Modelling in Sanitary Engineering

University of Natural Resources and Life Sciences, Vienna
Department of
Water, Atmosphere, and Environment

811.360 VU 3.0

Introduction

Thomas Ertl, Günter Langergraber, Thomas Telegdy

8 November 2011

Program

University of Natural Resources and Life Sciences, Vienna
, and Environment

	Monday	Tuesday	Wednesday	Thursday	Friday
	07.11.2011	08.11.2011	09.11.2011	10.11.2011	11.11.2011
09:00 - 12:00	-	Introduction, steady state design models	WWTP 1	WWTP 3	-
13:00 - 16:00	-	-	WWTP 2	WWTP 4	-
	Monday	Tuesday	Wednesday	Thursday	Friday
	14.11.2011	15.11.2011	16.11.2011	17.11.2011	18.11.2011
09:00 - 12:00	Urban Drainage 1	Urban Drainage 3	-	-	-
13:00 - 16:00	Urban Drainage 2	Urban Drainage 4	-	-	-
	Urban Drainage 1	Urban Drainage 3	-	-	-
	21.11.2011	22.11.2011	23.11.2011	24.11.2011	25.11.2011
09:00 - 12:00	Integrated modelling	Exam	-	-	-
13:00 - 16:00	-	-	-	-	-

Objectives

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1. Basic knowledge on modelling of sewers, wastewater treatment plants and receivers
2. Recognising the limits of classical dimensioning procedures and dynamic simulation
3. Better understanding on the processes in sewers and treatment plants

Overview

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1) Introduction

- Introduction into modelling
- Steady-state models for wastewater treatment plants
- Steady-state models for sewer networks and combined sewer overflows

2) Wastewater treatment plants

- Theory:
  - Components of a WWTP model
  - Control of AS plants
  - Simulation studies (Unified Protocol, data quality, calibration)
  - Simulation of constructed wetlands for wastewater treatment

Overview

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2) Wastewater treatment plants (cont'd)

- Modelling exercises:
  - Development of a biokinetic model (nitrification)
  - Dynamic simulation of a AS plant
  - Control of a AS plant
  - Calibration of a WWTP model

3) Urban Drainage

- Processes in Urban Drainage
- Surface Run-Off + Pipe Flow
- Dynamic Hydraulic Models
- Continuous Hydrological Models

4) Introduction to integrated modelling

(Modelling of Sewer + WWTP + Receiving waters)

"New rules"

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Decision of the Senate (19.1.2011):

- Bei einer VU erfolgt eine Trennung in den Vorlesungs- und den Übungsteil. Der Übungsteil ist immer prüfungsimmanent.
- Im Übungsteil sind mindestens 3 Teilleistungen zu erbringen. Eine einmalige Nichtteilnahme an einer Teilleistung darf nicht zu einer negativen Beurteilung führen.
- Die Lehrveranstaltungsleiter haben dafür Sorge zu tragen, dass die Übungsleistung am jeweiligen Institut in Evidenz gehalten wird.

→ that means for this course:

- Assessment of exercise part = active participation of the student
- Formal documentation of assessment = List of participation will be circulated on each day in one of the exercise parts, i.e. in total 6 times during the course

Design vs. simulation

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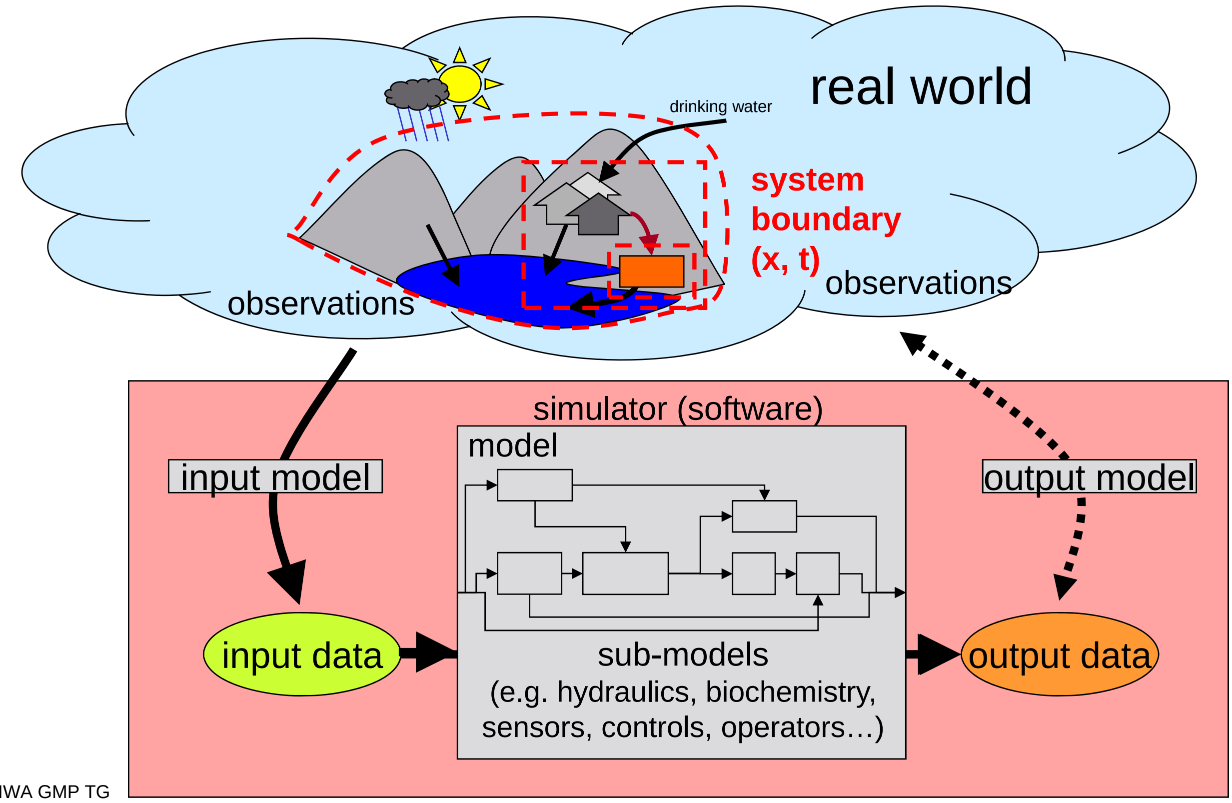
Simulation is a fundamentally **different concept than** the method used in traditional process **design**.

Example:

- A traditional **design calculation** may use a certain influent concentration/load and required effluent quality to provide a direct determination of the necessary reactor volume of the treatment plant i.e. the **volume is the output** of the calculation.
- In **simulation**, similarly to reality, the influent load and the available reactor volume will determine effluent quality, i.e. the load and volume are inputs and **effluent quality is the output**.

