
N-Kjeldahl	mg/l	1.5 -3.6		0.7 -1.1	0.68	0.8 - 5.1	2.2/3.6
P-total	mg/1	0.22-1.5	0.14-0.88	0.1 -0.6	0.08	0.05-0.48	0.3/0.5
Zn	µg/l	100-320	21-250	100-600	90	124-292	86.8/282.3
Pb	µg/l	50-310	94-510	400	282	143-352	6.6/62.4
Cu	µg/l	< 6-57[2]	l-46	-	6.5	25- 62	9.2/44.4
Cr	µg/l	< 5-45[2]	3-10	-	17	< 5.0- 14.4	7.1/26.6
Cd	µg/l	< 0.5-2.9[2]	3- 57	0.9	0.7	0.9- 2.2	0.2/2.3
Suspended matter	mg/l	59-930	36-390	45-303	15	15.9-171.7	36.7/113.0
Organic susp. mat.	mg/1	33- 74					7.0-49.6
Oil	mg/l	0.54-0.98[2]					

Water quality processes

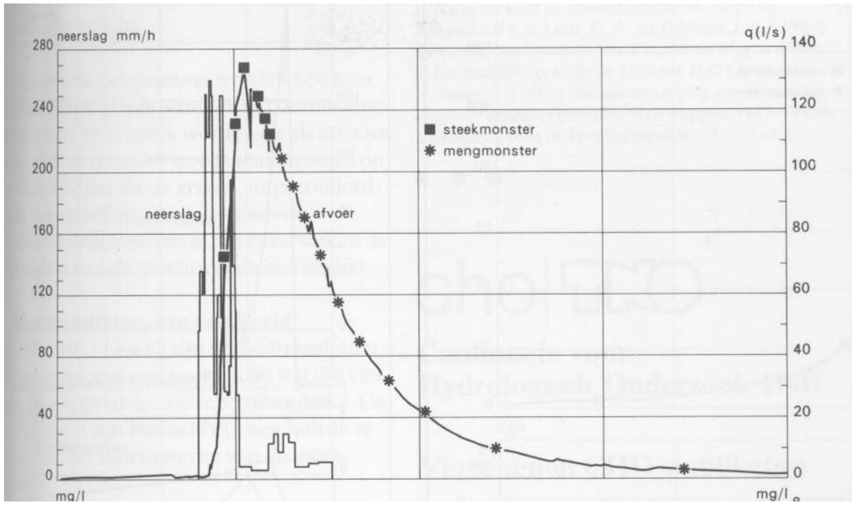
Stormwater runoff quality

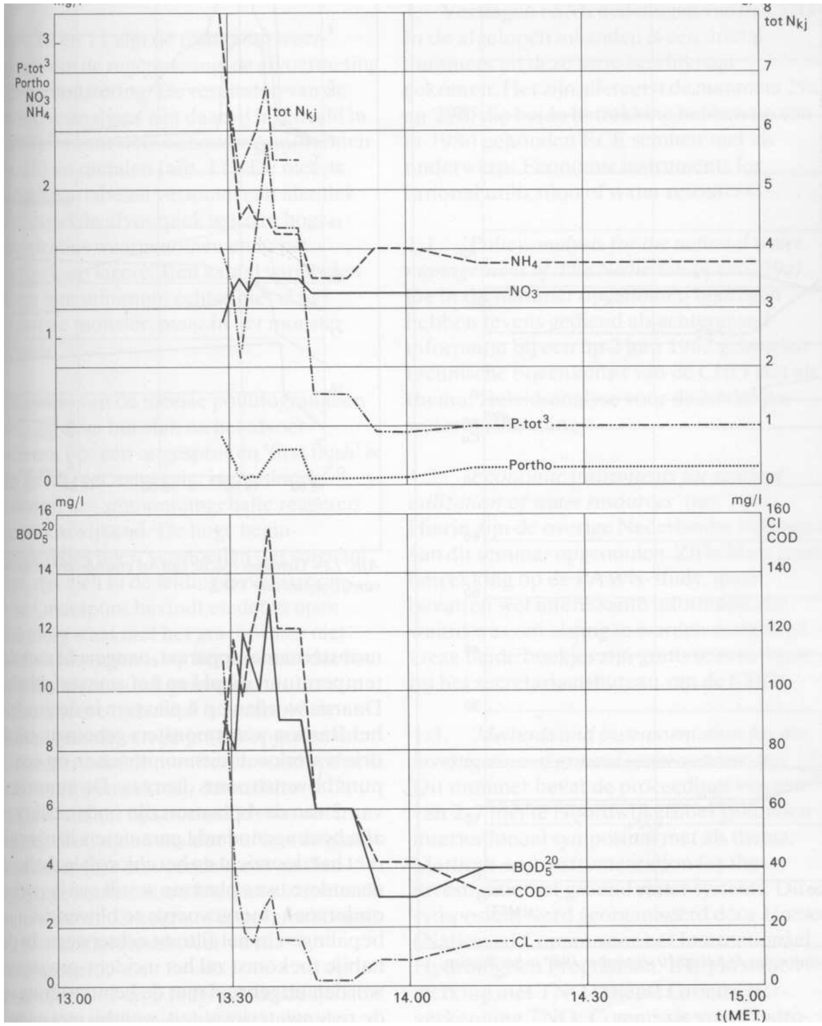
1. Accumulated waste washed into sewer during a shower
2. Characteristics of the location determine the runoff quality
3. Precipitation intensity influences amount of pollution running off

Water quality processes

Stormwater runoff quality

Source: Van de Ven, 1982.

