Metrology in in Urban Drainage (TVM4141)

Francois Clemens

Part of the sheets (no. 9-22) are based on a document by Jean-Luc Bertrand-Krajewski (INSA Lyon, France)

Norwegian University of Science and Technology

Personal info

- Francois Clemens
- MSc + PhD TU Delft
- Professor urban Drainage TUD
- Between 1986-2000 consultancy
- Since 2000-2012 combination between consultancy/university (TUD)
- 2017 Guest professor with INSA Lyon (France)
- 2012-now combination between research/TU Delft
- Per 15/9/2020 adjunct professor with NTNU

Personal Info

- Main (research) interests
  - Asset Management
  - Metrology in the context of Urban Drainage
  - Development of inspection technology
  - Multi-disciplinary projects (preferably water and physics/maths/IT involved)
  - Experimental work to validate, falsify and, as a result, help improve models/engineering tools
  - Working with enthousiastic people on ‘impossible projects’

- Get in touch (pls. don’t hesitate)
  - Gsm: +31619159840
  - E-mail: francois.h.l.clemens@ntnu.no/francois.clemens@me.com

Global content

- Introduction metrology (Ch1*)
- Measuring principles for rain, waterlevel, discharge (Ch 2,3,4)
- Design measuring setup (Ch 6)
- Uncertainty in measuring results (Ch 8)
- Data validation (Ch 9)

*Metrology in Urban Drainage and stormwatermanagement: plug and Play: Download for free:

https://www.iwapublishing.com/books/9781789060102/metrology-urban-drainage-and-stormwater-management-plug-and-pray

Metrology is NOT Meteorology

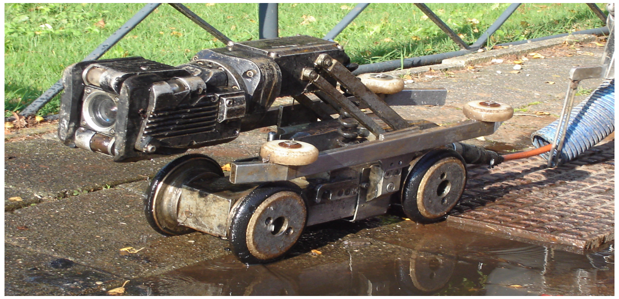
- Science of measuring, implications/applications for/in
  - Virtually all fields of science
  - Engineering
  - Trade
  - Legislation (e.g. speed limits in traffic)

- Important philosophical starting point for all aspects of metrology: “The truth cannot be known”

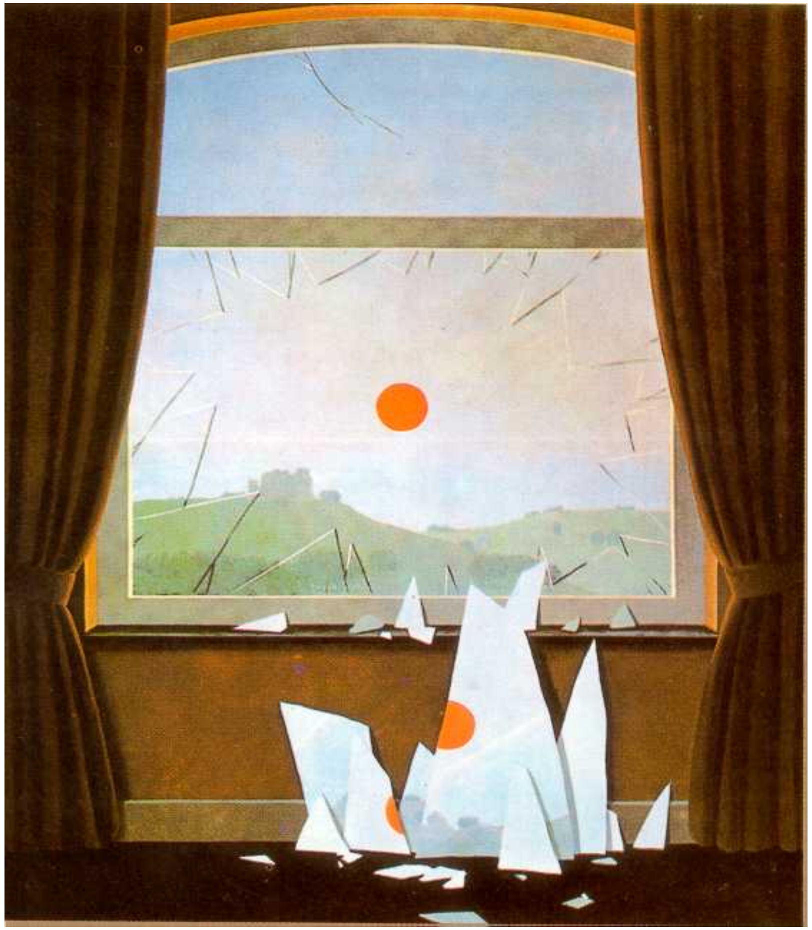
- “Birth” ~ French revolution, eventually -> SI system

Why monitor urban drainage systems?

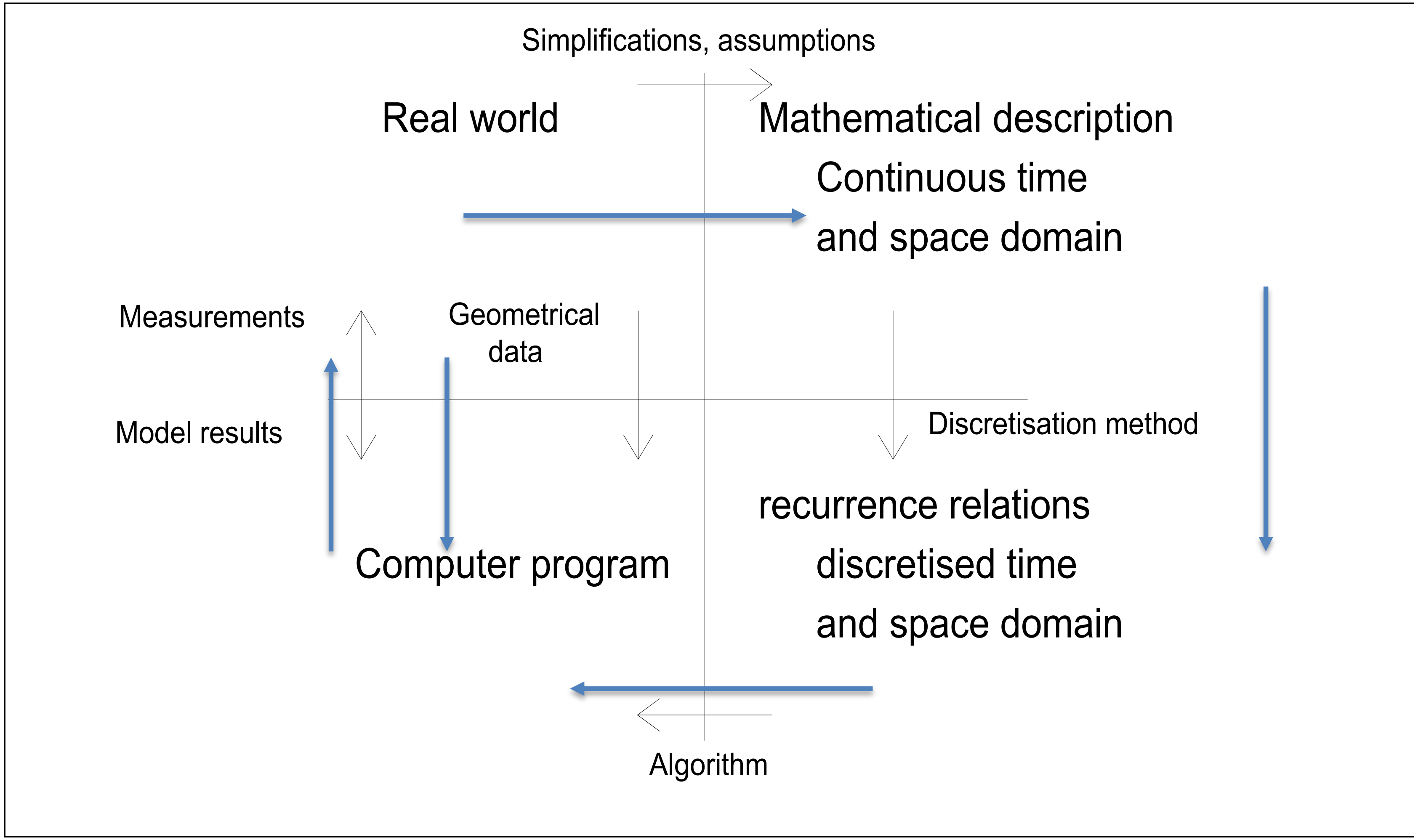
- Actual performance vs design performance (hydraulics, water quality)
- Real Time Control (hydraulics, water quality)
- Impact on environment (receiving surface water bodies, hydraulics +water quality)
- Actual safety level against collapse (inspection techniques)
- Actual safety level against flooding/health risks (inspection techniques + hydraulics + env. impact)



Model versus real world



Model versus real world

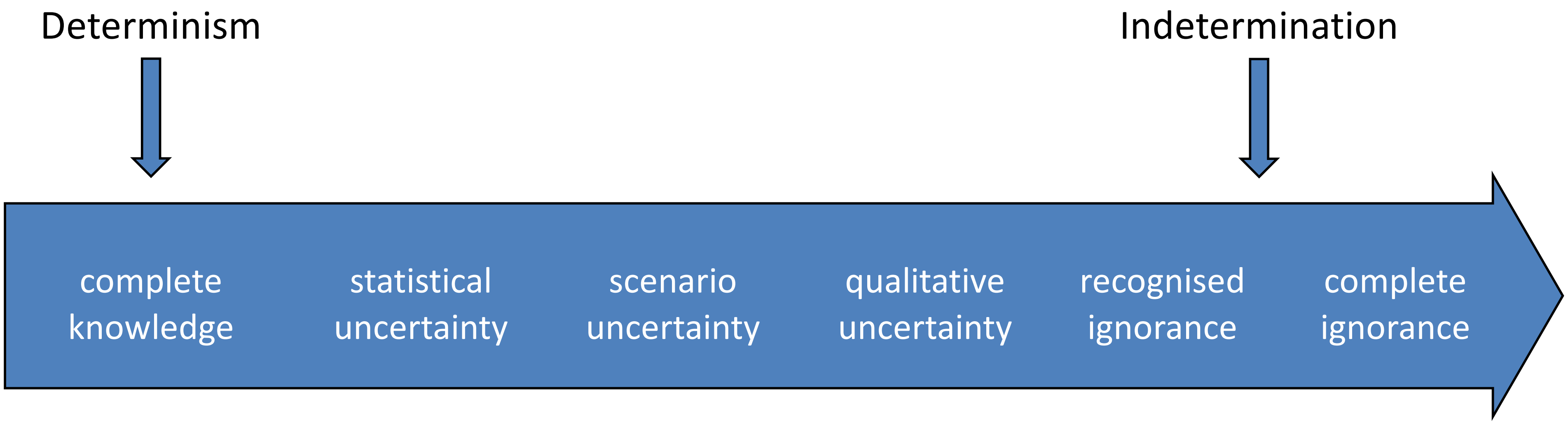


[…] so in contemplation,
if we begin with certainties, we shall end in doubts; but if we begin with doubts, and are patient in them, we shall end in certainties.

Francis BACON (1561-1626)

The Advancement of Learning (1605), p. 30 in Ebook PDF version

UNCERTAINTY

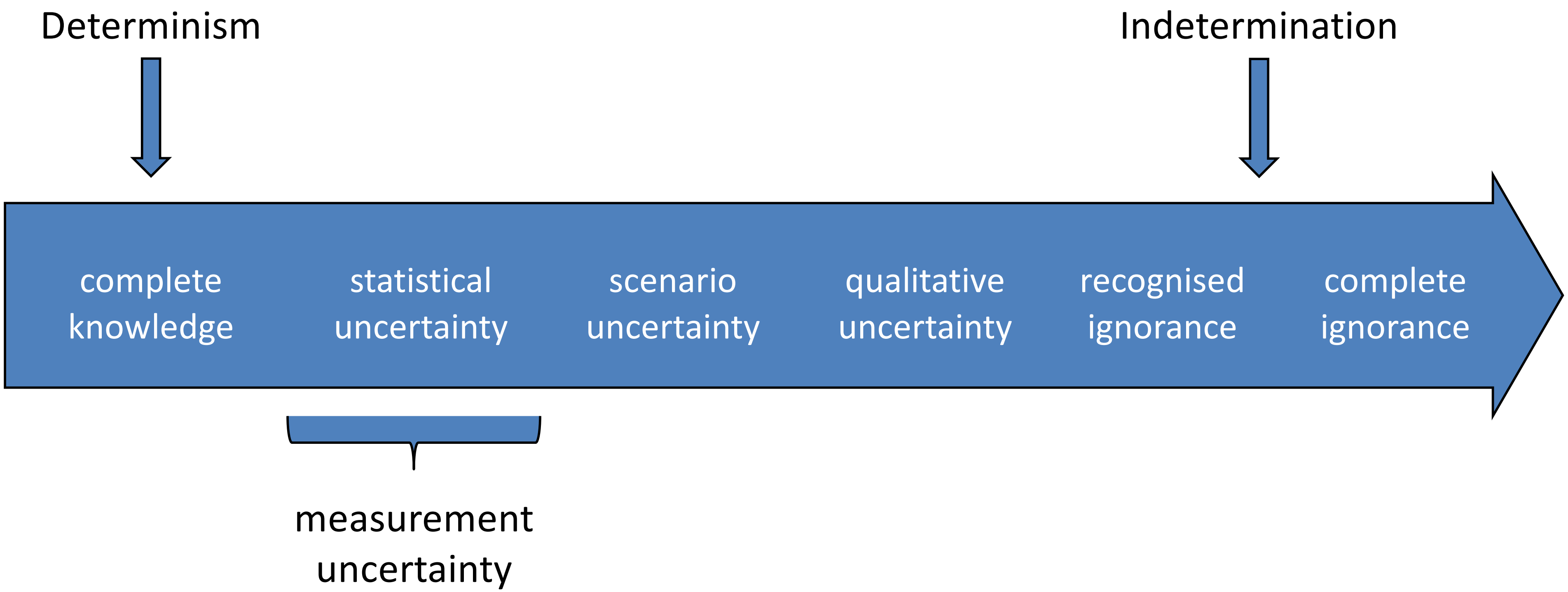


https://www.youtube.com/watch?v=REWeBzGuzCc&ab_channel=CNN

Rumsfeld theorema

UNCERTAINTY AND DECISION

UNCERTAINTY



TERMINOLOGY

- VIM : International Vocabulary of Metrology

TERMINOLOGY

- Measurand
- True quantity value : always unknown
- Measurement result
- Repeatability : unchanged conditions
- Reproducibility : changed conditions