Reality vs. model

Adapted from Hug, 2007



Model vs. software 1

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- The basis of all simulation models is the ***conceptual model***, which adequately describes the system and the relevant physical, chemical and microbiological processes
  - processes are independent from the system (transport processes, reactions, …)
  - different concepts for different objectives ("blackbox" vs. mechanistic models)
- ***Mathematical models*** transfer the conceptual model to a mathematical formulation
  - deterministic vs. stochastic models
  - mathematical formulation includes balance equations for continuity, momentum and energy, as well as the system dependent equations of state (state variables).

Model vs. software 2

Balance equations

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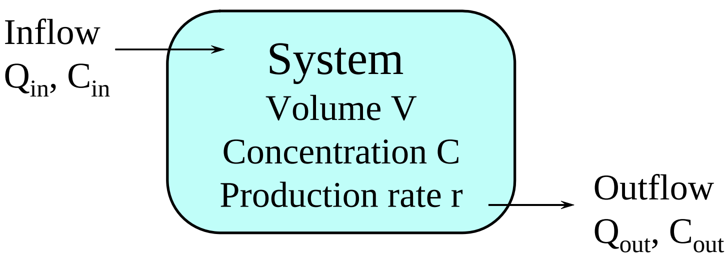

Units:
[Q] = m^3/d
[C] = g/m^3
[V] = m^3
[r] = $g/(m^3.d)$

Mass balance equation?

Model vs. software 3

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- ***Analytical model***: if analytical solution for governing (differential) equations is available (exception)
- ***Numerical model***: Implementation of a mathematical model into a numerical algorithm
  - Initial conditions initialise the variables at the beginning of the simulation
  - Boundary conditions must be defined for the boundaries of the system (constant or time-variant)
  - Numerical algorithms: Finite Element Method, Finite Differences, diverse numerical algorithm for integration (Euler, Runge-Kutta)
- ***Simulation program*** (software): Implementation of a numerical algorithm
- ***Model verification***: mathematical and experimental verification

Why models / simulation?

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- Research
  - Better knowledge on (parts of) complex processes
  - Test of new knowledge
- Design
  - Design optimisation
  - Comparison of different variants (e.g. influent loads)
- Analysis of existing plants
  - Extension of plants
  - Optimization of operation (also catchment area)
  - Test of different operation strategies and/or control strategies
  - Model-based and/or real-time control

Models - Summary

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- Models are simplified pictures of the reality and not the reality
- Also the most detailed mathematical models have their limits, to know the limits is the "art of modelling" and the duty of the modeller (= the user of the model)
- The common assumption – a computer program is a model that makes for all inputs good prognoses – is wrong!
- Computer programs are based on models – for a model many different simulators may exist
- Do not use simulation programs without understanding the fundamentals and limits of the models implemented

Steady-state design models
Wastewater treatment plant

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2 steady-state design models are commonly used (German speaking countries).

These models are based on :

1. volume loading / sludge loading (BOD_5/COD removal)
   - e.g. DWA A226 (former ATV A126, < 5000 PE)

2. sludge age (nitrification)
   - e.g. DWA A131 (former ATV A131, > 5000 PE)

Steady-state design models

Wastewater treatment plant

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Sludge loading concept (1955)

$$B_{TS} \equiv \frac{Q \cdot BOD_5}{V_{BB} \cdot TS_{BB}} = \frac{\text{Food}}{\text{Micro-organisms}} = \frac{F}{M}$$

B_{TS} = Sludge loading (kg BOD_5 kg^{-1} TSS d^{-1})
Q = Influent (m^3 d^{-1})
BOD_5 = BOD_5 influent concentration (kg BOD_5 m^{-3})
V_{BB} = Volume of the activated sludge tank (m$^{3)}$
TS_{BB}= Activated sludge concentration (kg TSS m^{-3})

Steady-state design models

Wastewater treatment plant

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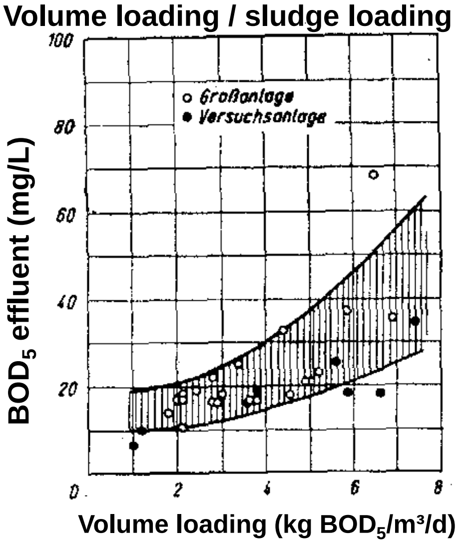
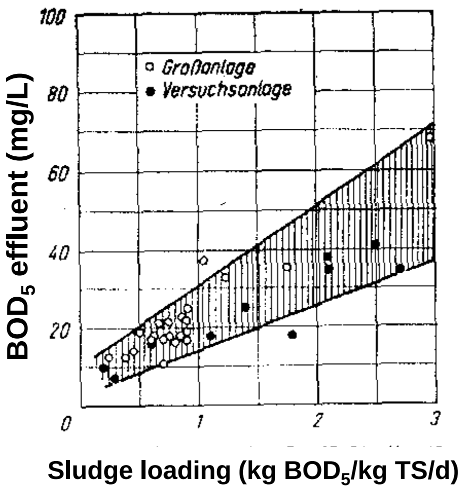
Volume loading / sludge loading





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Steady-state design models
Wastewater treatment plant

Sludge loading – critical points

Composition of AS depends on:

- Wastewater (urban drainage system – combined/separated, amount of inorganic compounds)
- Operation of the wastewater treatment plant (with/without primary settler and/or chemicals used for precipitation, respectively)

⇒ No direct relationship between treatment efficiency and sludge loading

⇒ Design not very reliable

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Steady-state design models
Wastewater treatment plant

Sludge age concept (1964, nitrification)

Definition

- The sludge age is the mean cell residence time of sludge (biomass) in the plant

Observation

- Nitrification requires a minimum (aerobic) sludge age

Design

- Direct coupling of design to growth of the most sensitive micro-organisms (nitrifiers)
- However, it is still a steady-state design model