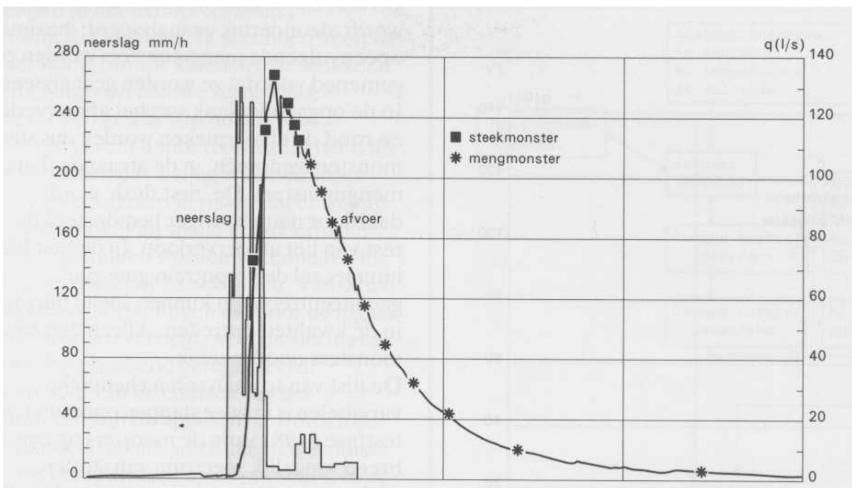


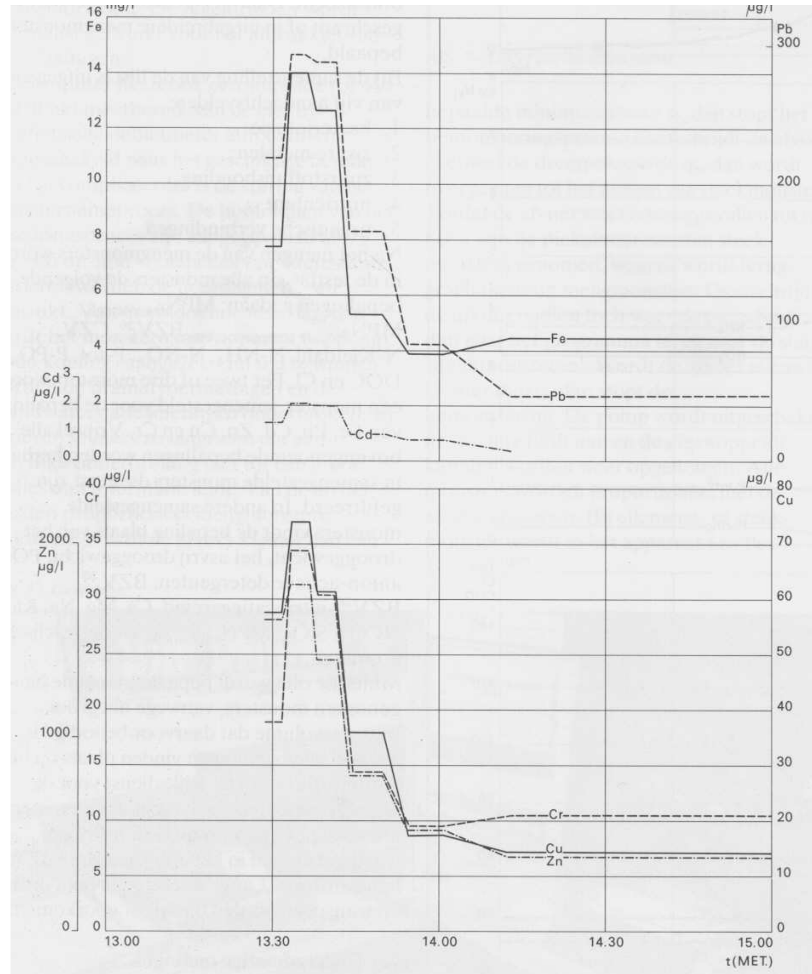


Water quality processes

Stormwater runoff quality

Source: Van de Ven, 1982.

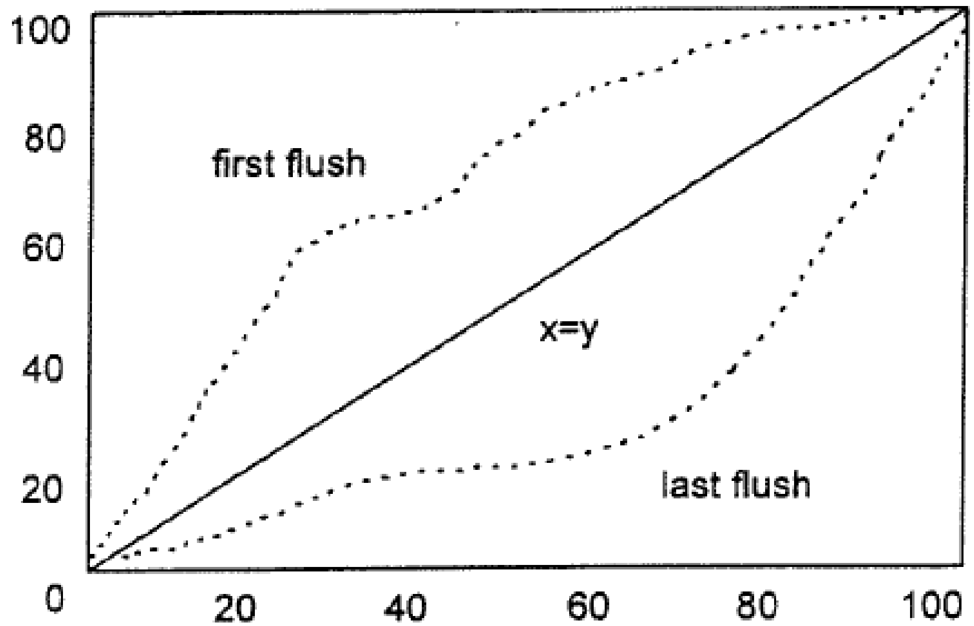




Water quality processes

First flush in stormwater drainage

Percentage of total pollution load



Percentage of total discharge

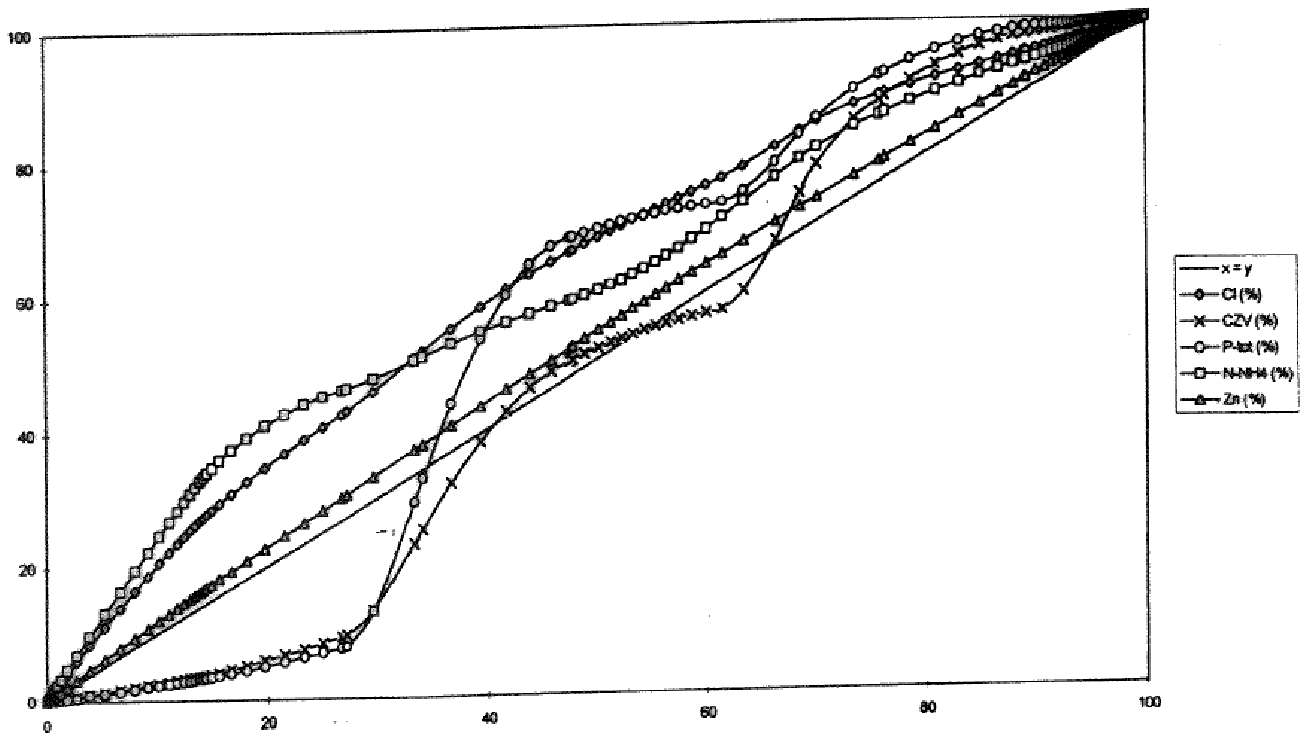
Water quality processes

First flush in stormwater drainage

Source: Dolman, 1998.