TERMINOLOGY

- Measurement error :
  measurement result – true or reference value
- Systematic measurement error
- Random measurement error
- Measurement accuracy

  closeness of agreement between a **measured quantity value** and a **true quantity value** of a **measurand**

- Measurement trueness

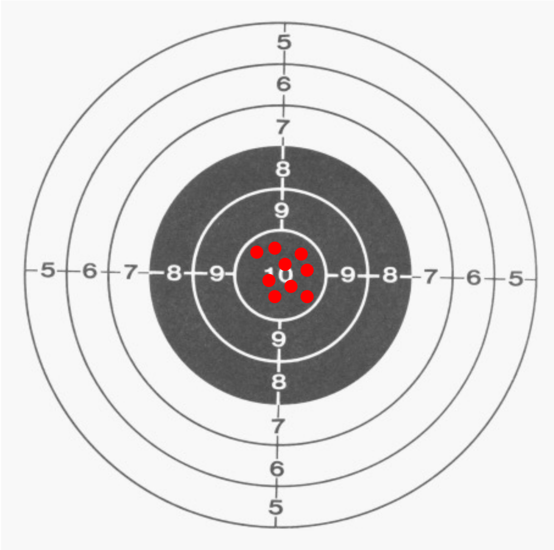
  closeness of agreement between the average of an infinite number of replicate **measured quantity values** and a **reference quantity value**

- Measurement precision

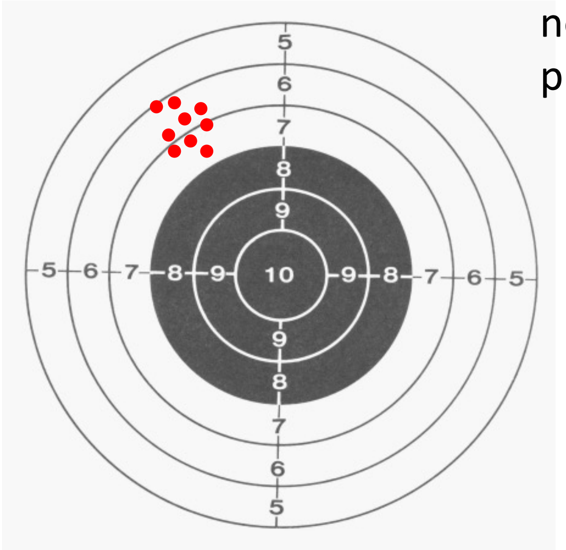
  closeness of agreement between **indications** or **measured quantity values** obtained by replicate **measurements** on the same or similar objects under specified conditions

REPEATED MEASUREMENTS

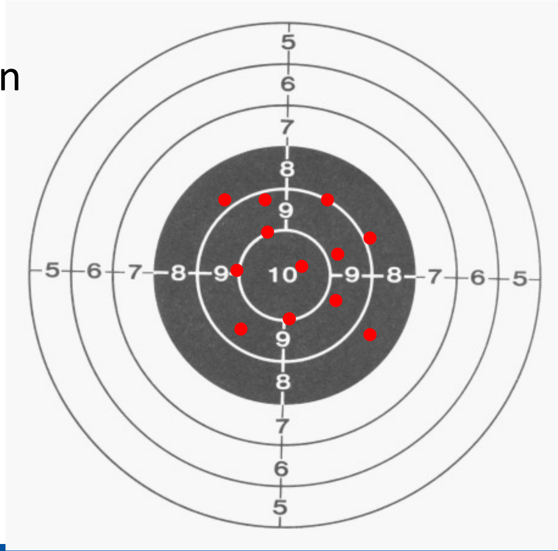
accuracy
trueness
precision



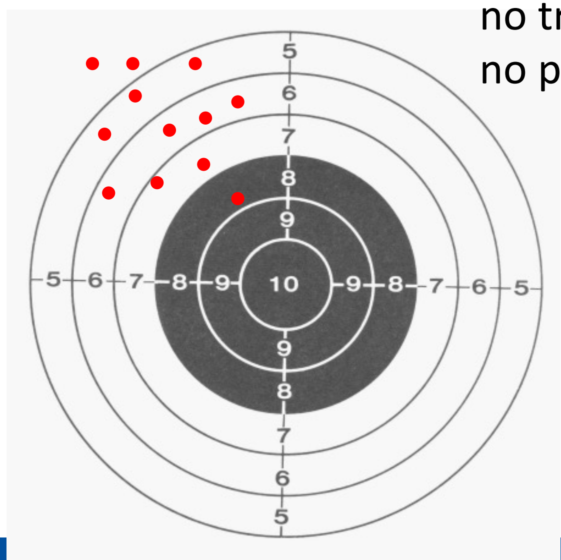
inaccuracy
no trueness
precision



inaccuracy
trueness
no precision



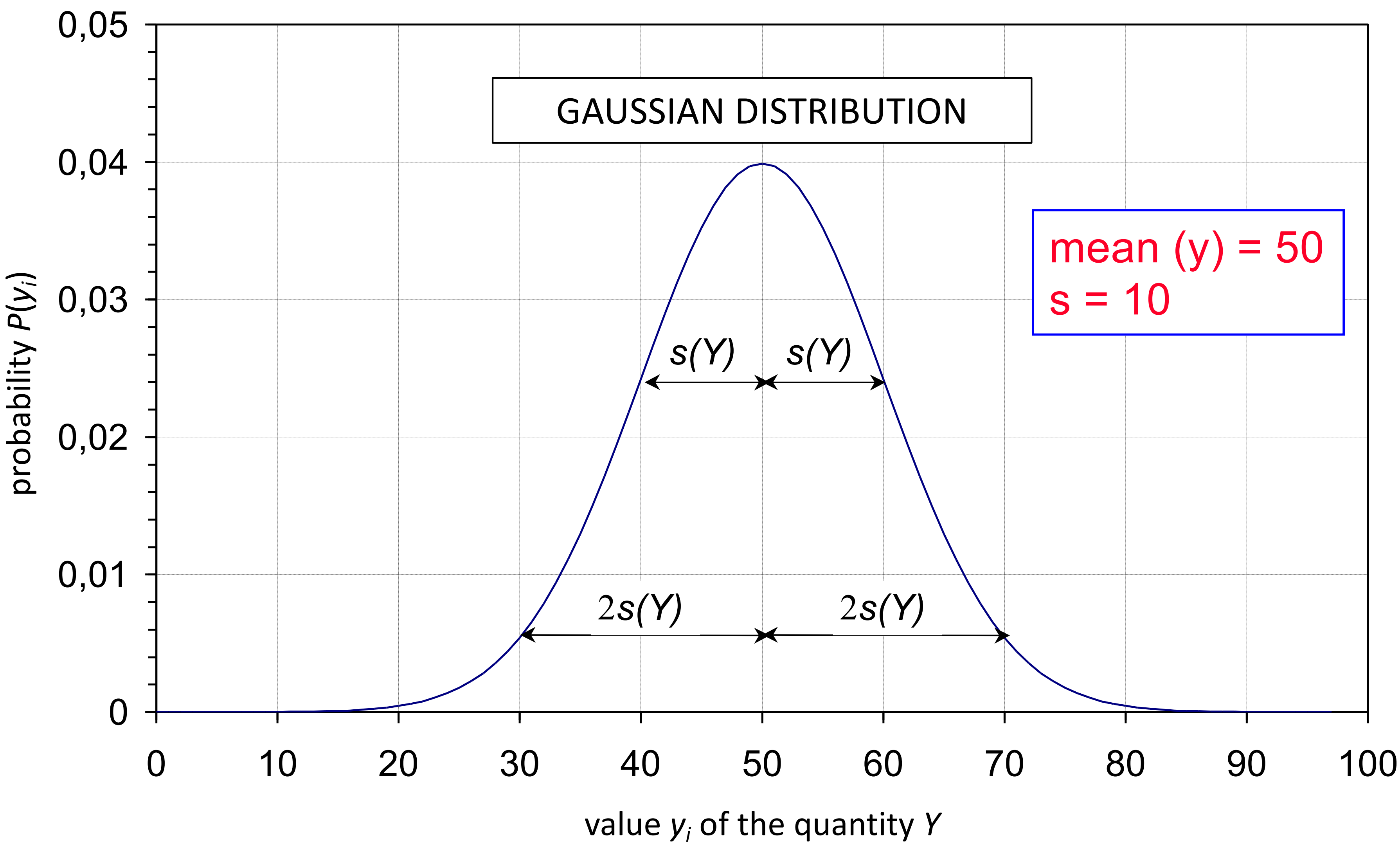
inaccuracy
no trueness
no precision



TERMINOLOGY

- Measurement uncertainty
  - dispersion of the quantity values being attributed to a measurand
  - probabilistic approach
- Sources of uncertainty
  - systematic and random errors due to
    - sensor
    - site
    - user
    - measurement conditions
    - etc…

NORMAL (GAUSSIAN) DISTRIBUTION



NORMAL DISTRIBUTION

an example of Stigler's Law of Eponymy, which states that no scientific discovery is named after its actual discoverer. Contrary to generally believed, Gauss did not invent this distribution: it was de Moivre.

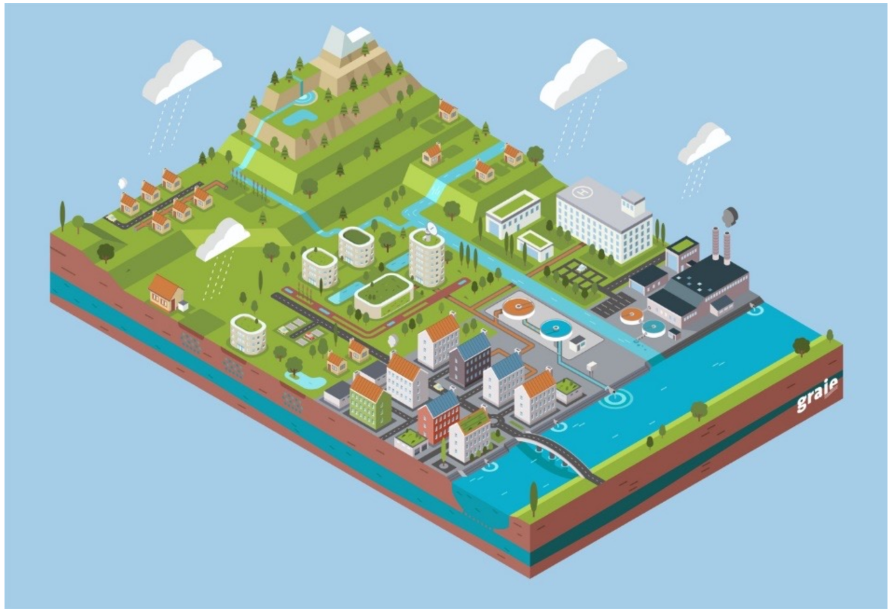
STANDARD UNCERTAINTY *u*(*X*)

- hypothesis : X random variable
- x : measurement result
- u(x) : standard uncertainty ≈ standard deviation (Type A)
- $k_e u(x)$: enlarged uncertainty, k_e enlargement factor
- [x - 2u(x), x + 2u(x)] : coverage interval, ≈ 95 % for $k_e = 2$
- : relative enlarged uncertainty

$$\frac{\Delta x}{x} = \frac{2u(x)}{x}$$

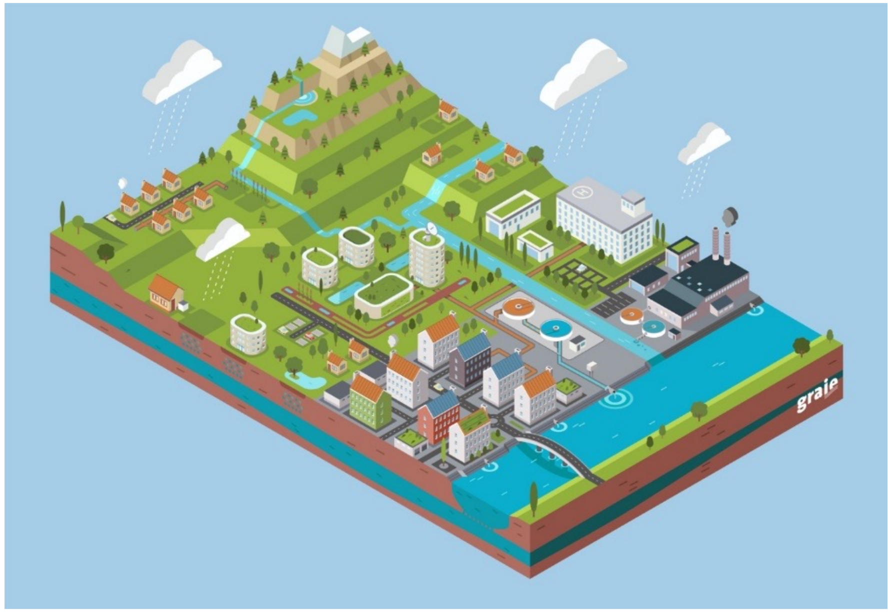
What parameters to measure?