Steady-state design models
Wastewater treatment plant

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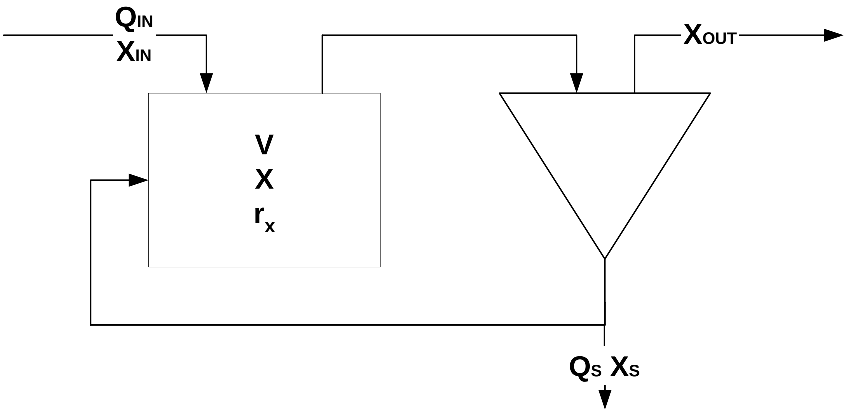
Sludge age



$$\frac{dX}{dt}\cdot V = Q_{IN}\cdot X_{IN} - Q_S\cdot X_S - (Q_{IN}-Q_S)\cdot X_{OUT} + r_x\cdot V$$

Steady-state design models
Wastewater treatment plant

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Sludge age

$$\frac{dX}{dt}\cdot V = Q_{IN}\cdot X_{IN} - Q_S\cdot X_S - (Q_{IN}-Q_S)\cdot X_{OUT} + r_x\cdot V$$

Steady state: $$\frac{dX}{dt}\cdot V = 0$$

$$Q_S\cdot X_S = Q_{IN}\cdot X_{IN} - (Q_{IN}-Q_S)\cdot X_{OUT} + r_x\cdot V$$

for XA: $$Q_S\cdot XA_S = Q_{IN}\cdot XA_{IN} - (Q_{IN}-Q_S)\cdot XA_{OUT} + r_x\cdot V$$

$$XA_{IN} = 0 \text{ and } XA_{OUT} = 0 \text{ and } r_{XA} = \mu_{XA}\cdot XA$$

$$Q_S\cdot XA_S = \mu_{XA}\cdot XA\cdot V_{BB}$$

$$\boxed{\frac{1}{\mu_{XA}} = \frac{XA\cdot V_{BB}}{Q_S\cdot XA_S} = t_{SA}}$$

Steady-state design models
Wastewater treatment plant

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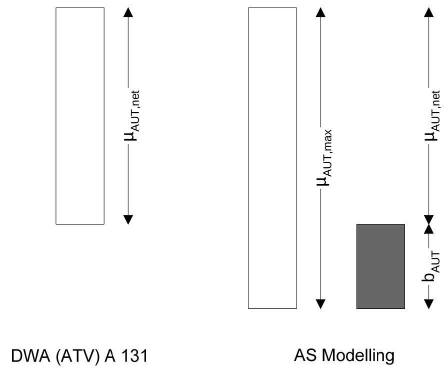
Sludge age

$$\frac{1}{\mu_{XA}} = \frac{XA \cdot V_{BB}}{Q_S \cdot XA_S} = t_{SA}$$

- t_{SA} depends on (net) growth rate →
- to determine V_{BB} additionally required are:
  - Composition of wastewater (TS_0/BOD_5)
  - Temperature
  - Dry matter content of AS tank



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Urban Drainage - Introduction

(steady state sewer design - requirements & proof)

IS2

Thomas Ertl

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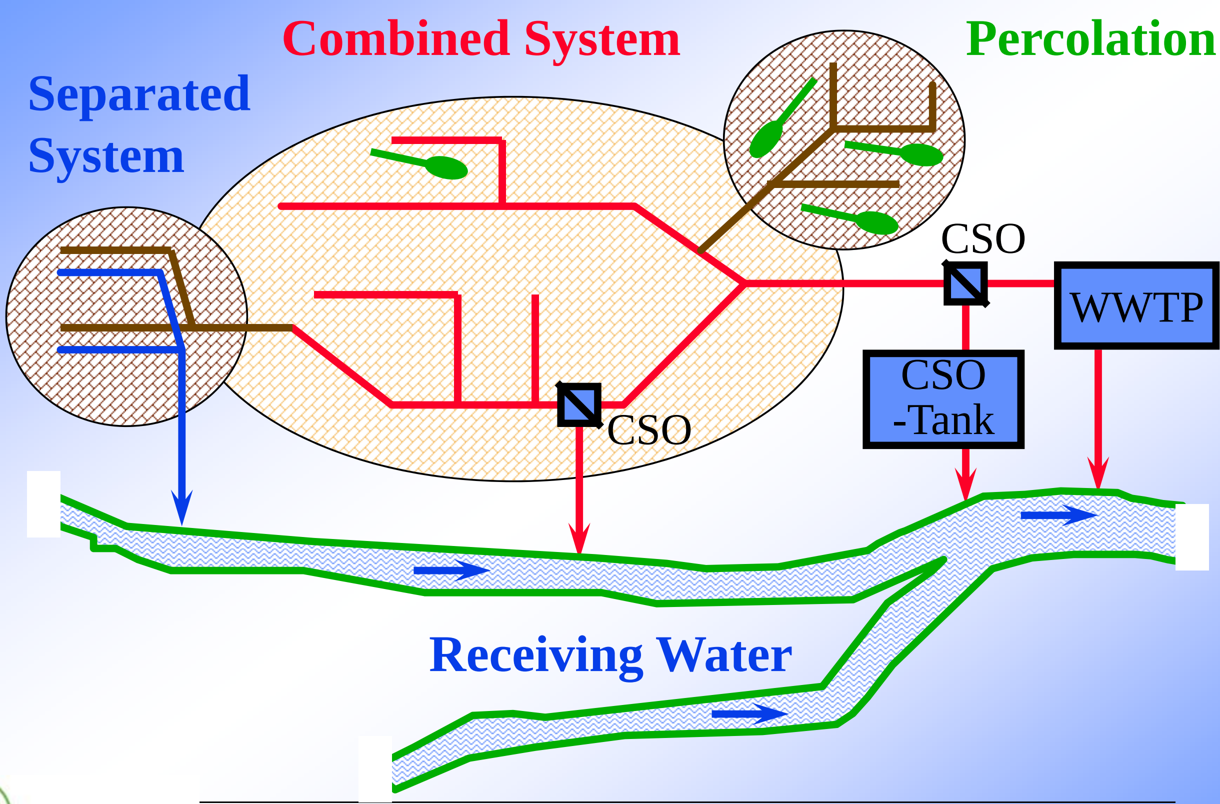
Folie 1