Example: Residential area Julianapark in Amsterdam

Percentage of total pollution load

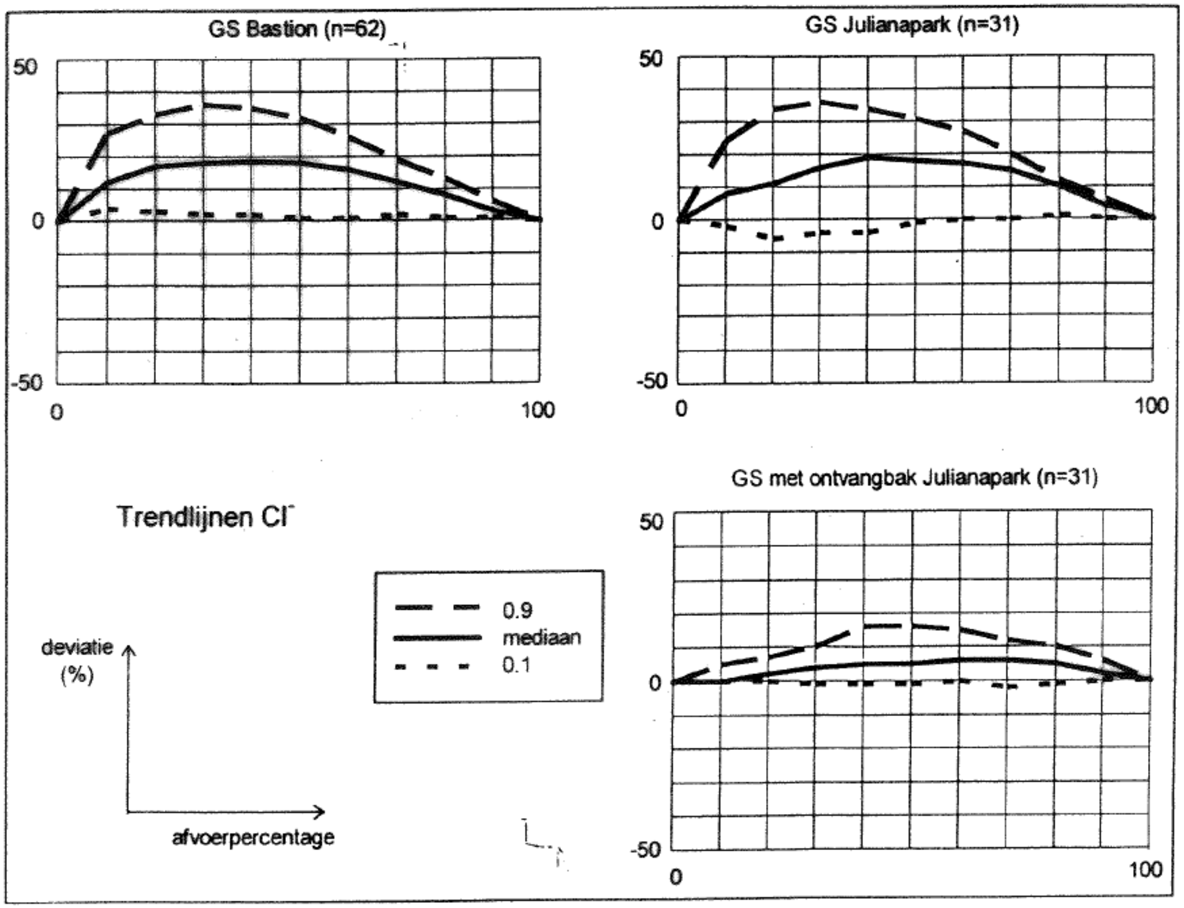


Percentage of total discharge

Water quality processes

First flush of Cl in stormwater drainage

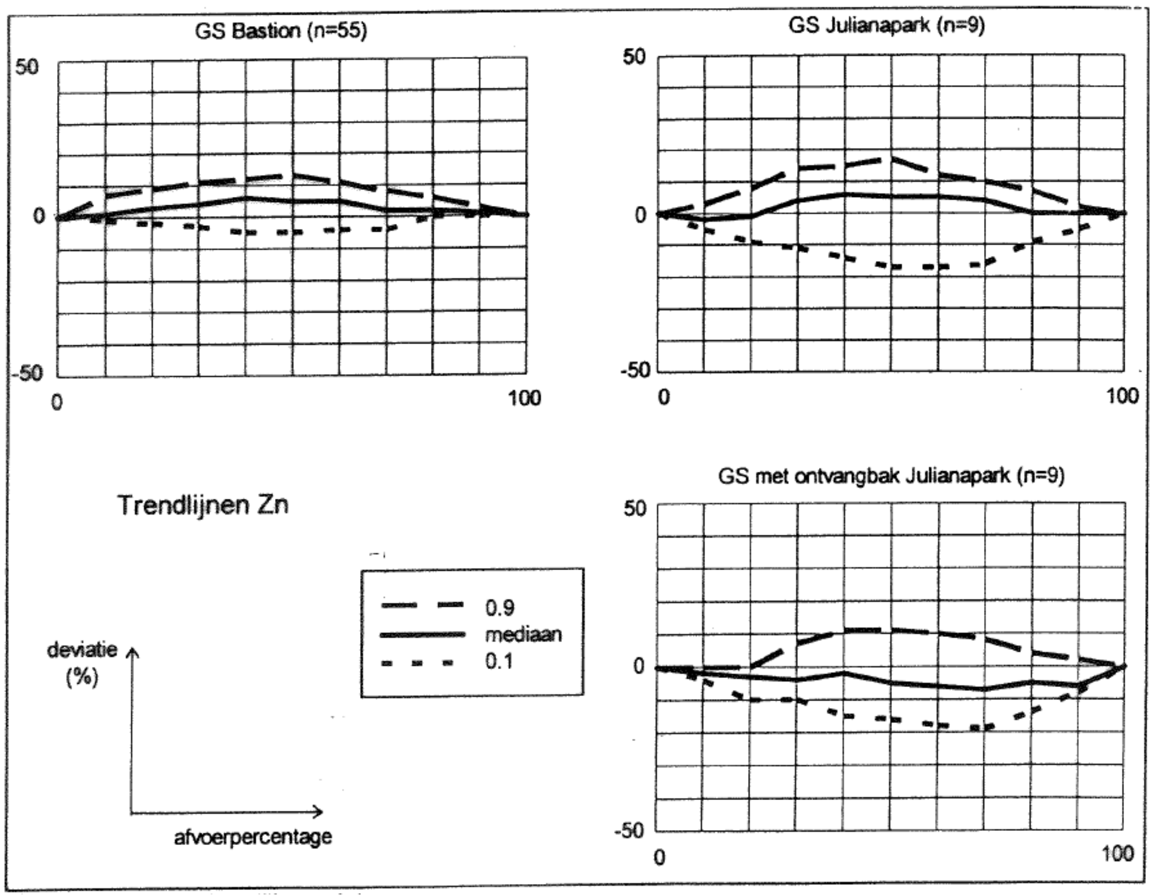
Source: Dolman, 1998.