- Urban drainage (limited to quantity):
  - Precipitation
  - Waterlevel
  - Discharge



Measuring principles

- Precipitation
- Waterlevels
- Discharge

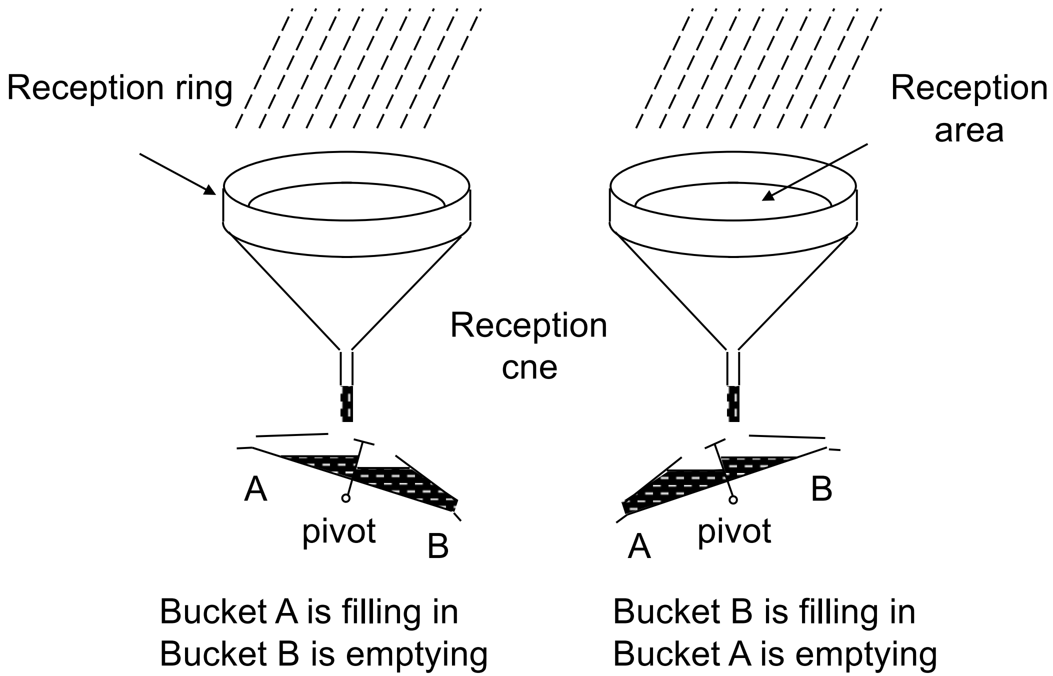


- (important as well but for now out of scope: TSS, T, N, P, BOD, micropollutants etc. etc. etc.)

Measuring rainfall

- Rain gauges
- Disdrometers
- Radar
- Microwave links

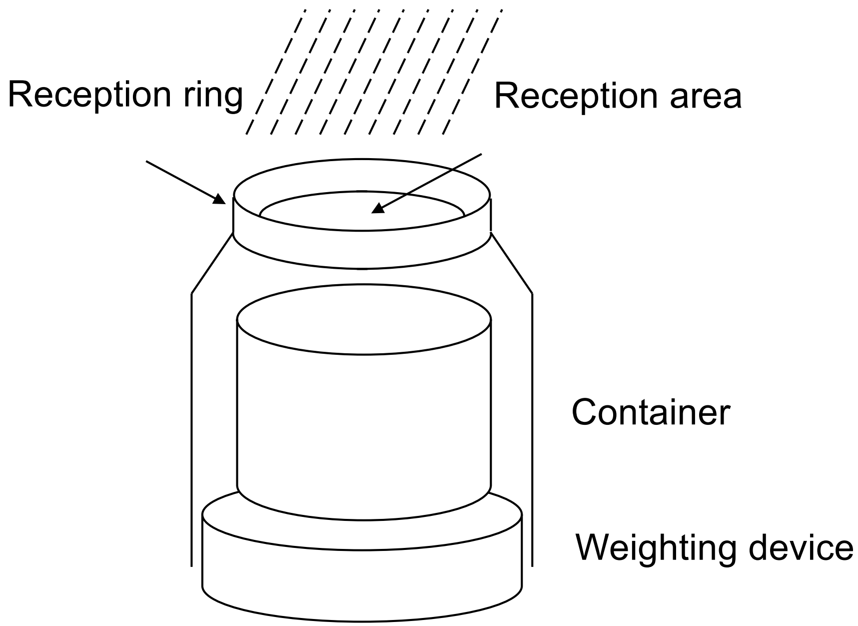
Rain Gauges



Tipping bucket principle

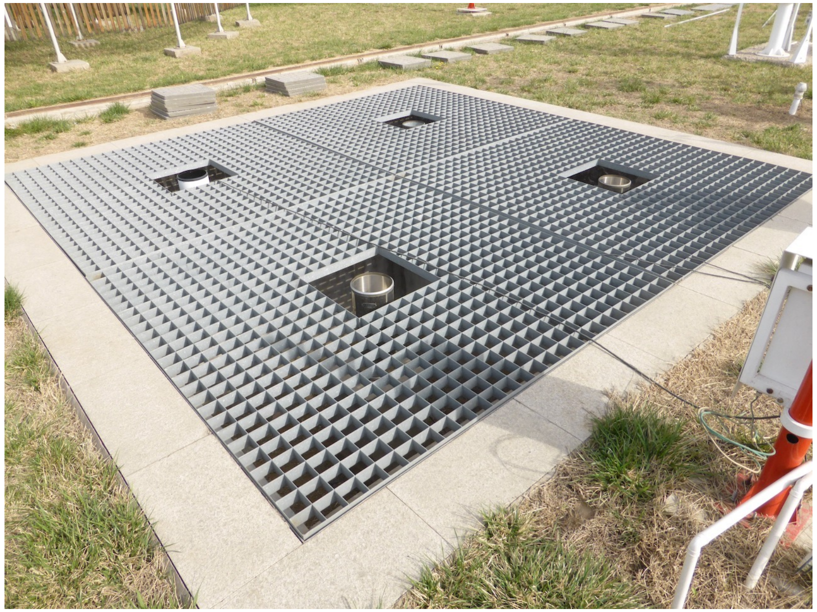
Print your own!

Rain gauges



Weighting principle

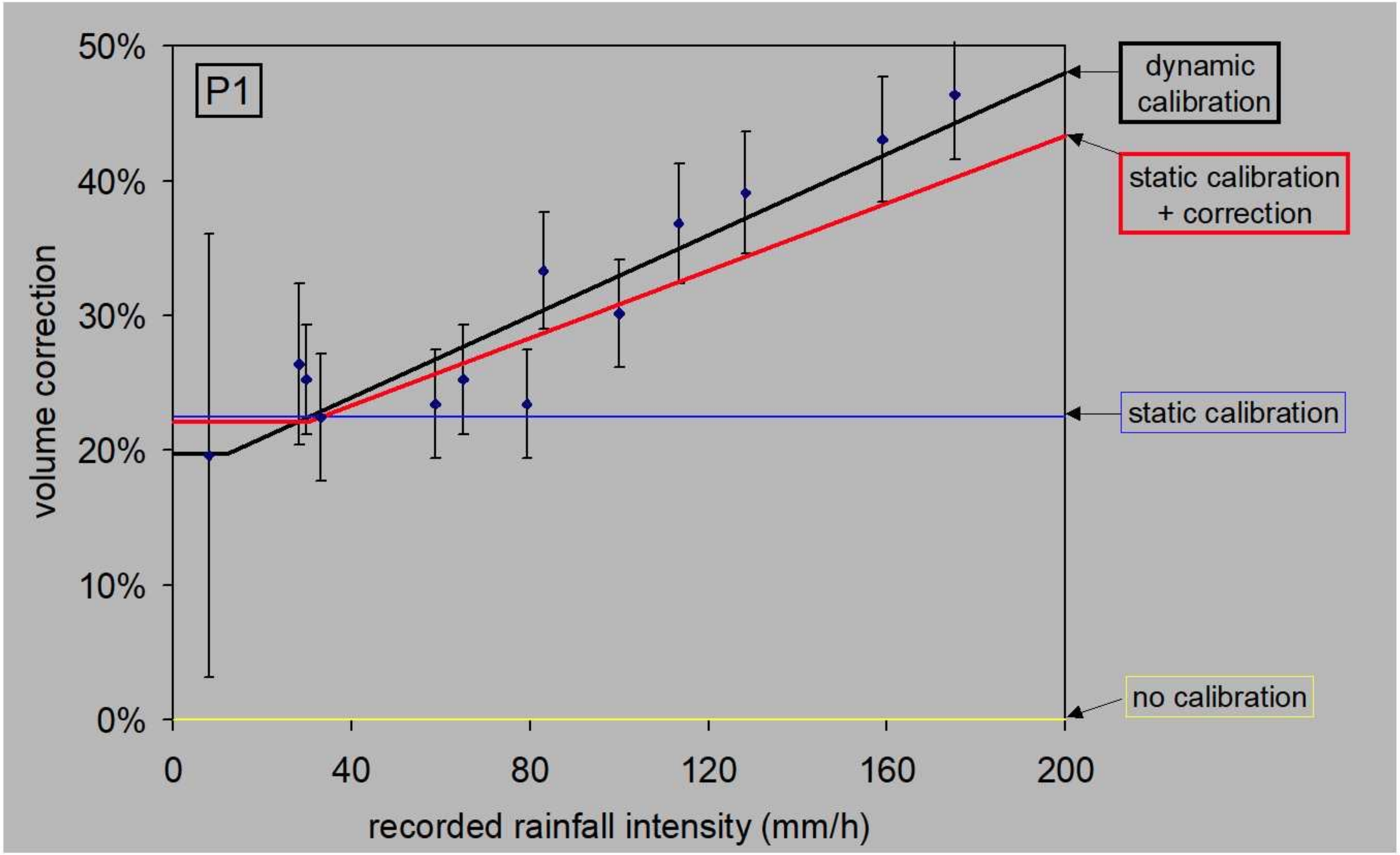
Placement of rain gauges



Characteristics

- Spot measurement (200 – 400 cm^2)
- Very sensitive to disturbances from wind (up to 20% underestimation)
- Snow, hail (sometimes a heating element is installed) alway unreliable results
- TBR’s: Minimal intensity (why?)
- TBR’s: Maximal intensity (why?