IS2 Dynamik: Lehre von der Bewegung von Teilchen unter dem Einfluss von Kräften. Die D. befasst sich mit den Ursachen einer Bewegung, im. Ggs. zur Statik, welche die Bedingungen untersucht, in denen keine Bewegung stattfindet.
Ein thermodynamisches System befindet sich i.e. stationärem Zustand, wenn seine intensiven Variablen zeitunabhängig sind. (Enzykl. NWuT)
GL: Stationärer Z. charakterisiert eine Situation, in der keine Zustandsänderungen auftreten.
IWGA SIG; 07.01.2004

Contents of UD-Introduction

- Goal of this Lecture:
  - Understanding Dimensioning (Steady State Models) versus Dynamic Modelling in Urban Drainage
- Basics of Urban Drainage
  - Pollution Control
  - Hydraulic Requirements
- Combined Sewer Overflows & Tanks
  - Example: First Flush Stormwater Tank Dimension
- Stormwater Hydraulics
  - Example: Dimensioning Stormwater Pipes

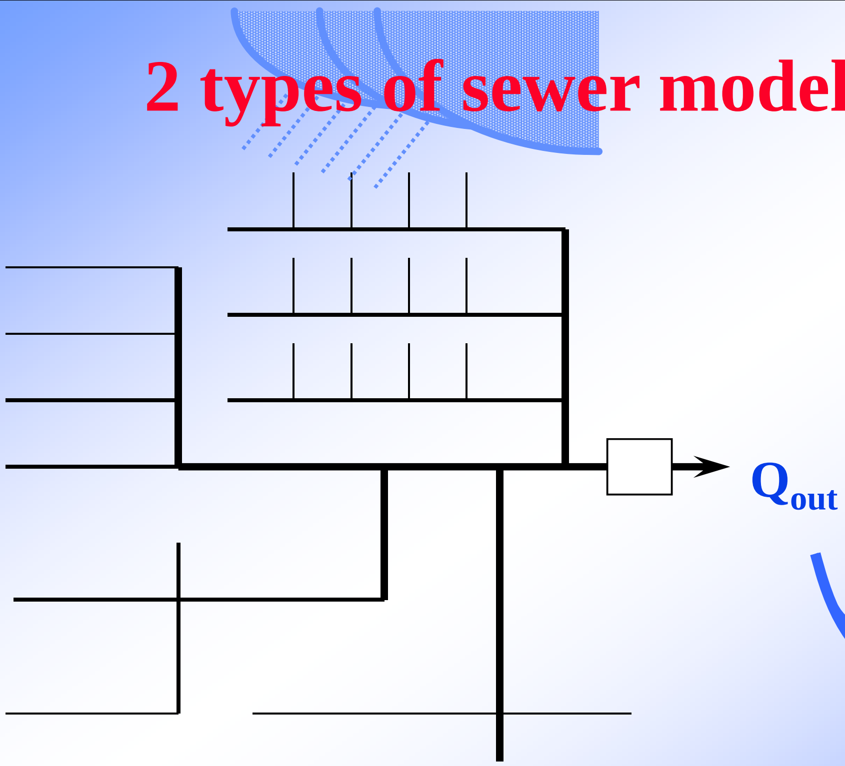
Urban Drainage Elements

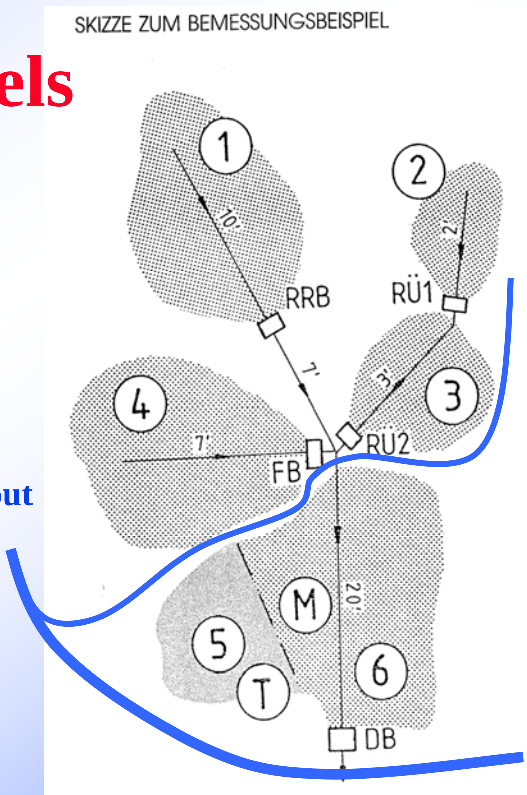


Urban Drainage Objectives

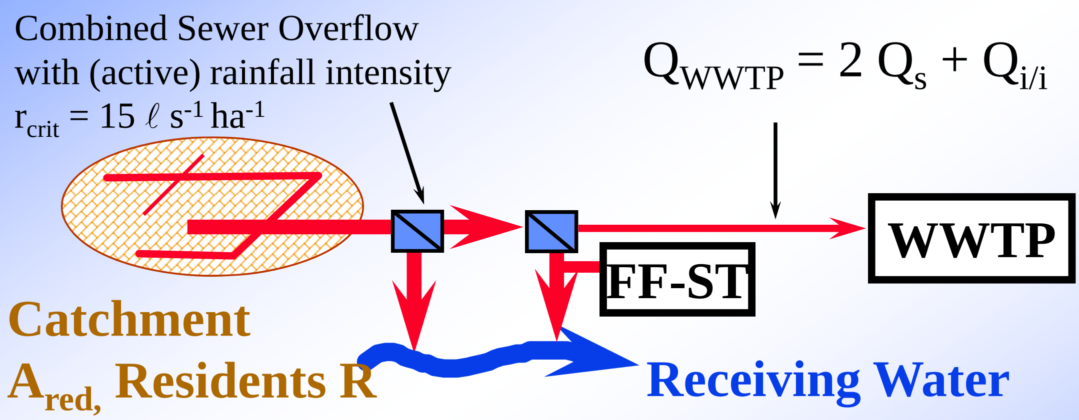
- Multiple Objectives
  - Pollution Control (incl. of WWTP), Safety of Drainage and Cost-Efficiency
- Quality Standards → Pollution Control!
  - Restriction of WWTP inflow → necessity of Overflow-Treatment. Total Emission to Receiving Water!
- Quantity Standards → Flooding Prevention!
  - Flooding of properties, buildings and infrastructure. Question of risk and cost-efficiency → rainfall intensity (return period, duration) and flooding probability (return period)