Water quality processes

First flush of Zn in stormwater drainage

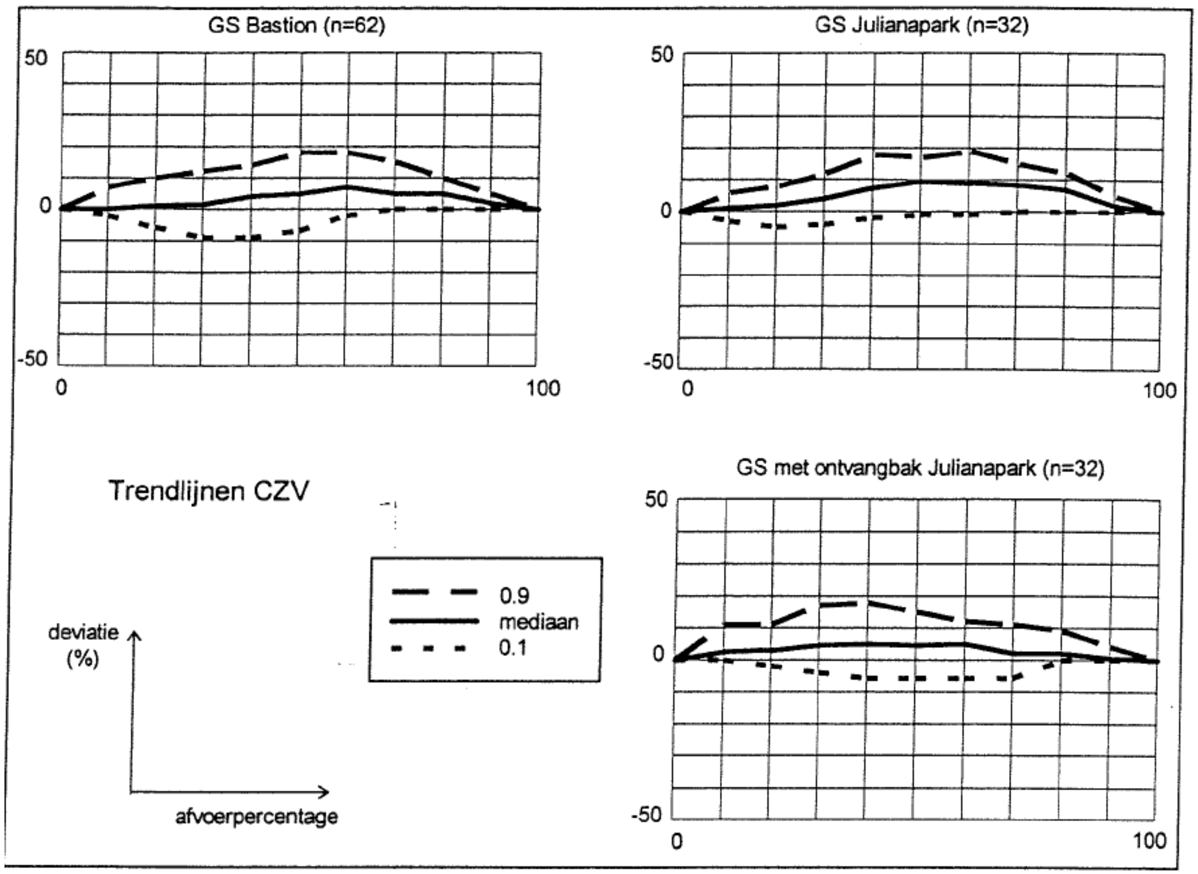
Source: Dolman, 1998.



Water quality processes

First flush of COD in stormwater drainage

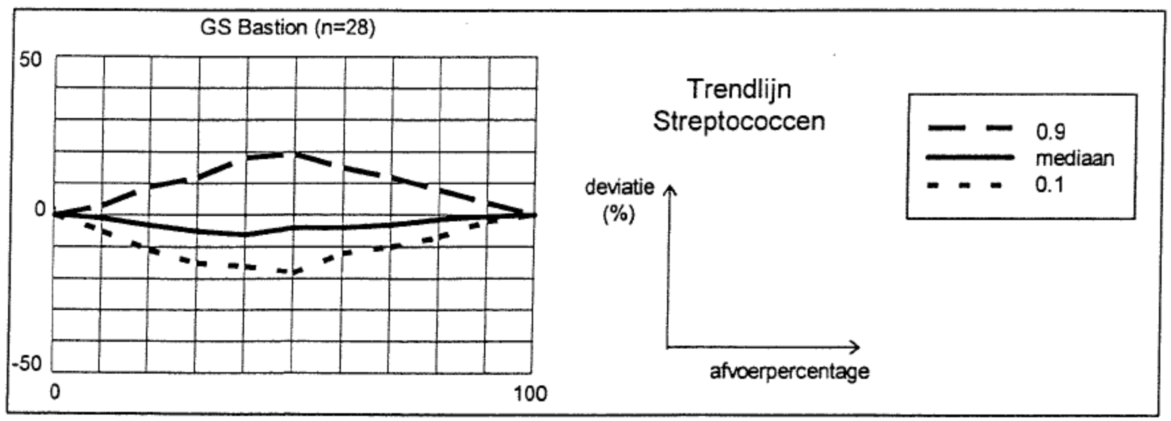
Source: Dolman, 1998.



Water quality processes

First flush of Streptococci in stormwater drainage

Source: Dolman, 1998.