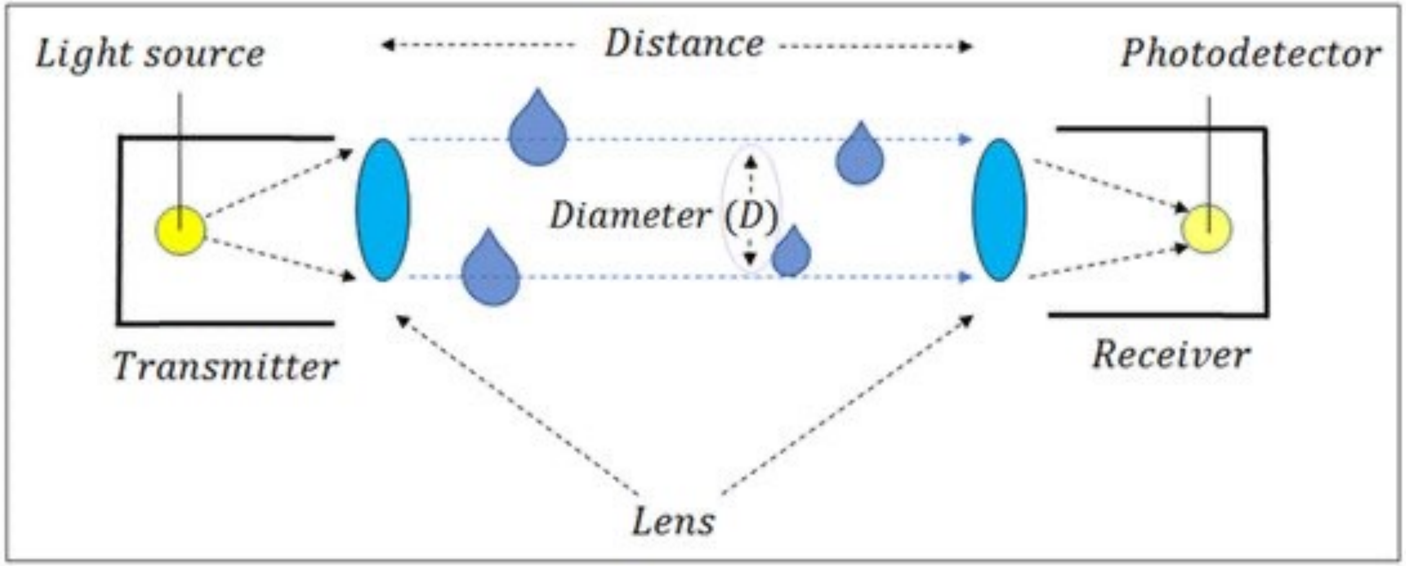
calibration



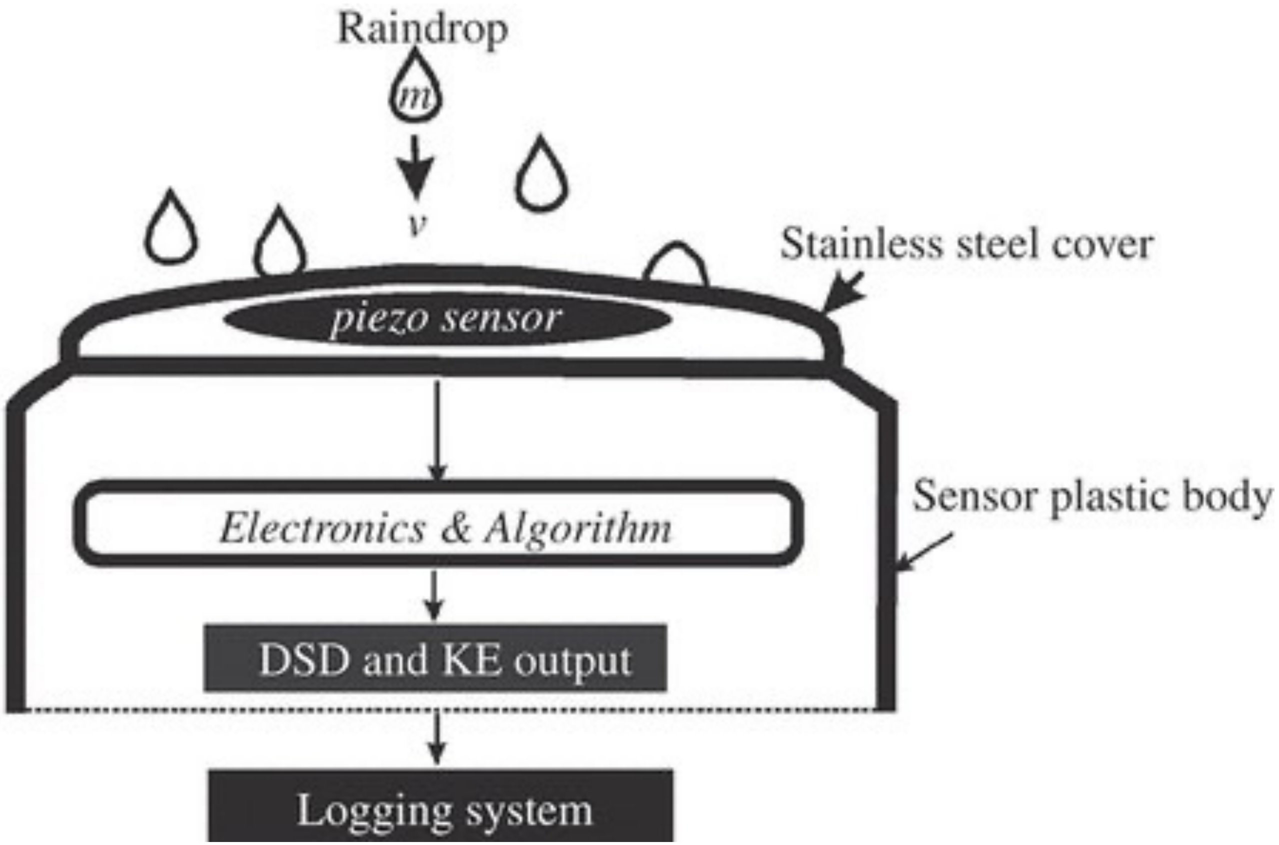
Disdrometers

- 'Counting drops'
- Optical
- Acoustic

Optical disdrometer



Acoustical disdrometer



Characteristics

- Spot measurement
- Can handle snow, hail
- For optical systems:
  - *i)* the estimation of size and velocity of drop relies on theoretical drop shapes that are often different in reality
  - *ii)* a significant sampling error for small time steps occurs because of the small sampling area (up to 15% error on the rain intensity for 1 min time steps and decreasing for larger ones
  - *iii)* there is a non-homogenous laser beam pattern for disdrometers computing the occluded light

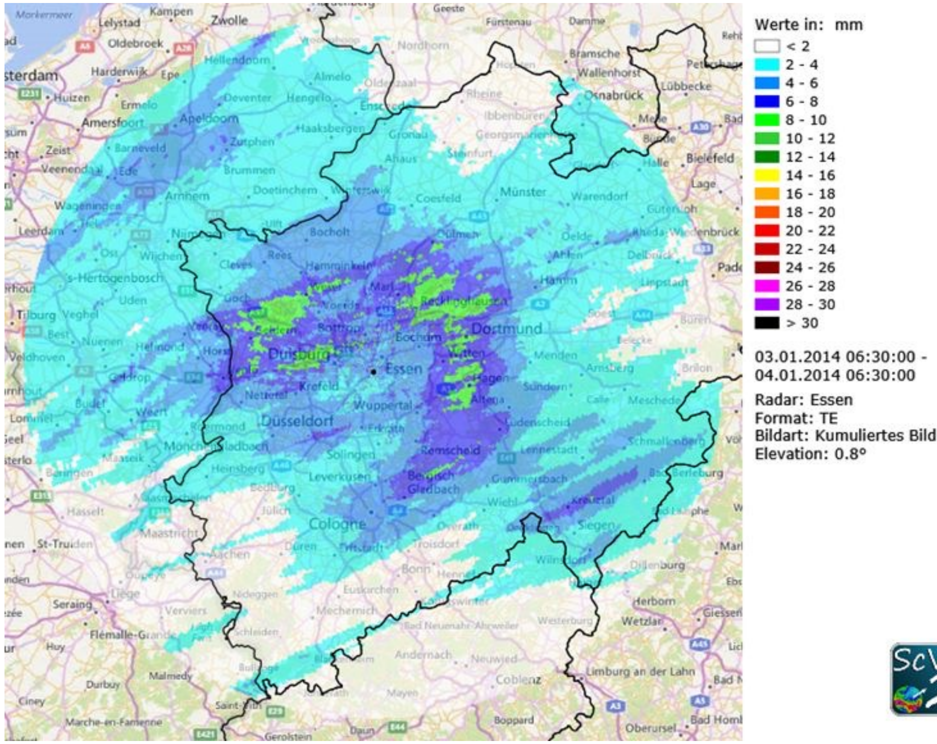
Characteristics

- Acoustical disdrometers:
  - Cheap!
  - Max intensity
  - Not very accurate

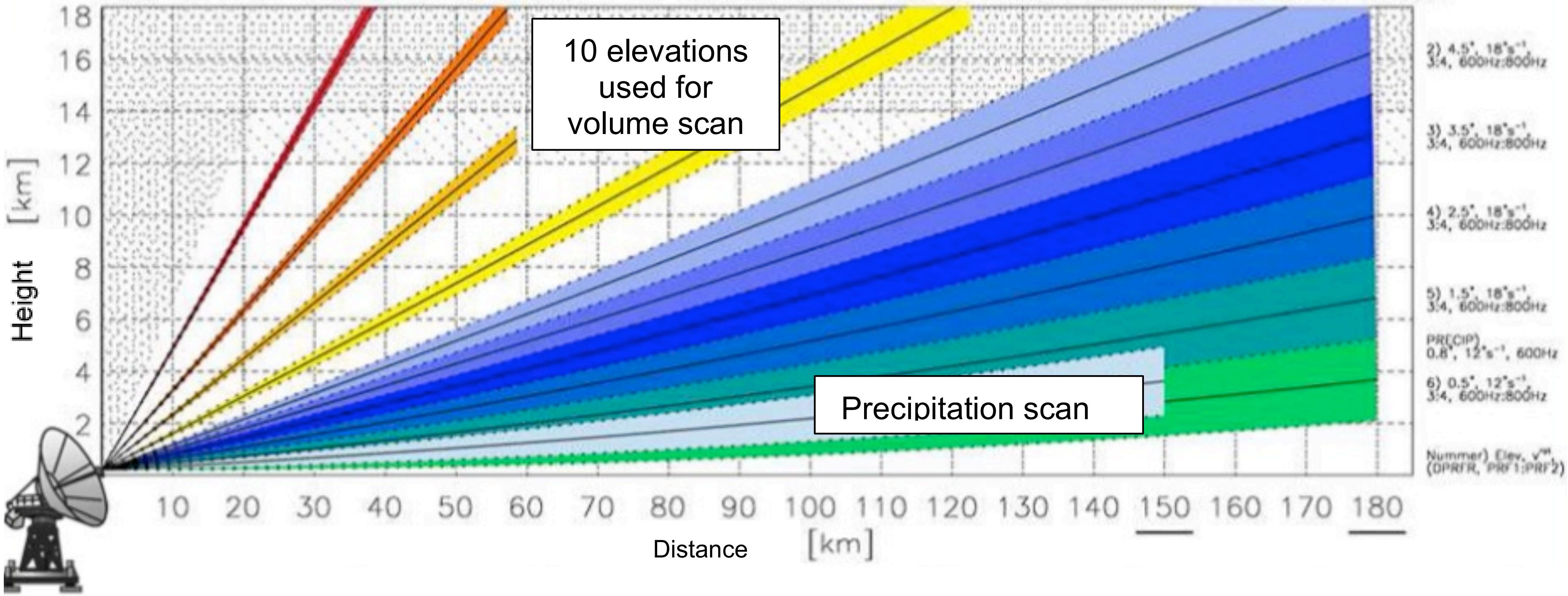
Built one yourself

Some practical issues with raingauges

Radar

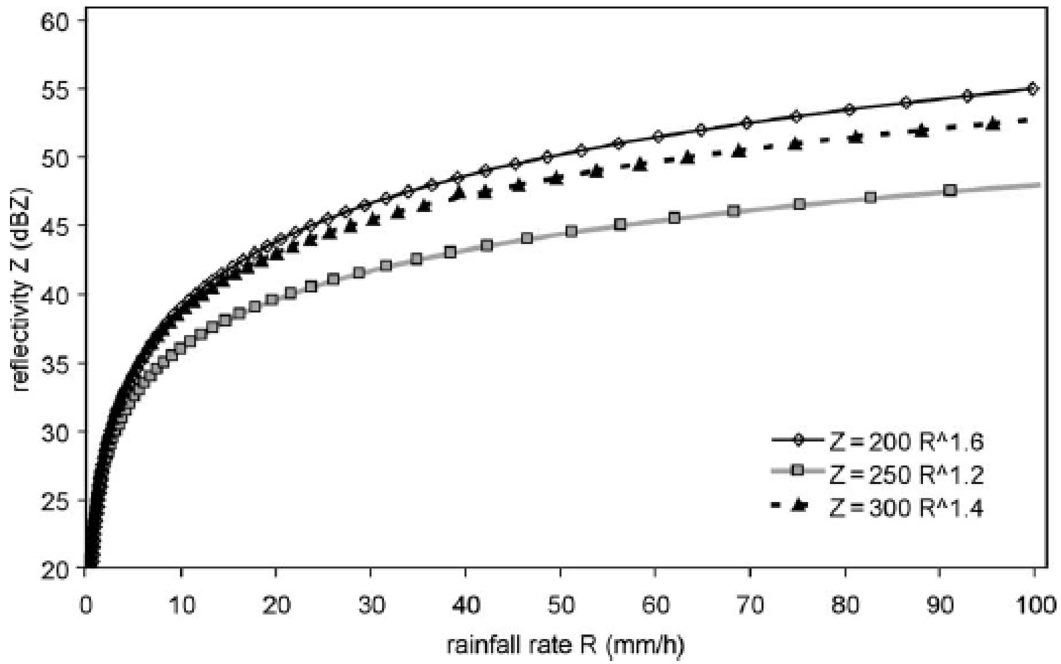

Dortmund
Essen
Duisburg
Düsseldorf
Cologne
Werte in: mm
< 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
22 - 24
24 - 26
26 - 28
28 - 30
> 30
03.01.2014 06:30:00 -
04.01.2014 06:30:00
Radar: Essen
Format: TE
Bildart: Kumuliertes Bild
Elevation: 0.8°

Radar (reflection)



	X-band	C-band	S-band
Spatial resolution	100-1000 m	250-2000 m	1000-4000 m
Temporal resolution	1-5 min	5-10 min	10-15 min
Maximum quantitative range (see section 2.4.3)	30-60 km	100-130 km	100-200 km

Relation radar reflection and Rainfall



$$Z = aR^b$$

Reflectivity *Z* (in mm^6/m^3 or dBZ)
rain intensity R (mm/h)

Characteristics

- Synoptical measurement
- Potentially significant deviations between Radar observation and ‘ground-truth’ (Why?)
- To a certain extent ‘forecasting’ is possible -> applications in Real Time Control of urban water systems

How would you measure discharge?

Suggestions??