2 types of sewer models



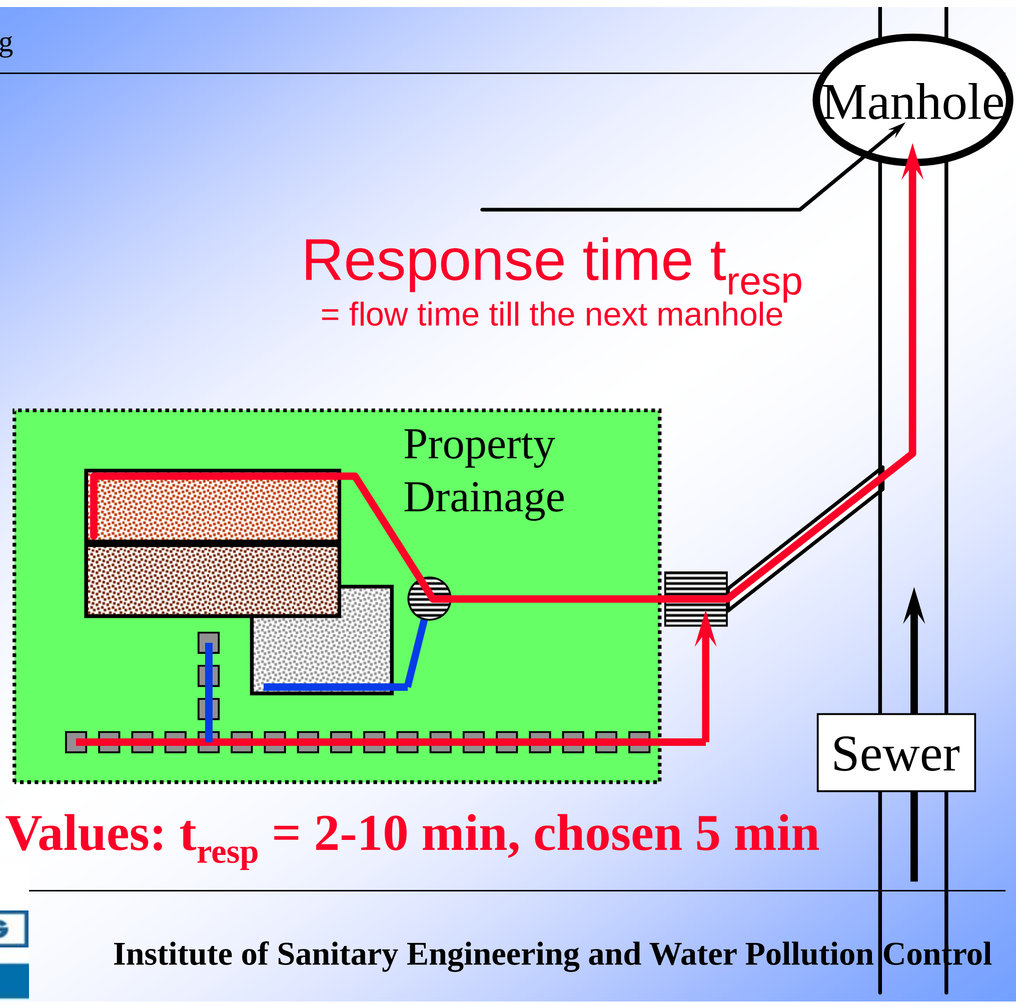


Dimensioning a Combined Sewer Overflow Tank



Question:

How much capacity/ volume does the **Stormwater Tank** need for retaining the **First Flush**?



Typical Values: t_{resp} = 2-10 min, chosen 5 min

Example: Dimensioning a first flush stormwater tank

Assumptions:

- At the site of the Stormwater tank: $t_0 = t_{resp} + t_f$.
- Duration of First Flush ca. t_0 = 15 min
- Rainfall intensity at which the CSO comes into action
  $r_{crit} = 15\ \ell\ s^{-1}\ ha^{-1}$
- Q_{DW}: 5+3=8 $\ell\ s^{-1}$ 1000 R^{-1}; e.g. 200 R ha_{red}^{-1} -> 1,6 $\ell\ s^{-1}\ ha_{red}^{-1}$
- $Q_{WWTP} = 2\ Q_s + Q_{i/i}$ or 2,6 $\ell\ s^{-1}\ ha_{red}^{-1}$

$$V_{FFST} = (Q_{DW} + A_{red} \cdot r_{crit} - Q_{WWTP}) \cdot t_0$$

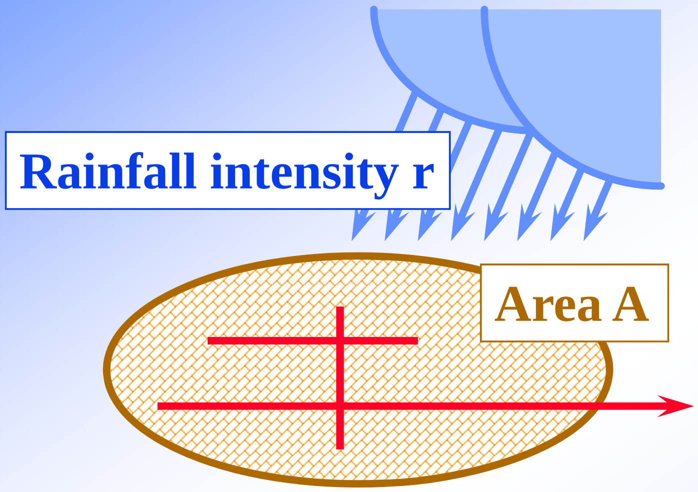
$$\frac{V_{FFST}}{A_{red}} \cong 13\ m^3 ha_{red}^{-1}$$

(1,6+15-2,6)*15*60=12600 *l*/ha

Conclusion of CSO Example

- Question: Volume of Stormwater Tanks?
  - ÖWWV Rbl. 19 (1987): Vs= 15m³ (to 25m³)/ ha_{red}
    - Very simple steady state design within requirements!
- New ÖWAV-Guideline 19 (2007)
  - The effect of the whole CSO concept in a sewer network has to be proved by a combination of **hydrological modelling techniques** with simplified pollution load calculations. There is also a requirement for the verification of the model results by full scale monitoring data. (Fenz & Kroiss, 2003) →
- Method of Proof --> Long-Term-Simulation
  --> Question: overflow rates where and when?