Water quality processes

Ground- and drainage water quality

- Limited research
- Significant for contaminated soils (former dumps/industrial sites)

			% O_2	Milligram per litre						
Drain	Date	pH	satur.	N-NH_4	N-NO_3	N-Kjeld.	BOD_5^{20}	COD	P-total	Cl
		6.5	0.0	1.9	0.0	1.2	0.6	19	0.1	158
4 drains	1975	7.1	35	1.5	0.25	2.2	1.6	27	0.82	326
		7.4	74	3.0	1.2	4.1	2.8	38	2.4	664
Drain	27/8/82	7.2	20	2.1	2.8	2.8	2	30	2.0	156
Drain	13/10/82			2.0	2.6	2.6	1	25	0.77	151
Cunette-drain	13/10/82	7.9	95	0.31	1.1	1.1	1	29	0.10	270

Source: Uunk, 1984. Quality values of drainage water in Lelystad

Water quality processes

Combined sewer overflow (CSO)

- Combined sewer system
  - Stormwater runoff
  - Domestic waste water
  - Sewage silt
- Total load determines impact

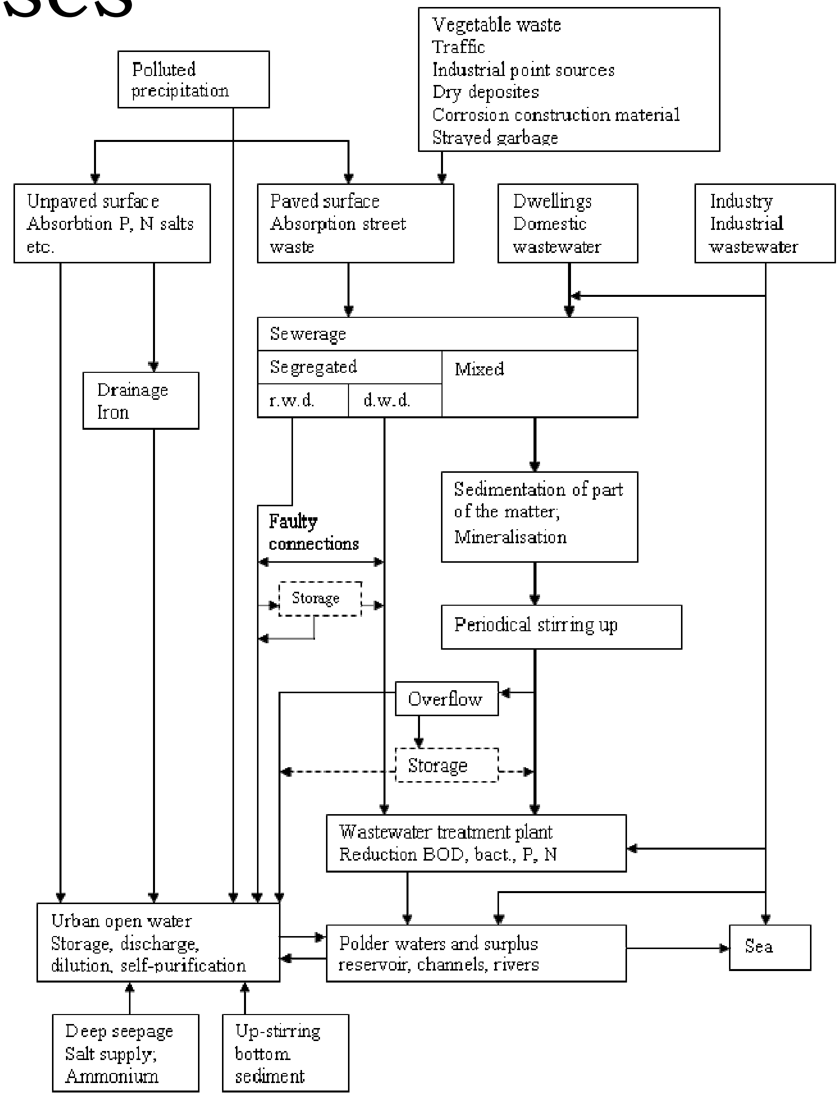
Variable	San Fransisco[1]	Loenen/Oosterhout[2]	North-Hampton[3]
	1 shower	average concentration	Av.-concentration
Discharge (m^2/s)	0.2-3.1		
E-Coli (faec) 10^4 /ml	0.6-13		
Susp. matter mg/1	73-442	394/165	325 – 525
Org. Susp.matt. mg/1	56-264		
Grease mg/1	16.2-63.4		
COD mg/l	165-458	271/345	
BOD mg/1	41-252	34/79	50 - 160
Floating matter mg/l	0.4-2.3		
Settling matter mg/1	7-40		
N-Kj mg/l	3.9-20.0		
NH_4 –N mg/l	2.45-10.5	2.5 –17	
tot-PO_4 mgP/l	1.13-3.20		
SO_4 mg/l	10-29		
Cl mgll	5.5-32	10- 50	
Na mg/1	6.0-29.5		
K mg/1	1.2-6.7		
Ca mg/1	4.8-11.2		
Mg mg/l	2.4-4.9		

Source: 1) Kibler; 2) Vat, 1985/NWRW, 1986; 3) Gameson, Davidson, 1963. Range of water quality parameters from combined sewer overflow measurements.

Water quality processes

Surface water

- Pollution enters surface water
- Internal processes
  - Physical
  - Chemical
  - Biological
- Discharged to the surroundings



Water quality processes

Surface water

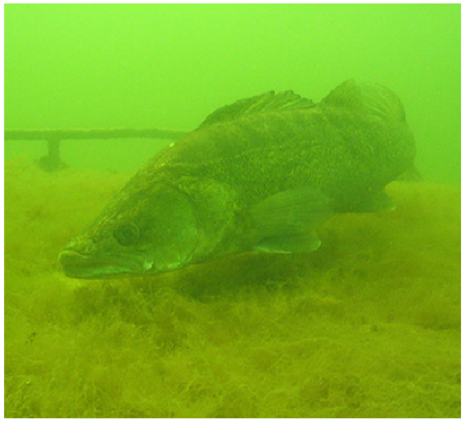
Focus on processes relevant to engineering:

- Oxygen management
- Nitrogen management
- Bacteriological pollution
- Pollution absorbed to suspended matter

Water quality processes

Oxygen management

- Biological aspects
  - Production through photosynthesis
    - Green plants
    - Light intensity
  - Consumption by organisms
  - Significant diurnal fluctuations
    - Oxygen deficits



Water quality processes

Oxygen management

- Chemical aspects
  - Aeration (equilibrium with air)
  - Saturation concentration $C_s = K_s \cdot p$

    K_s solvability

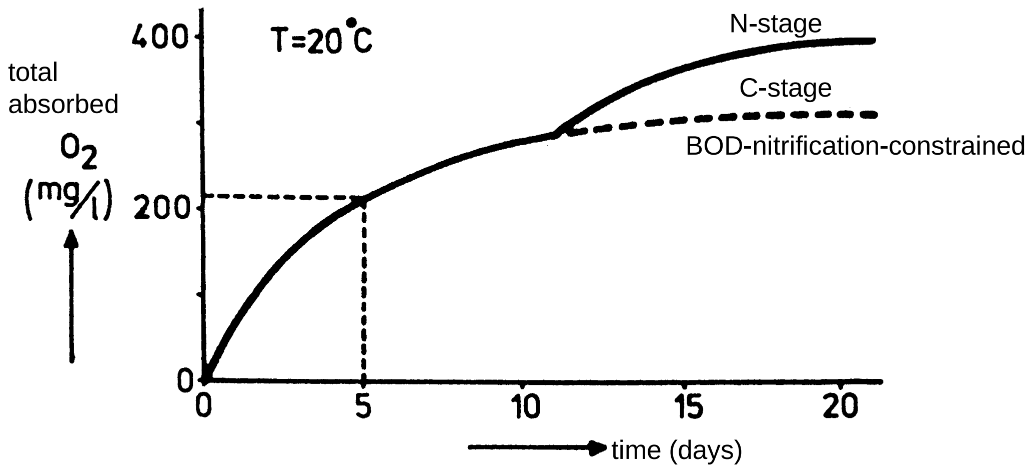
    p vapour pressure
  - Oxygen demand
    - Sediment (SOD)
    - Degradation of organic matter (BOD)
  - Stratification in deeper water bodies