Waterlevel and discharge measurement

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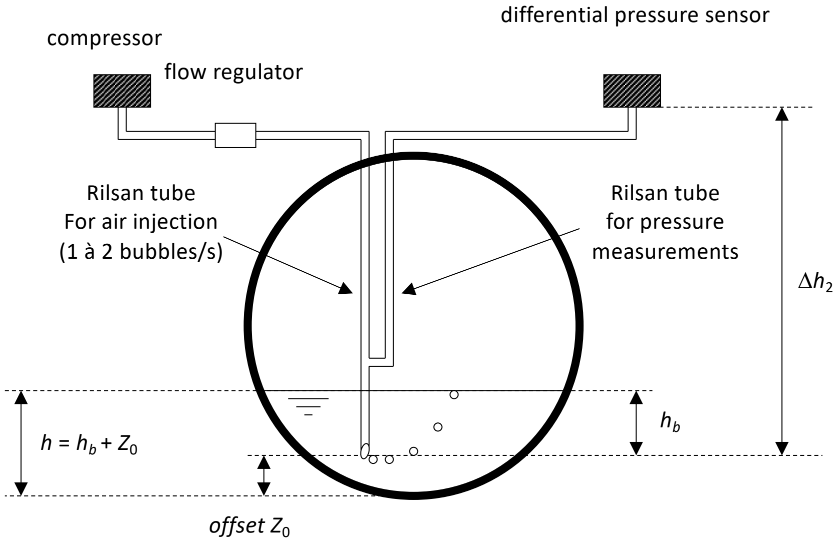
Discharge

- Cannot be measured directly
- The ‘measured’ discharge is ALWAYS the result of combined measurements and underlaying assumptions)
- Volume/time unit
  - Volumometric (pro’s, con’s)
  - Some relation between flow velocity, geometry and waterlevel
  - Some relation between waterlevel and discharge (e.g. a weir)
  - Electromagnetic

Waterlevel (pressure)

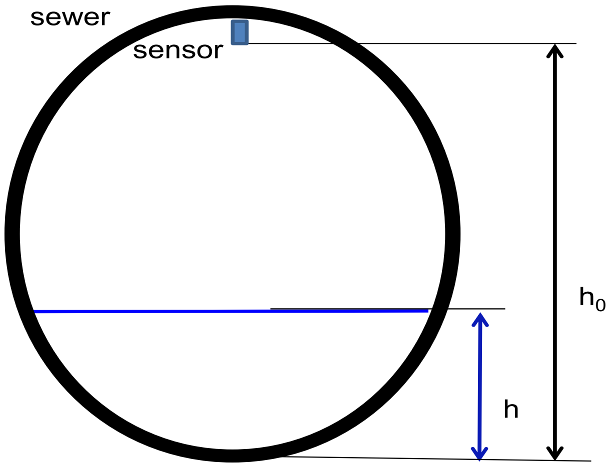
$$\frac{P}{\rho g} + z(x,y) + \frac{V(x,y)^2}{2g}$$