Stormwater Hydraulics



Stormwater run-off / discharge

$$Q_R = r \cdot A \cdot \Psi$$

$$= I * A * C$$

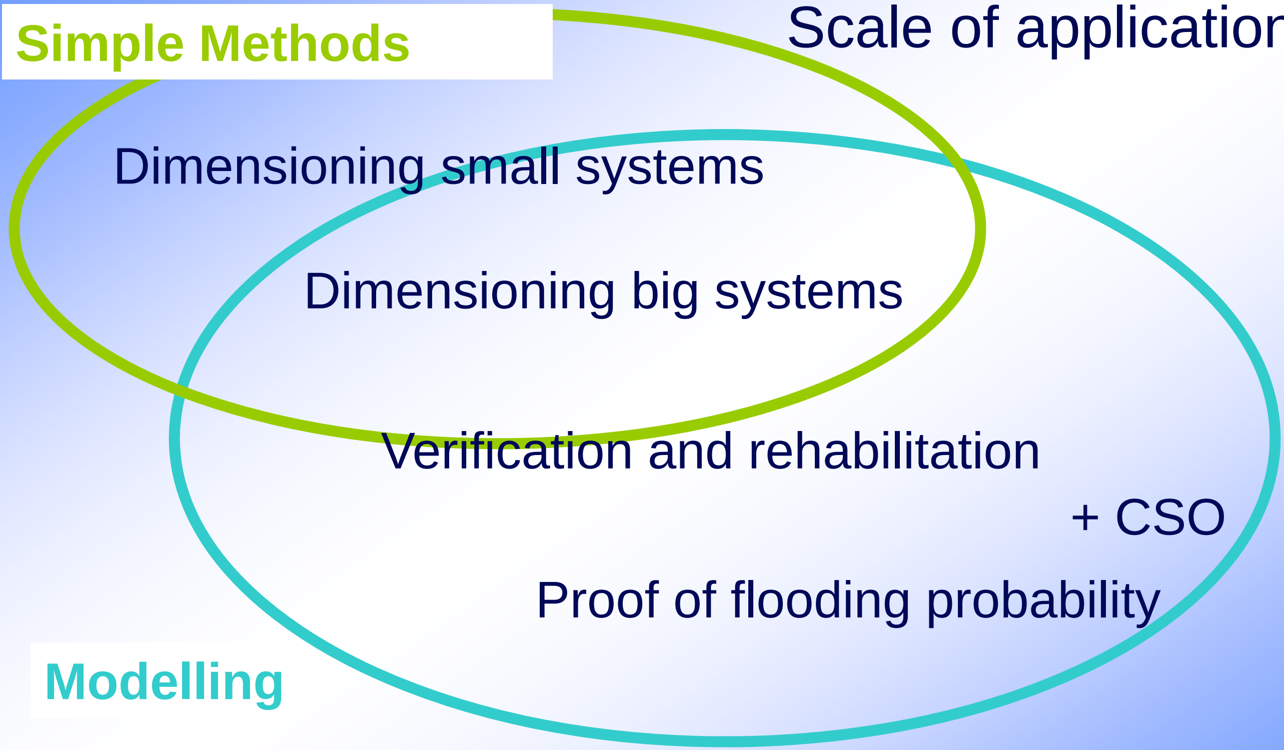
$$\rightarrow C * I * A$$

Ψ = **run-off coefficient**

Dimensioning a stormwater pipe

- Question: Dimension of the pipe?
  - Stormwater Run-off: Q_R
    - Maximum flow = Rainfall intensity * Area * run-off coefficient
    - rainfall intensity for dimensioning: ÖWAV Leitfaden [NIEDA] (federal gov. / acc. to REINHOLD / flat rate) !New: EHYD!
  - hydraulic dimensioning of a pipe
    - section, pipe grade, operating roughness
  - simple methods: e.g. rational method (“CIA”, „Zeitbeiwertverfahren“) / Time-Area Method
- But for question: what happens when and where?
  - Answer: Try it with Modelling --> proof of flooding!!

Scale of application



VU Modelling

Resulting requirements and proof

Hydraulic Capability

⇨ Recommended return periods for design storms & for flooding probability (EN 752-4, 1996)

Recommended return periods for design storms (once in „n“ years)	Location	Recommended return periods for flooding probability (once in „n“ years)
1 in 1	Rural Area	1 in 10
1 in 2	Residential Area	1 in 20
1 in 2	Downtown, Industrial- and Commercial Areas a) with proof of flooding	1 in 30
1 in 5	b) without proof of flooding	-
1 in 10	Underground traffic facilities, subways	1 in 50

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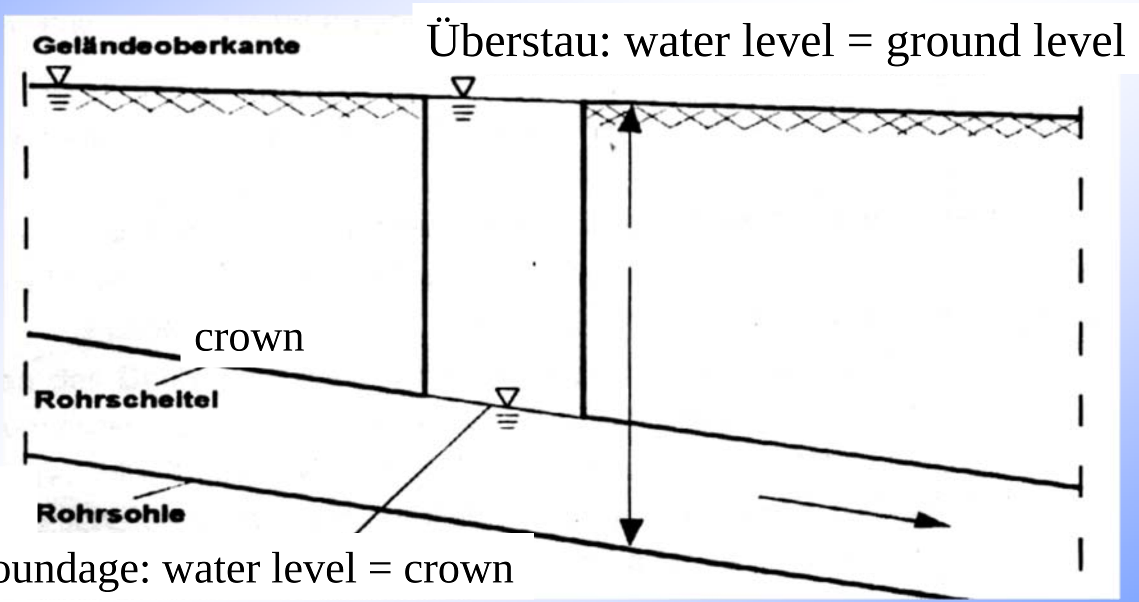
Definitions