T	C_s (mg/1) O_2	
°C	dist. water	seawater
0	14.6	11.3
5	12.8	10.0
10	11.3	9.0
15	10.2	8.1
20	9.2	7.4
25	8.4	6.7
30	7.6	6.1

Water quality processes

Bio-chemical oxygen demand

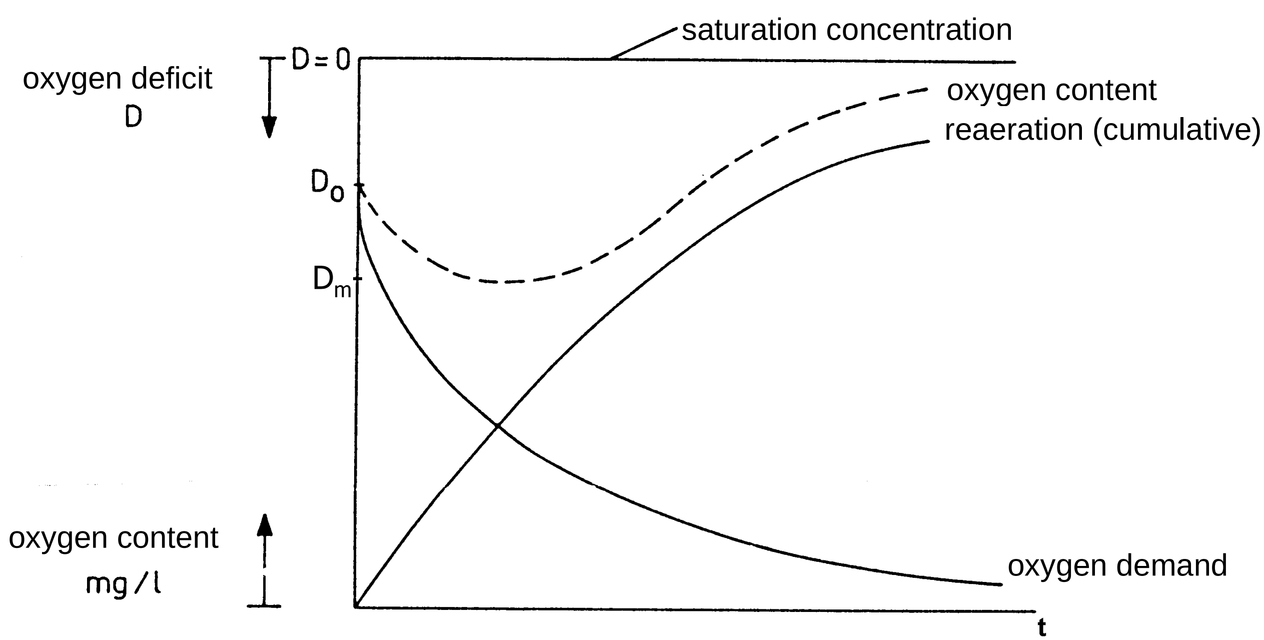
- Amount of oxygen [mg] necessary to mineralize bio-chemically-oxidizable components by bacteria
- Standard determination over 5 day's at 20°C: BOD_5^{20}
- Notion of organic carbon content
- $BOD_{20}^{20} \approx$ total BOD



Water quality processes

Bio-chemical oxygen demand

Oxygen concentration after introducing a oxygen consuming load



Water quality processes

Bio-chemical oxygen demand

- Self-purification: $f_{20} = \frac{k_d}{k_b}$

  f_{20} = self-purification at 20°C
  k_d = bio-chemical degradation constant
  k_b = re-aeration constant

	f_{20}
Small pond	0.5 - 1.0
Large lake	1.0 - 1.5
Slowly flowing river	1.5 - 2.0
Large river	2.0 - 3.0
Fast flowing river	3.0 - 5.0
Rapid	5.0 - 25.0

- Temperature dependence: $f_T = f_{20}(1.03)^{20-T}$

temperature °C	5	10	15	20	25	30
f-value	1,58	1,35	1,16	1,00	0,86	0,74

Water quality processes

Bio-chemical oxygen demand

	f_{20}
Small pond	0.5 - 1.0
Large lake	1.0 - 1.5
Slowly flowing river	1.5 - 2.0
Large river	2.0 - 3.0
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  f_{20} = self-purification at 20°C
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  k_b = re-aeration constant

  - Temperature dependence: $f_T = f_{20}(1.03)^{20-T}$

temperature °C	5	10	15	20	25	30
f-value	1,58	1,35	1,16	1,00	0,86	0,74

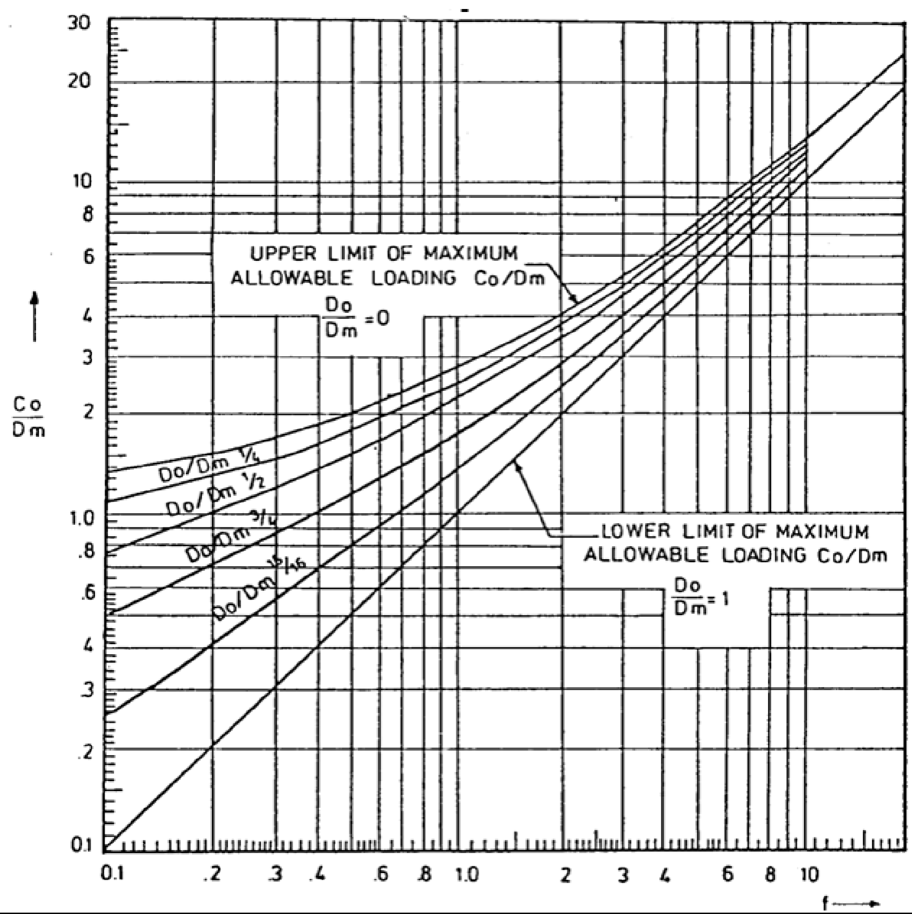
- Maximum oxygen deficit: $D_m = \frac{C_0}{f}\left[f\left\{1-(f-1)\frac{D_0}{C_0}\right\}\right]^{\frac{1}{1-f}}$