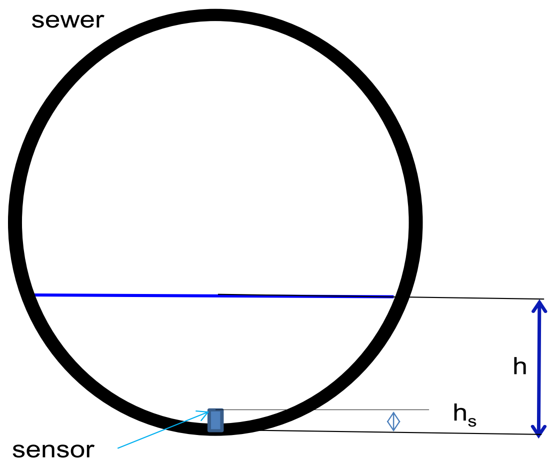


Ultrasonic

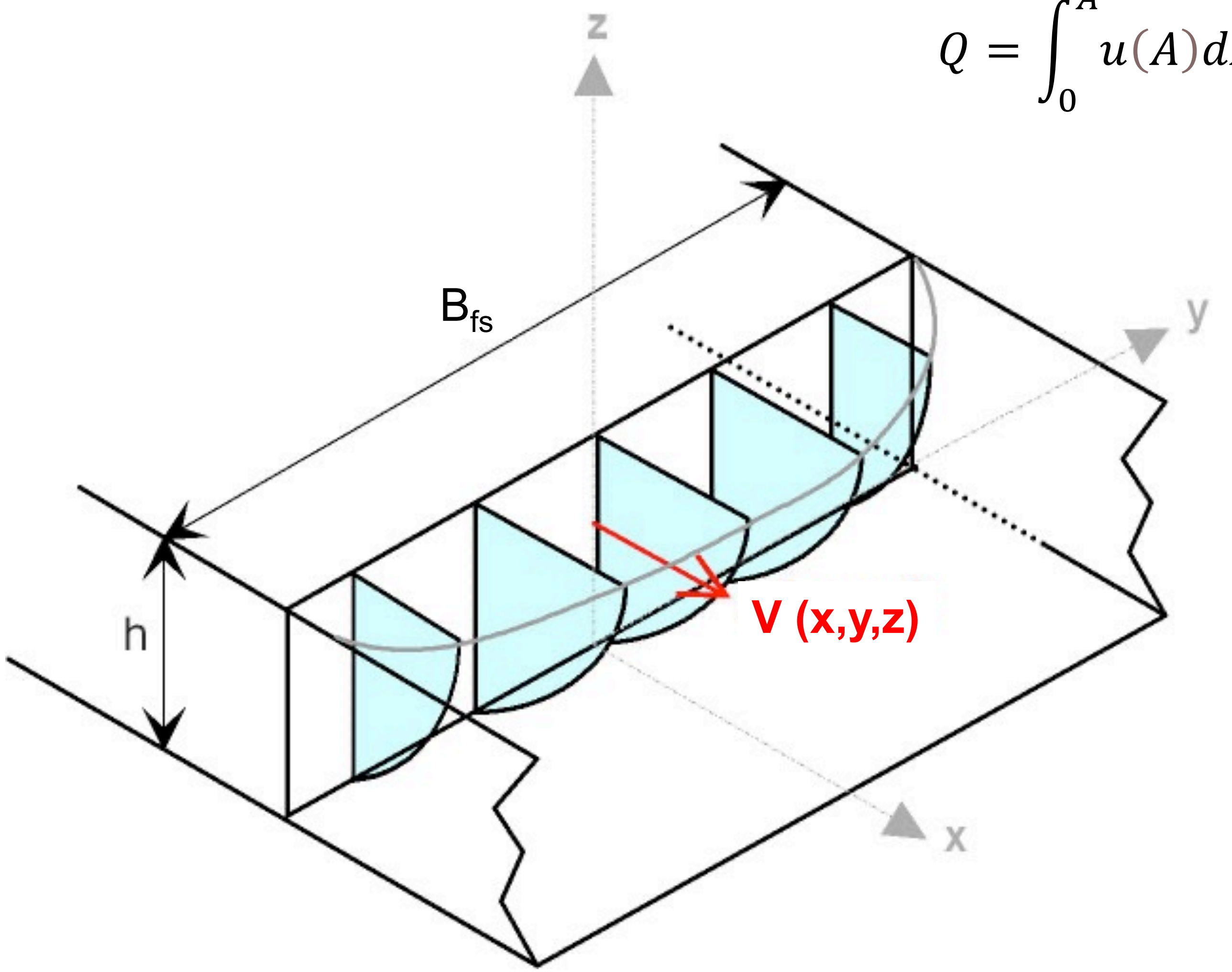
$$h = h_0 - \frac{c_{air} T_r}{2}$$

$$h = h_s + \frac{c_{water} T_r}{2}$$

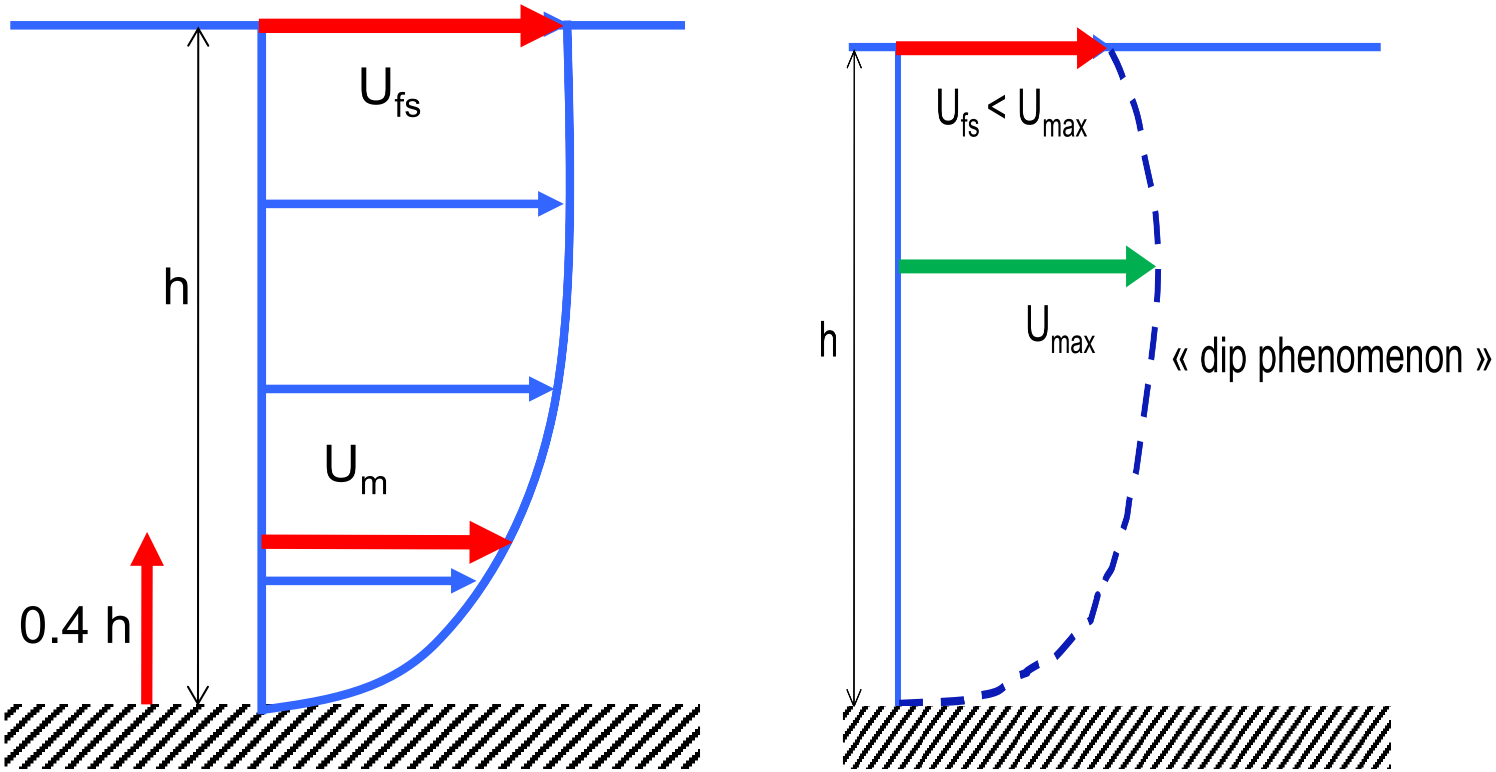




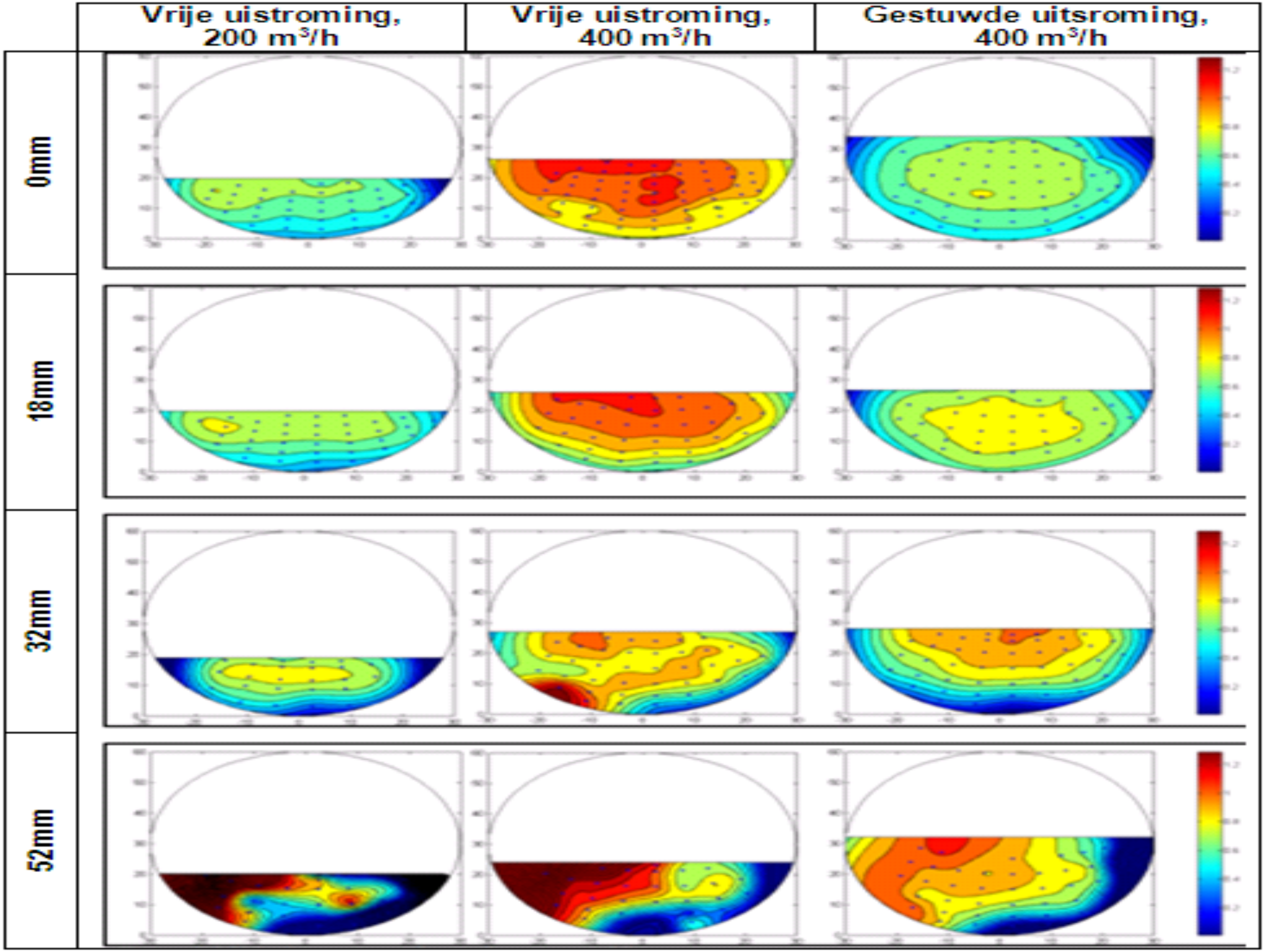
Velocity-> discharge



$$Q = \int_0^A u(A)dA$$

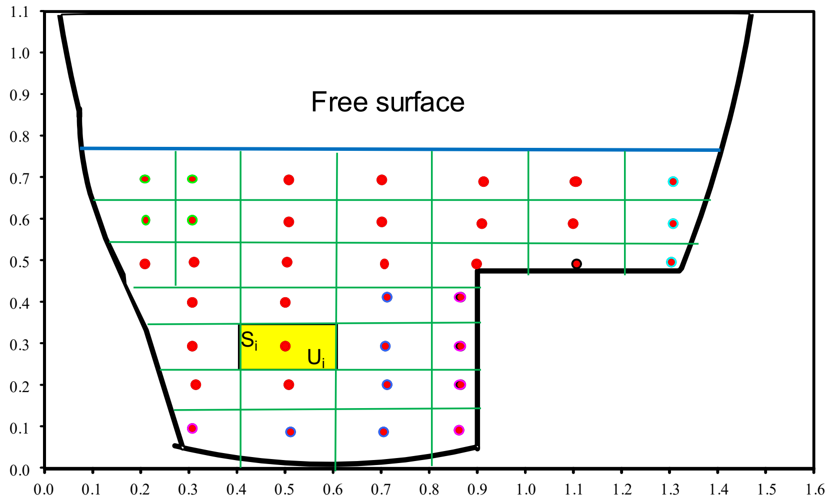


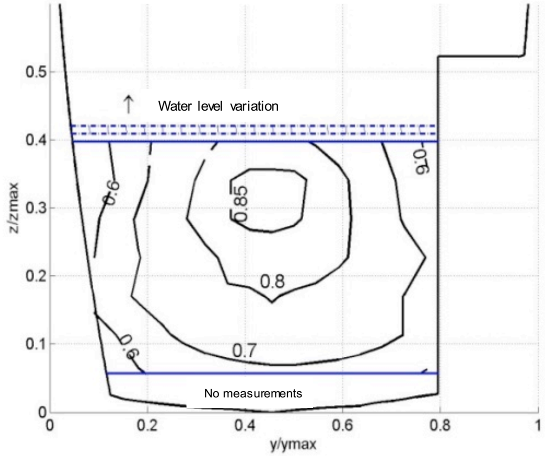
U_{fs}
h
U_m
0.4 h
$U_{fs} < U_{max}$
U_{max}
h
« dip phenomenon »



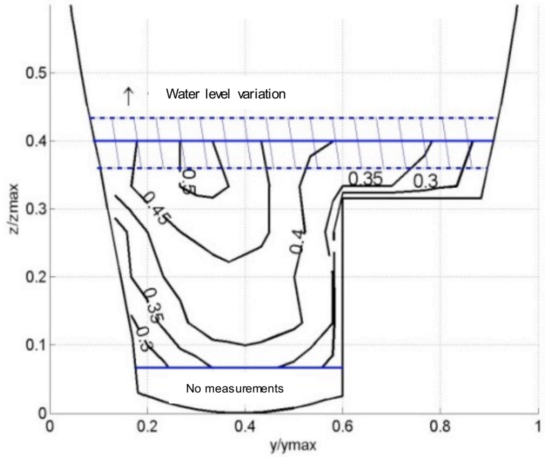
Vrije uistroming, 200 m³/h
Vrije uistroming, 400 m³/h
Gestuwde uitsroming, 400 m³/h
0mm
18mm
32mm
52mm

Velocity area methods

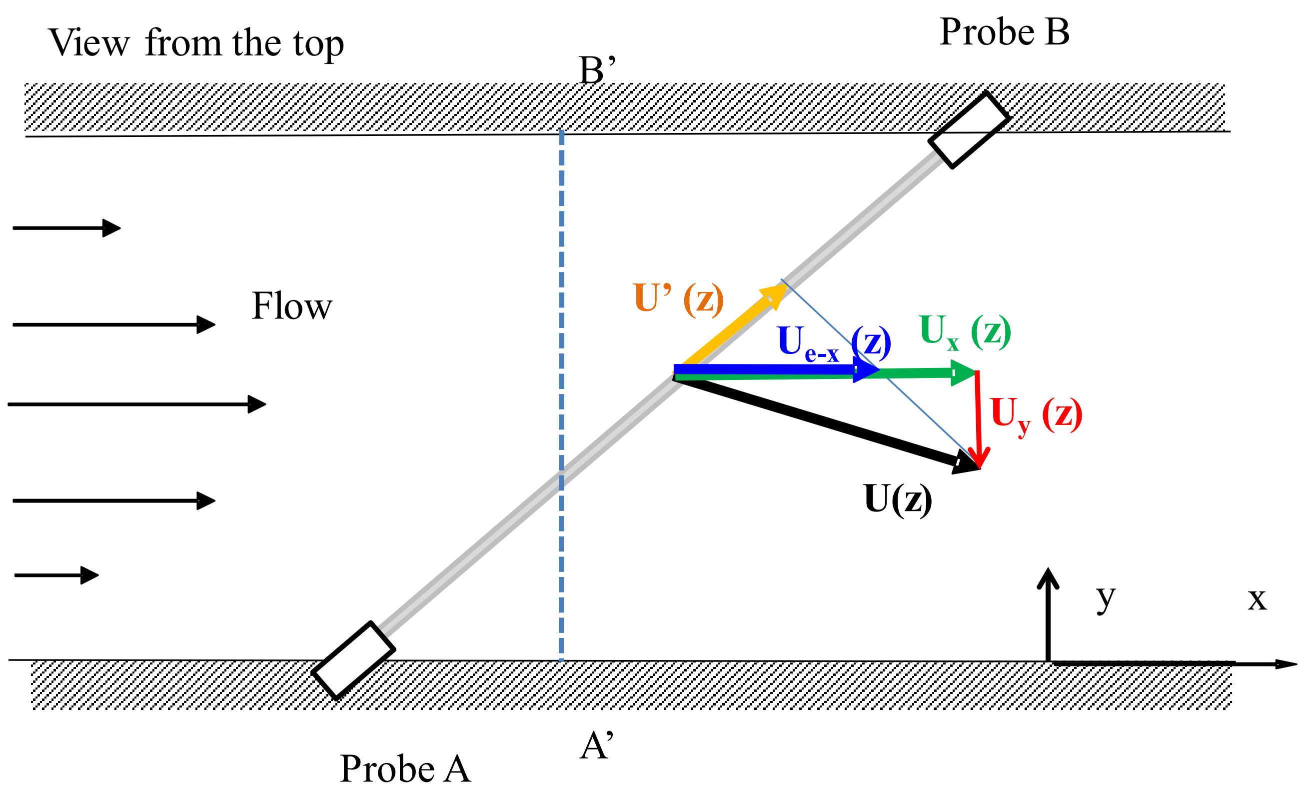


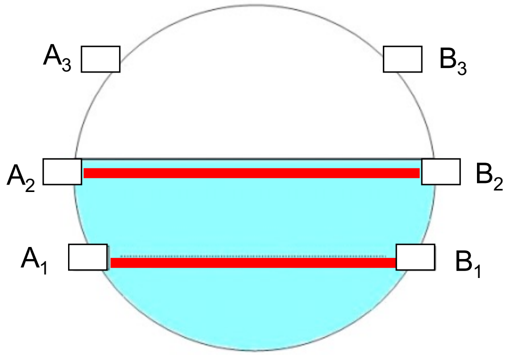


$$u_m = \frac{1}{S_m} \sum U_i S_i$$



Velocity area methods





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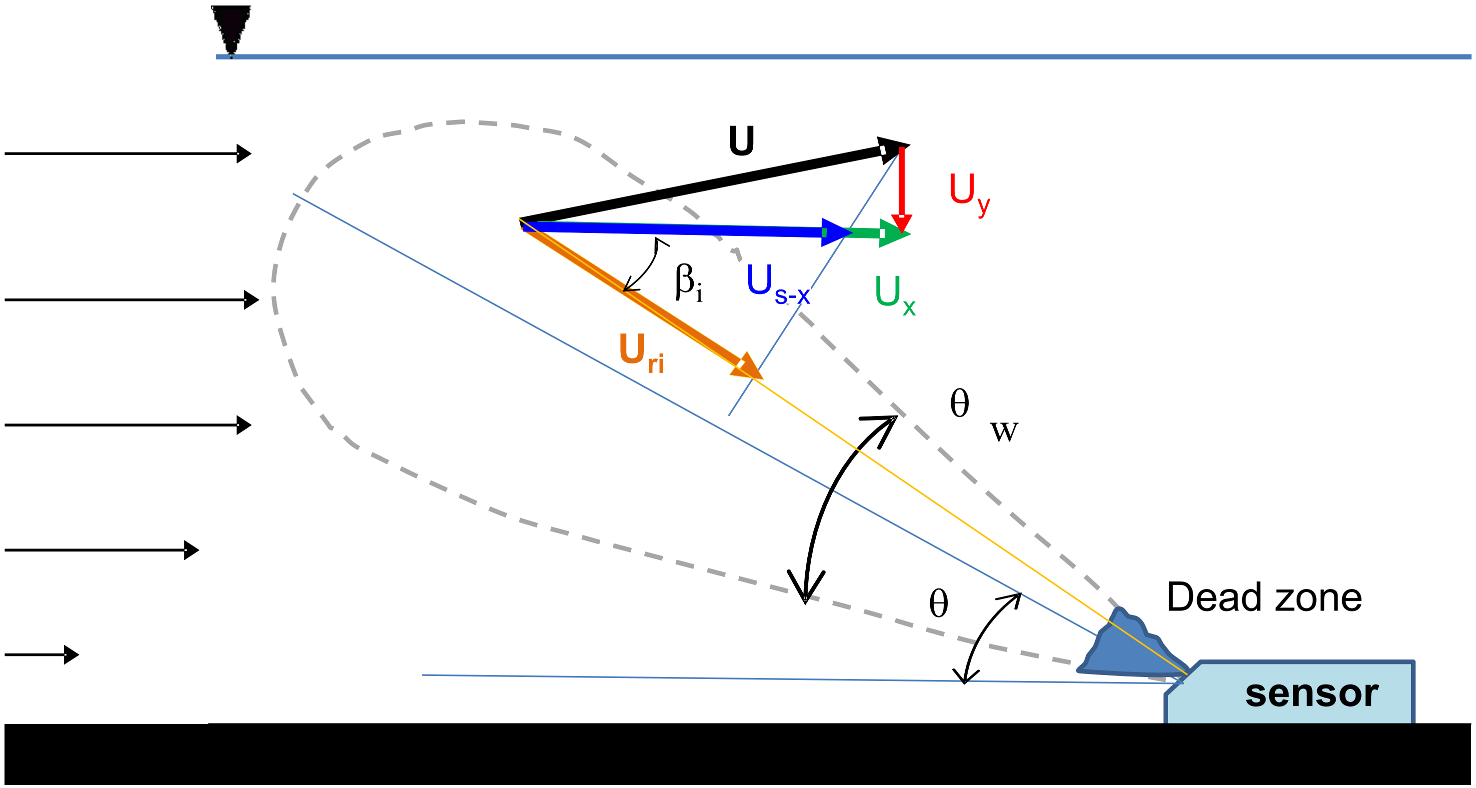
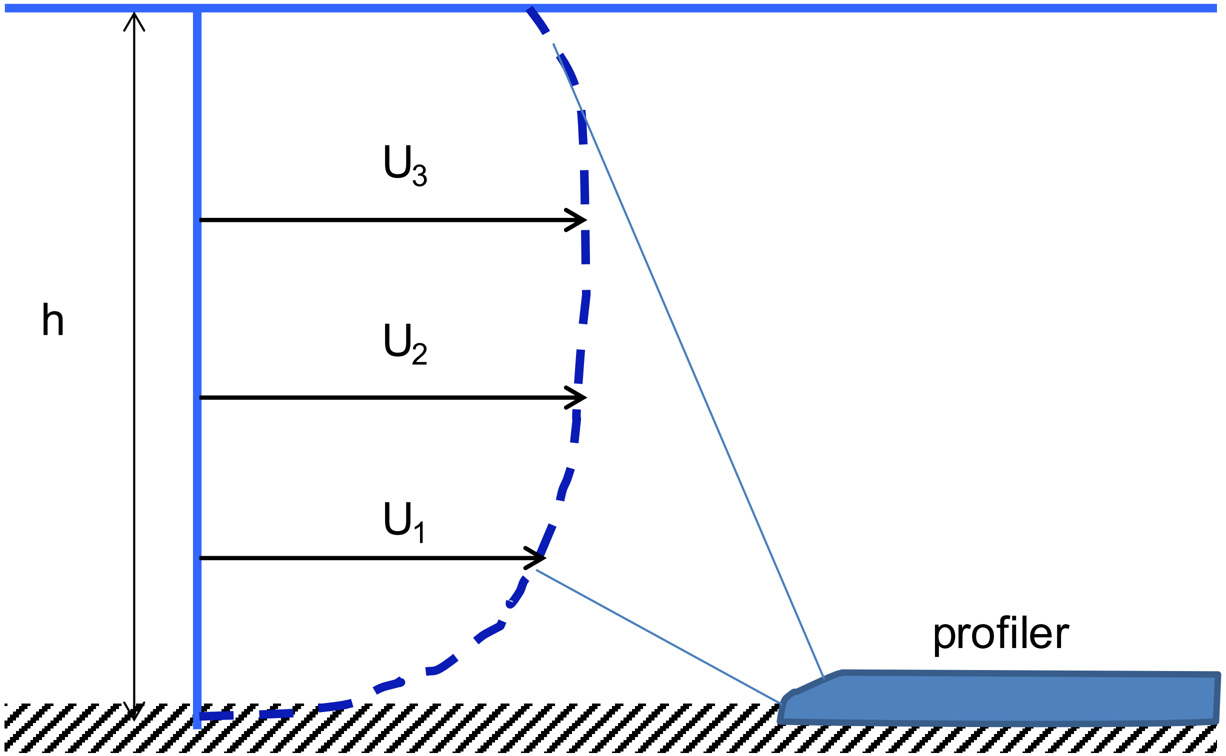
Velocity Area methods (doppler)