flooding: damage caused by overflow

⇘Impoundage / *Überstau* / Flooding



Reliability & Safety of Sewer Systems

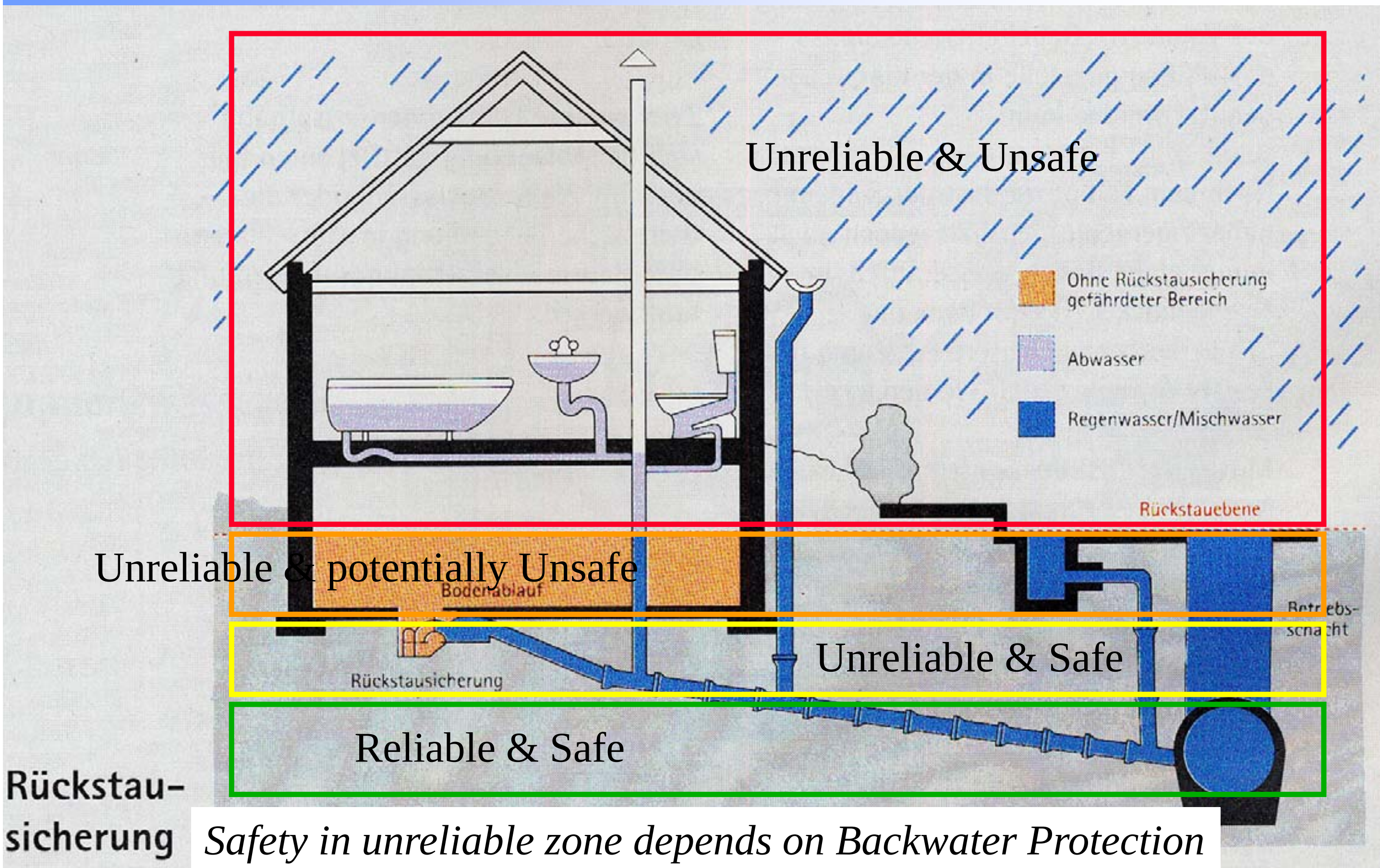
(Stransky & Fatka, 2005)

Table 1. Regimes of the hydraulic behaviour of the sewer system

	Regime	Lower limit	Upper limit
1	Non-pressure	-	$Q \equiv Q_{max}$ (design discharge)
2	Non-pressure	$Q > Q_{max}$	$Q \equiv Q_{cap}$ (capacity discharge)
3	Pressure (Pr)	Water level > crown of pipe arch	Water level ≡ lower basement level
4	Pressure (Pr)	Water level > lower basement level	Water level ≡ ground level
5	Pr & Flooding	Water level > ground level	-

Table 2. States of sewer system reliability and safety

	Regime	Reliability	Safety	Surcharge
1	Non-pressure	Reliable within design values	Safe	None
2	Non-pressure	Reliable out of design values	Safe	None
3	Pressure	Unreliable	Safe	Low
4	Pressure	Unreliable	Potentially unsafe	Medium
5	Pressure & Flooding	Unreliable	Unsafe	High



Safety in unreliable zone depends on Backwater Protection

Example: Comparison of steep and shallow stormwater sewer grade

- Question: Which one has more hydraulic capability in case of higher rainfall intensity?
  - Given data:
    - A = 4 ha; psi = 0.33; Pipe: L = 300m; kb =1.0mm
    - r(10,0.5)= 227 l/s.ha; r(10,0.2)=295; r(10,0.1)=354
  - Case 1 shallow: Js = 0.6%, return period n=0.5
  - Case 2 steep: Js = 3.0%, return period n=0.2
  - What happens in these sewers with a rainfall n=0.1? (Coverage 2,5m each)
  - Result: pipe-result.ppt

Resulting requirements and proof

Hydraulic Capability

- EN 752 introduces **flooding probability** as crucial criteria for the **proof** of the capability respectively of the flood protection measures.
  - Difficulties (SCHMITT, 1998):
    - Reference Level + local situation (street gradient, -track, curbstones etc.) are critical parameter for flooding (very hard to implement in model)
    - check of frequency of occurrence:
      - doesn`t make sense with today`s computer models and software
      - instead of long term rain series → selection of intense rainfalls and then calculation of probabilities