  C_0 = initial BOD concentration including the load
  D_0 = initial oxygen deficit of the water without the load

Water quality processes

Bio-chemical oxygen demand

Source: Fair et al, 1968.



Water quality processes

Nitrogen management

- Double stage nitrification process:
  - Nitrosomonas $2NH_3 + 3O_2 \rightarrow 2NO_2^- + 2H^+ + 2H_2O$
  - Nitrobacter $2NO_2^- + O_2 \rightarrow 2NO_3^- + 2H^+ + 2H_2O$

$$2NH_3 + 4O_2 \rightarrow 2NO_3^- + 2H^+ + 2H_2O$$

- Denitrification:
  - Restricted oxygen availability:

$$2H^+ + 2NO_3^- + 5AH_2 \rightarrow N_2\uparrow + 6H_2O + 5A$$

Water quality processes

Bacteriological pollution

- Indicator organisms (faecal Coli, faecal Streptococci)
- Exponential decrease in surface water conditions
    - water temperature
    - salt content
    - light intrusion
    - turbulence
    - competing organisms

Water quality processes

Absorbed pollution

- Pollutants absorbed to suspended matter
  - Suspended organic matter / clay minerals
  - Suspended iron-hydroxide flocks
- Settling of particles according to Stokes

$$v = \sqrt{\frac{2}{C_d}\frac{V}{A}.g.\frac{\rho_d - \rho}{\rho}}$$

v = velocity of the settling
C_d = resistance coefficient
V = volume of a particle
A = projected area of the particle
ρ_d = density of the particle
ρ = density of the water

Water quality processes

Absorbed pollution

- Settling depends on
  - Diameter of the particles (coagulation!)
  - Specific density of the particles
  - Water temperature
  - Hydraulic conditions (turbulence, dispersion)

Water quality processes

Ecology

- Ecosystem: interactive, coherent entity of living (biotic) and non-living (abiotic) factors

- Abiotic
  - Physical factors
    - light
    - temperature
    - turbulence
  - Chemical characteristics
    - dissolved gasses
    - major elements
    - nutrients
    - trace elements
    - organic substances

- Biotic
  - Primary producers

    converting inorganic into organic matter
  - Consumers

    using organic matter
  - Decomposers

    converting organic into inorganic components

Water quality processes

Ecology in urban water systems

- Artificial character of the urban water system
  - European Water Framework Directive: ‘heavily modified waters’
  - No straightforward reference system
- Specific kinds of pollution
  - Sewer Overflows
  - Stormwater runoff
- Relevant processes:
  - Oxygen balance
  - Nitrogen balance
  - Bacteriological pollution
  - Pollution absorbed to sediments
  - Eutrophication

Water quality processes

Eutrophication

- Trophic state classification of ecosystems
  - Total phosphorus
  - Chlorophyll a
  - Secchi depth

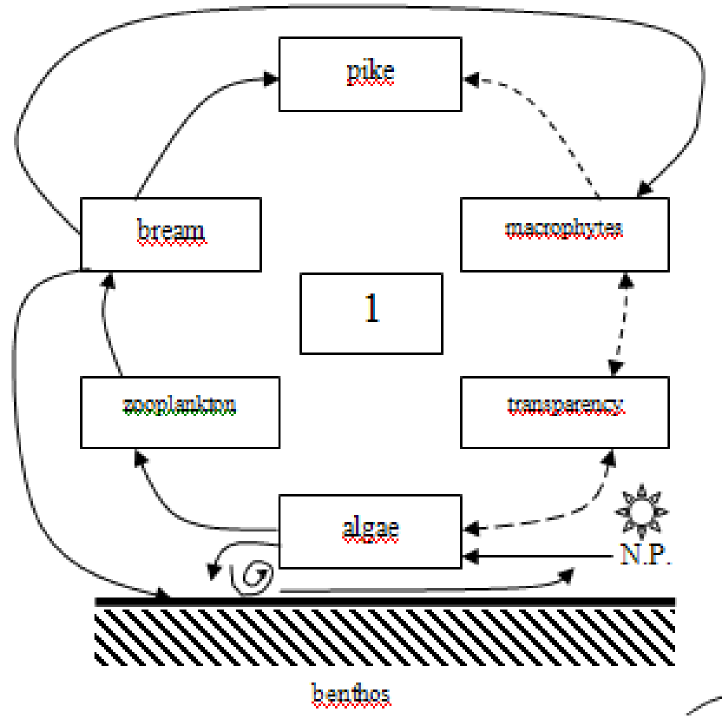
Trophic state	TP ($\mu g.l^{-1}$)	Chl ($\mu g.l^{-1}$)		Secchi (m)	
		mean	maximum	mean	maximum
Oligotrophic	< 10.00	< 2.5	< 8.0	> 6.0	> 3.0
Mesotrophic	10 – 35	2.5 - 8	8 – 25	6 - 3	3 – 1.5
Eutrophic	35 – 100	8 - 25	25 – 75	3 – 1.5	1.5 – 0.7
Hypertrophic	>100	> 25	> 75	< 1.5	< 0.7

Water quality processes

Eutrophication

1. Dynamic equilibrium
   - Aquatic plants provide spawning place for predatory fish which control fish population and thereby daphnids
   - Aquatic plants prevent suspension of sediment