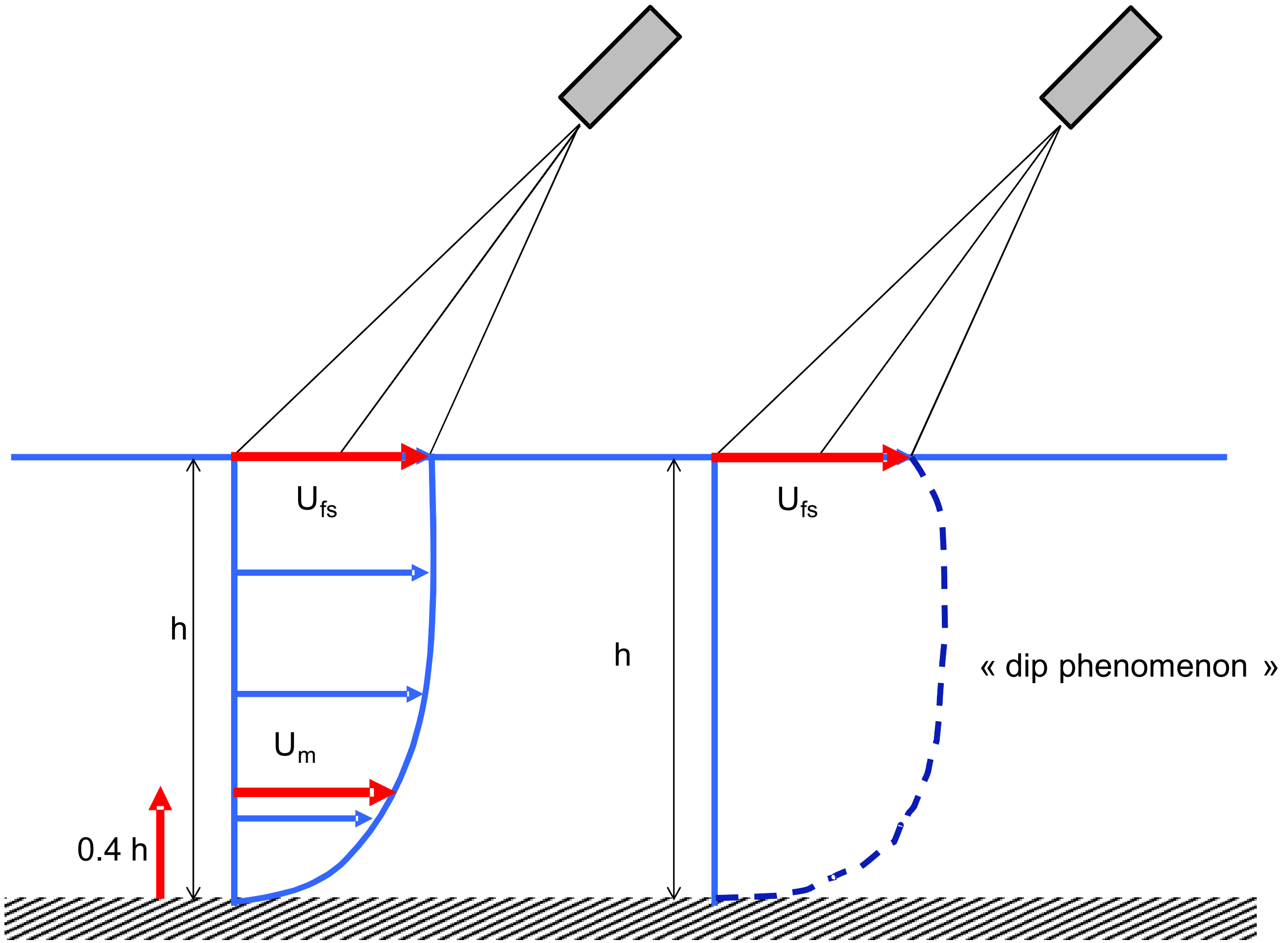
$$U_{s-x} = \frac{U_{ri}}{cos(\beta_i)}$$



Velocity area methods: velocity profilers



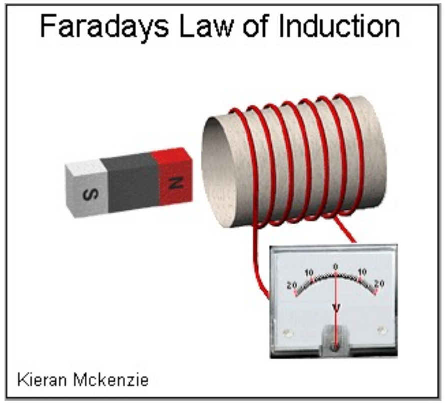
Velocity area methods: surface velocity

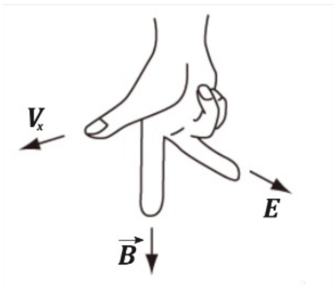


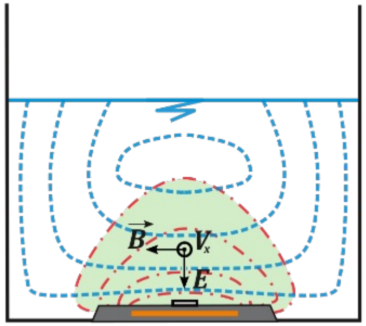
Electromagnetic

$$E_m = -\int_\tau (\vec{V}\times\vec{B})\cdot\vec{j}\,d\tau = \int_\tau \vec{V}\cdot(\vec{B}\times\vec{j})\,d\tau = \int_\tau \vec{V}\cdot\vec{W}\,d\tau$$

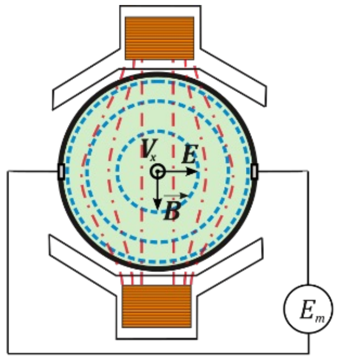
-$\vec{V}$ is the streamwise velocity field,
-$\vec{B}$ is the magnetic induction
-$\mathrm{div}(\vec{V}\times\vec{B})$ is treated as a charge distribution.



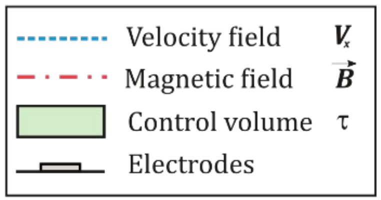




EMV



EMF



$$\hat{U} = \int_{Z_L}^{Z_U} w(z)\cdot V_x(z)\,dz$$

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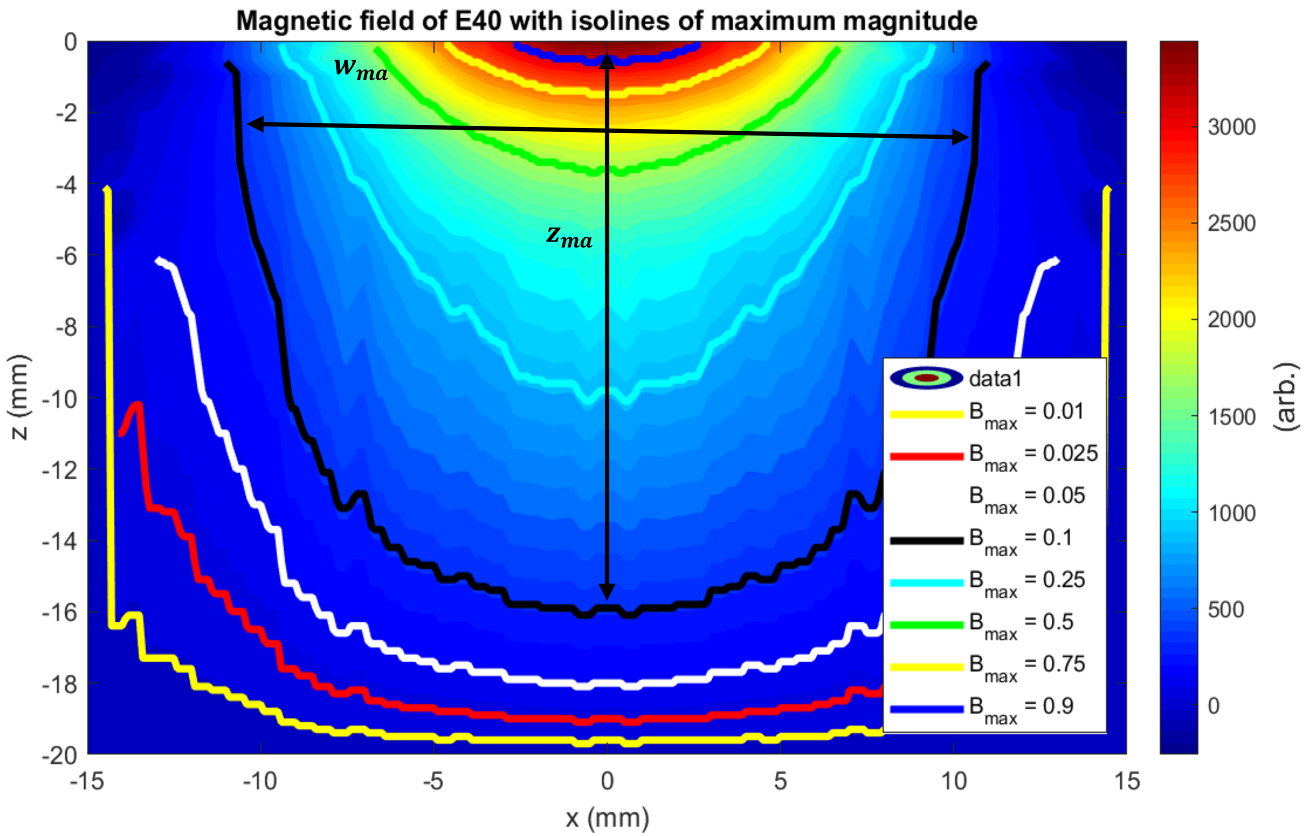
Limited measuring volume (example EMS E-M field measurements Deltares)



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Q-H relations (Stage-Discharge relations)

- Measure waterlevel(s)
- Apply some (known?) relation between measured waterlevel(s) and discharge.
- Examples:
  - Weir
  - Strickler-Manner equation (will come back to this later on)

Weirs (under lab conditions)

- Standard (ISO defined) geometries (e.g. V-notch, rectangular weir)-> standard relations, e.g. V-notch:
- $Q = c_d c_v \frac{2}{3} \sqrt{2g} b h^{\frac{3}{2}}$, with known values for the constants
- Depends on (temperature, geometry of the approach channel, stationarity
- For ISO documentation on this look on: https://www.iso.org/obp/ui/#iso:std:iso:18320:ed-1:v1:en
- Does this apply in field work???????

Weirs in practise:

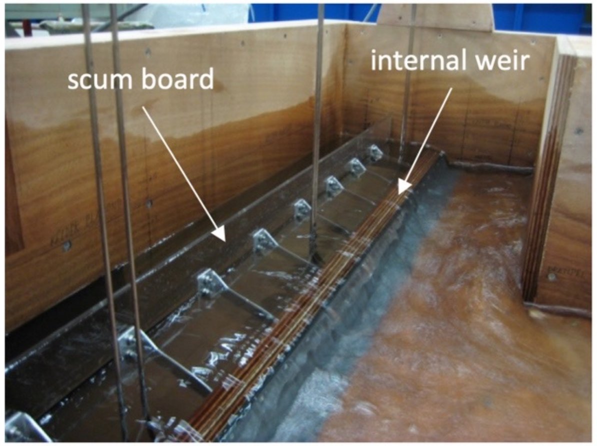
$$Q(h) = \alpha h^{\beta}$$

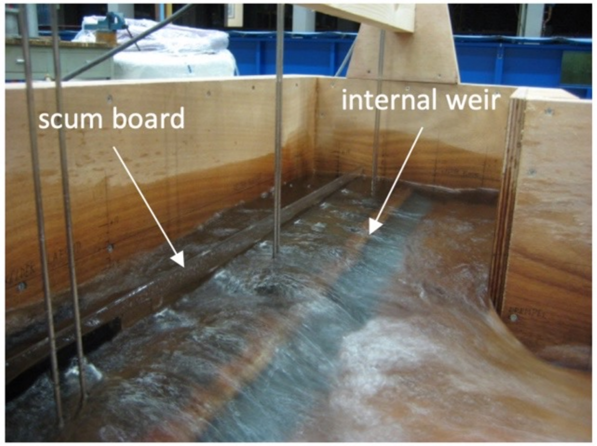
How to calibrate?