Resulting requirements and proof

Hydraulic Capability

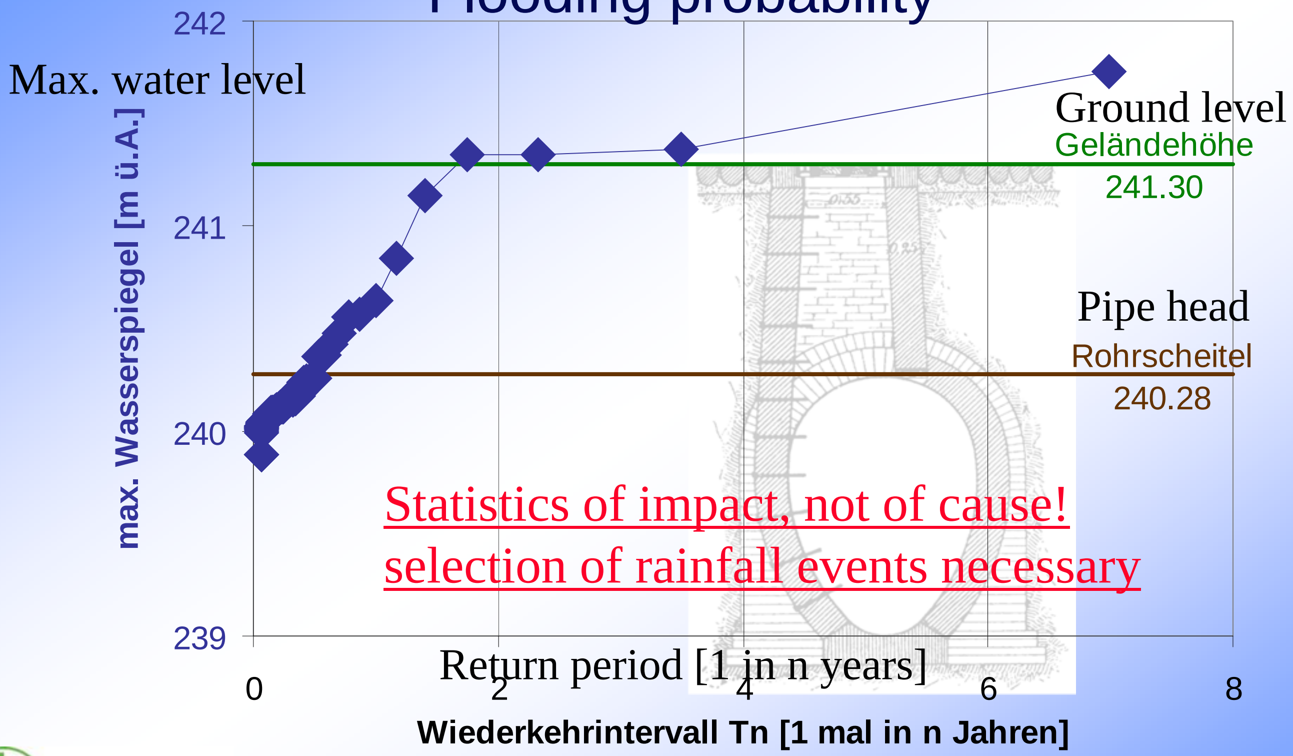
- ATV A 118 introduces „**Überstau“-probability**

Location	Recommended return period for "Überstau" [Impoundage] probability (once in „n“ years)
Rural Area	1 in 2
Residential Area	1 in 3
Downtown, Industrial- and Commercial Areas	1 in 5
Underground traffic facilities, subways	1 in 10

- 2 steps of examination (A 118):
  1) hydraul. proof of critical „Überstau“-probability

  2) check & assess flooding protection under consideration of local situation and if necessary secure with constructional arrangements

Flooding probability



Technical Standards

- **BS EN 752** (2008) „Drain and sewer systems outside buildings "
  - BS EN 752 provides a framework for the design, construction, rehabilitation, maintenance and operation of drain and sewer systems outside buildings.
  - BS EN 752 specifies the functional requirements for achieving these objectives and the principles for strategic and policy activities relating to planning, design, installation, operation, maintenance and rehabilitation.
  - It is applicable to drain and sewer systems, which operate essentially under gravity, from the point where wastewater leaves a building, roof drainage system, or paved area, to the point where it is discharged into a wastewater treatment plant or receiving water. Drains and sewers below buildings are included provided that they do not form part of the drainage system for the building.
- BS EN 752 (1996-1998)
  - Part 1: Generalities and definitions
  - Part 2: Performance requirements
  - Part 3: Planning
  - Part 4: Hydraulic design and environmental considerations
  - Part 5: Rehabilitation
  - Part 6: Pumping installations
  - Part 7: Maintenance and operations

British Standards Online http://www.bsi-global.com/

Rules & Standards (A + GER)

- ÖWAV- Regelblätter
  - Nr. 5 Richtlinien für die hydraulische Berechnung von Abwasserkanälen. (1980) → ATV A 110 (2006) & → ÖWAV RB 11
  - Nr.11 Abwassertechnische Berechnung von Schmutz-, Regen- und Mischwasserkanälen (2, vollständig überarbeitete Auflage, 2009)
  - Nr.19 [old] Bemessung und Gestaltung von Regenentlastungen in Mischwasserkanälen (1987)
  - Nr.19 [new] Richtlinien für die Bemessung von Mischwasserentlastungen (2, vollständig überarbeitete Auflage, 2007)
  - Leitfaden GEP, Schriftenreihe (1998)
  - Leitfaden Niederschlagsdaten zur Anwendung der ÖWAV-Rbl. 11 und 19 (2007) [NIEDA, ÖKOSTRA-Auswertung]
- ATV Arbeitsblätter (www.dwa.de)
  - A 118 (1999) Hydraulische Bemessung und Nachweis von Entwässerungssystemen
  - A 128 (1992) Bemessung und Gestaltung von Regenentlastungen in Mischwasserkanälen

The New Austrian guideline on CSO abatement (ÖWAV-Regelblatt 19, 2007)

- For CSO discharges the minimum requirements in Austria will be defined in the near future as percentage of the annual ammonium and percentage of the annual suspended solids load contained in storm water runoff that has to be treated biologically in waste water treatment plants.
- The minimum requirements set by the regulation have to be applied for the entire catchment of the combined sewer system but not for single combined sewer overflow structures.
- The effect of the whole CSO concept in a sewer network has to be proved by a combination of hydrological modelling techniques with simplified pollution load calculations. There is also a requirement for the verification of the model results by full scale monitoring data. (Fenz & Kroiss, 2003)

Abbreviations used in UD-Introduction

- A_{red} … reduced/ impervious Area
- CSO … Combined Sewer Overflow
- EN … European Standard
- FF-ST … First Flush Stormwater Tank
- psi … Run-off coefficient
- Q_{DW} … Dry Weather Flow
- $Q_{i/i}$ …Infiltration/Inflow
- Q_R … Stormwater Runoff
- Q_s … Sanitary Flow
- R … Residents
- Rbl. … Regelblatt (Guideline)
- r_{crit} … rainfall intensity → CSO in action
- t_{resp} … response time
- t_f … flow time
- UD … Urban Drainage
- WWTP … WasteWater Treatment Plant