→ Increase of nitrogen and phosphate



Water quality processes

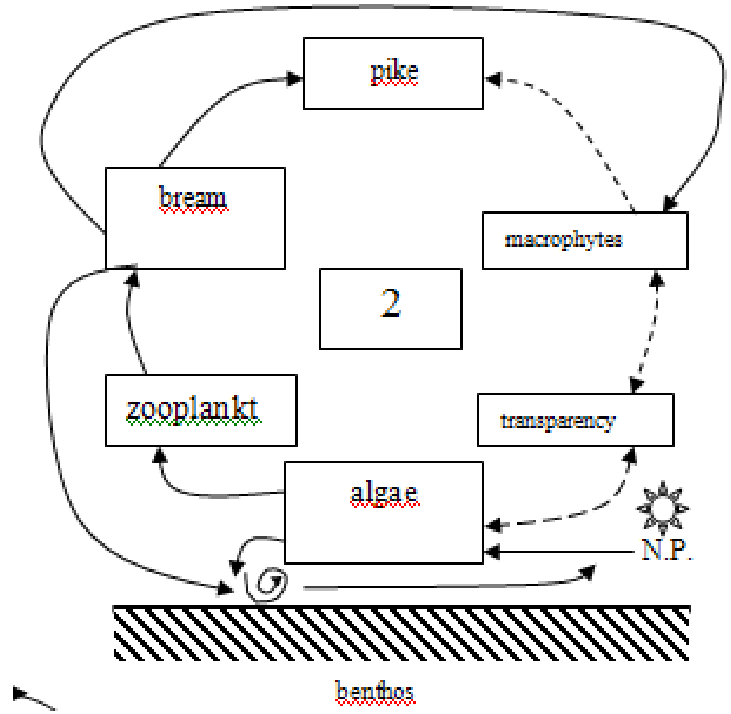
Eutrophication

1. Dynamic equilibrium
   - Aquatic plants provide spawning place for predatory fish which control fish population and thereby daphnids which control algae growth
   - Aquatic plants prevent suspension of sediment

→ Increase of nitrogen and phosphate

2. Algae growth
   - Decrease of light intrusion
   - Decrease of aquatic plants, less predators, more bream, less daphnids

→ Further increase of eutrophication

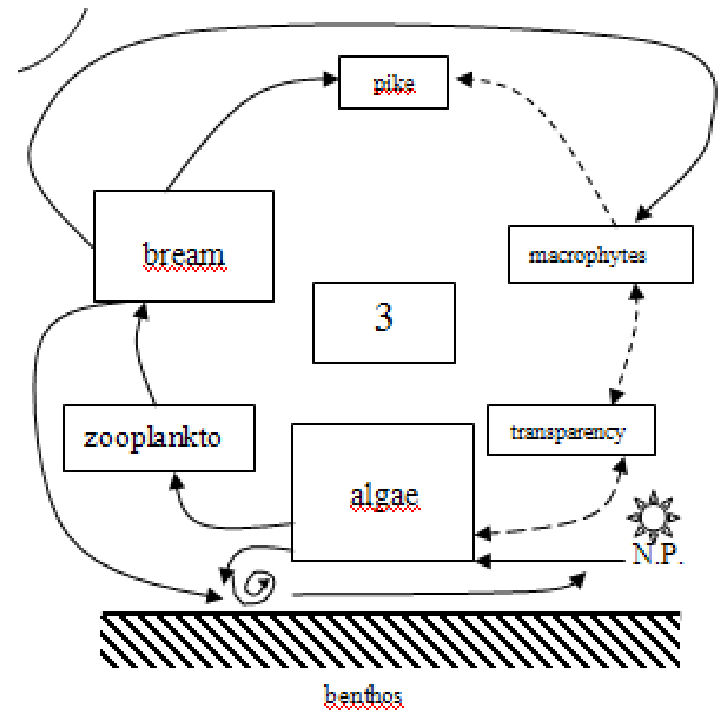


Water quality processes

Eutrophication

3. Algae bloom
   - Aquatic plants dissapear, predators dissapear
   - Benthivorous fish flourish

→ Further increase of eutrophication



Water quality processes

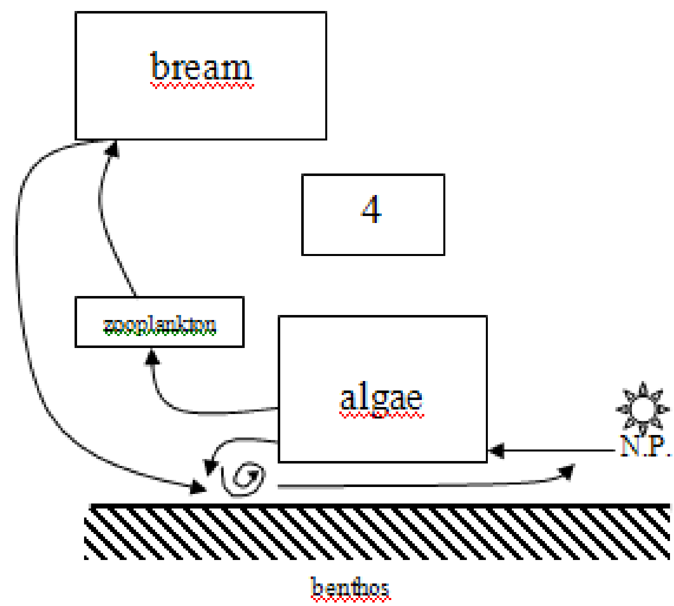
Eutrophication

3. Algae bloom
   - Aquatic plants dissapear, predators dissapear
   - Benthivorous fish flourish

→ Further increase of nutrients

4. Algae and bream dominated ecosystem
   - Turbid water
   - Low biodiversity
   - Toxic conditions

→ Alternative stable state



Water quality processes

Ecological water quality assessment

- Physical and chemical parameters → conditions for an ecosystem
  - Water sample is exact value of a specific aspect at a specific time
- Ecological based assessments → state of the ecosystem
  - Sample of organisms indicates conditions over longer period
- STOWA: urban ecological water quality assessment system (EBEOstad)
  - Perception by man
  - Ecological water quality
  - Ecological quality of the embankments

Water quality processes

Ecological water quality assessment

- Ecological indicators

Indicator	Description	Indicator organisms
Saprobity	Measure for organic load (oxygen demanded load)	Macro invertebrates Diatoms
Trophism	Measure for nutrient balance (ammonium-, nitrate, phosphate concentration and oxygen saturation)	Diatoms
Construction and management	Connection with type of water body	Macro invertebrates Morphology
Characteristics belonging to that variant of water body	Characteristics belonging to that variant of water body	
Characteristics belonging to that specific water body	Flora and fauna of that special type of water bodies	Macro invertebrates

Exchange with the surrounding

Water quantity

- Surplus water discharge
  - Stormwater runoff and drainage (via open water courses)
  - Effluent of waste water treatment plants
  - Combined sewer overflows
- Shortage during drought
  - Water inlet from rural surface water
- Hydraulically disconnect the urban water from the rural area
  - Backwater effect
  - Weirs
  - Pumps

Exchange with the surrounding

Water quality

- Quality difference between in- and outflow
  - Discharge of relatively good quality storm- and drainage water

	P	N	BOD
Discharge to the canal system	3,4	20	17
Discharge to the surrounding	1,1	9	19
Retention in the canal system	2,3	11	-2

- Flushing of canal systems to restrict retention times
- Water intake during drought introduces poor quality water from the surroundings

Exchange with the surrounding

Water quality

Treatment efficiencies of a sewage treatment plant