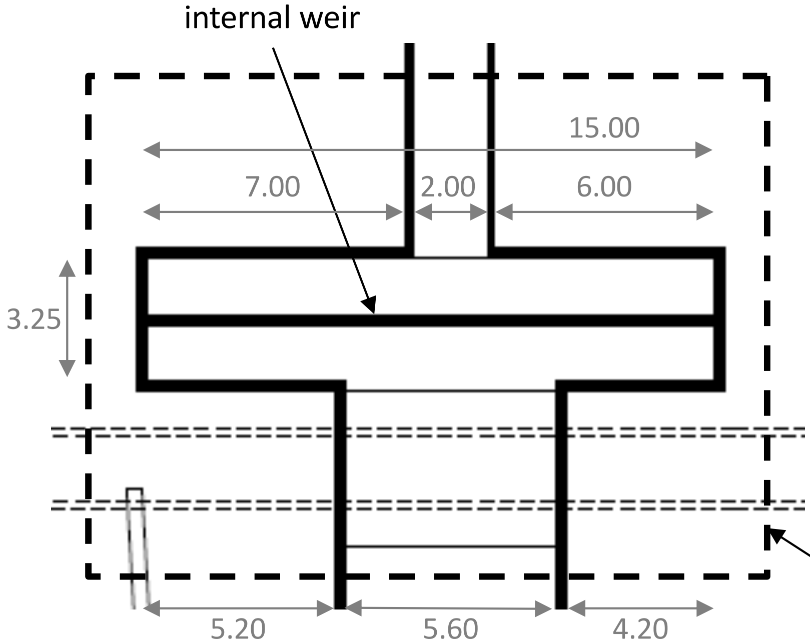
- Field experiments
- Scale experiments in the lab
- CFD model

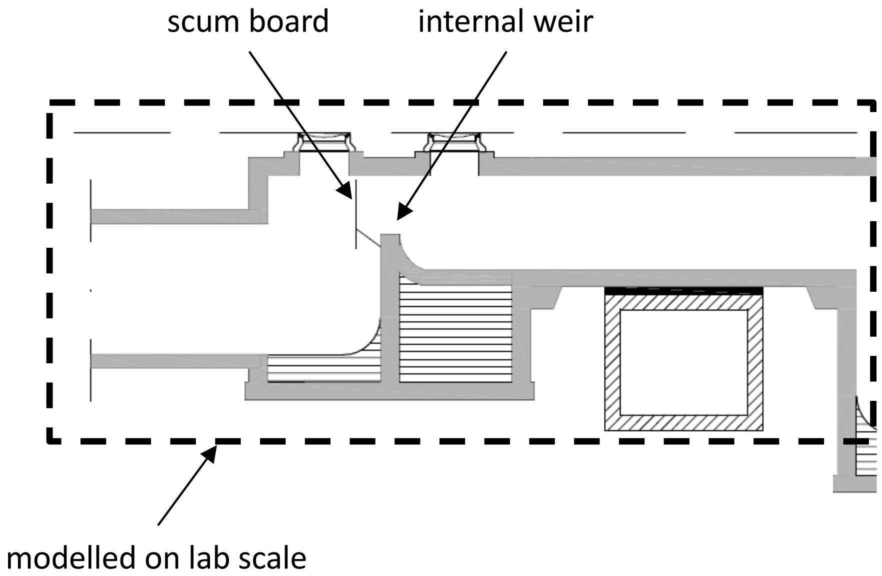
Field calibration

Lab calibration

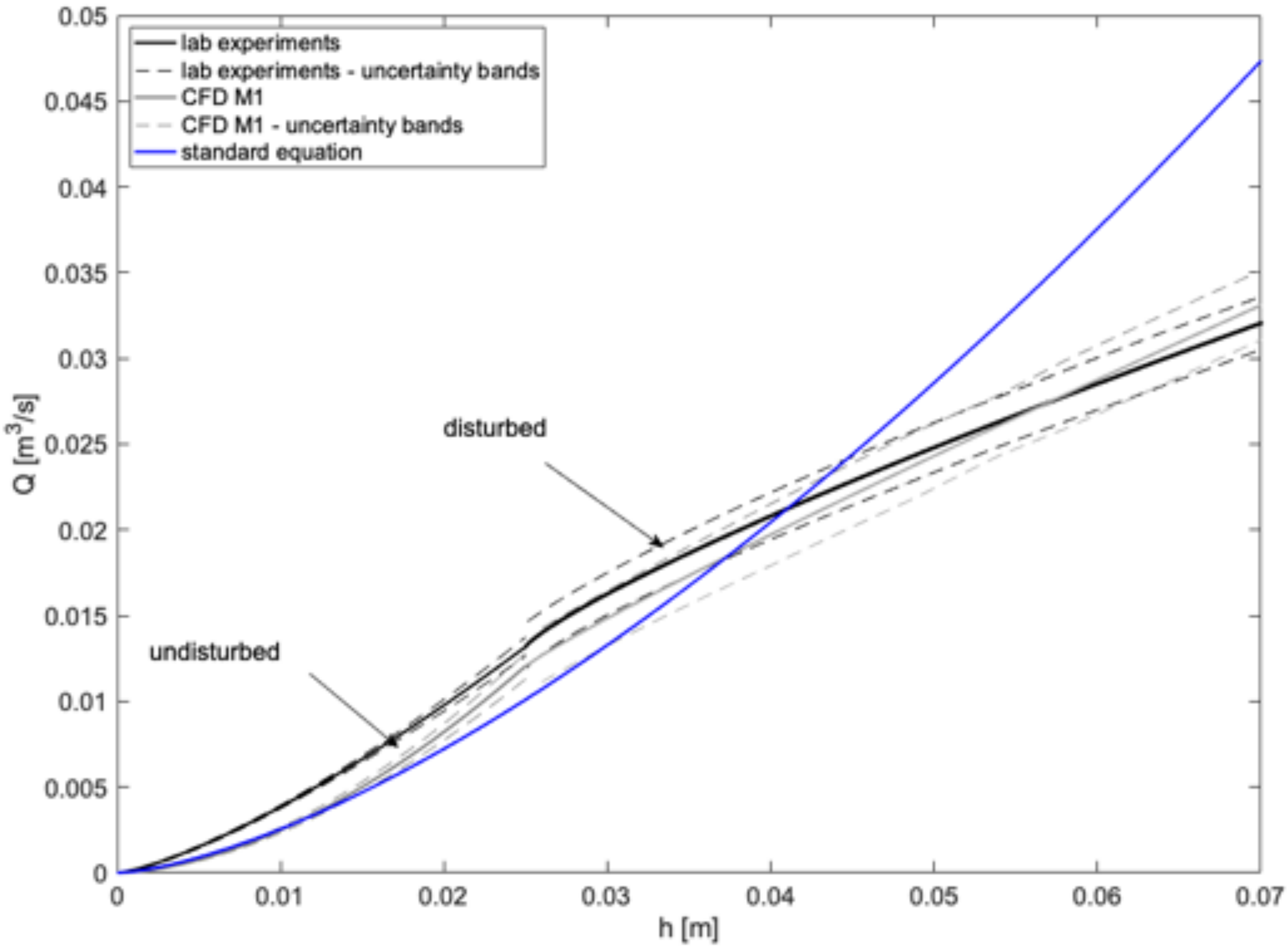








Results



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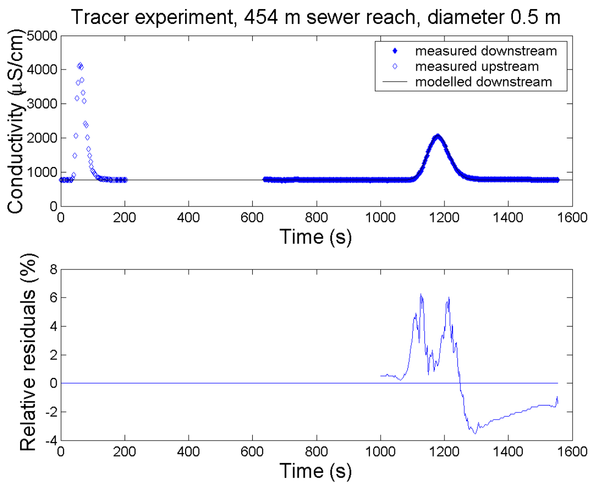
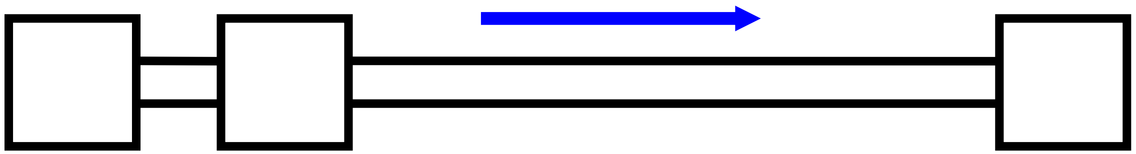
Tracer experiments



Dosing location

Flow



Optional Measuring upstream

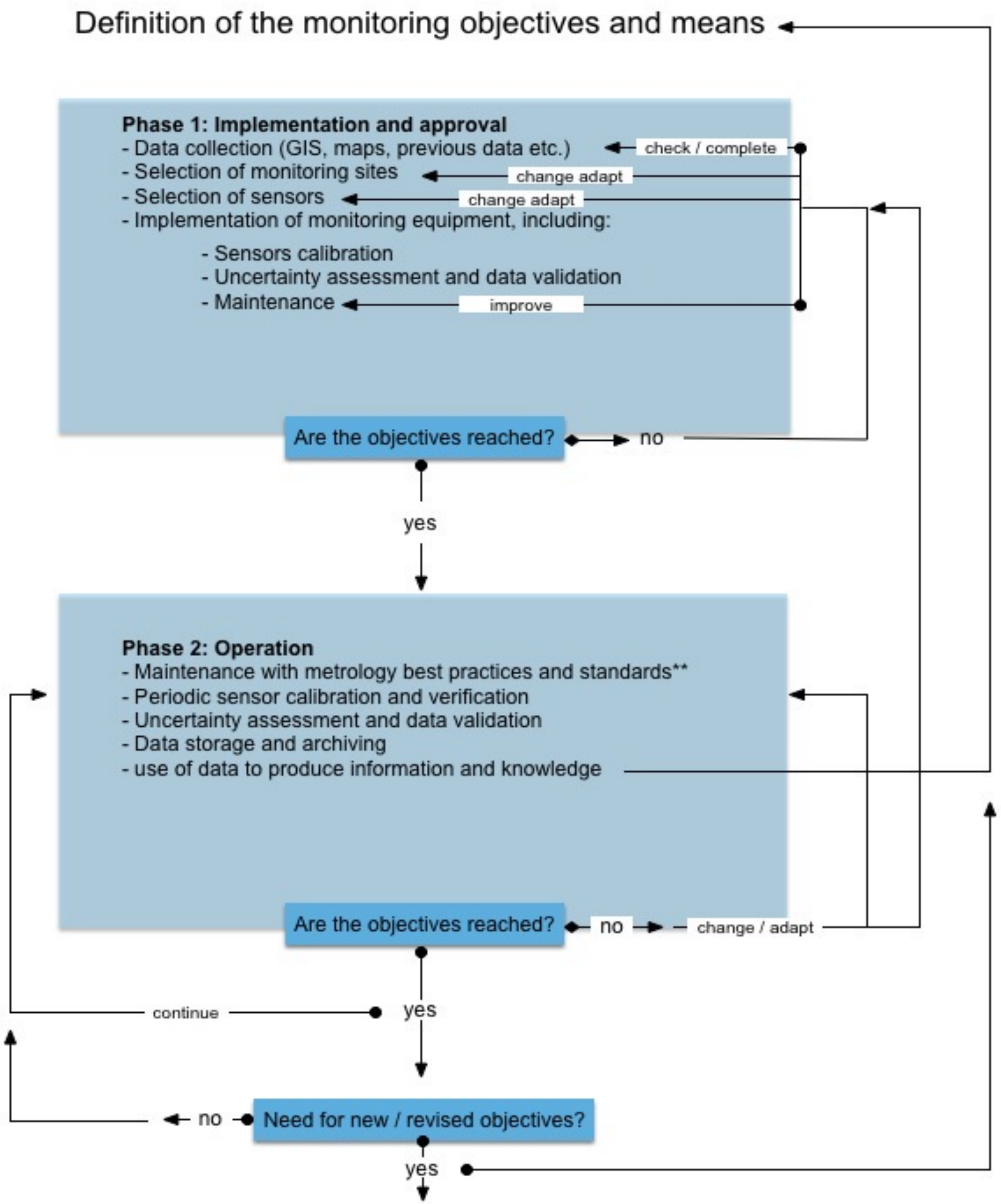
Measuring manhole downstream

Issues with tracers

- Demands on tracer: conservative, measurable with low uncertainty
- Conditions: no environmental impact, societal acceptable (e.g. isotopes)
- Based on dilution: so be sure there are no unknown in- of exfiltration processes in the measured reach.
- High accuracy possible (~2% of nominal value uncertainty (2k->95%))
- Need for specilised personnel, expensive (~ 100.000 nok for one measuring day)

Design of a measuring set-up

- Macro vs micro design
- Needs multi-disciplinary expertise:
  - Scientific/engineering domain knowledge (e.g., Hydraulics)
  - Metrology
  - Planning
  - Detailed system knowledge
  - ICT capabilities
  - Legal aspects
  - Communication (between all stake holders)

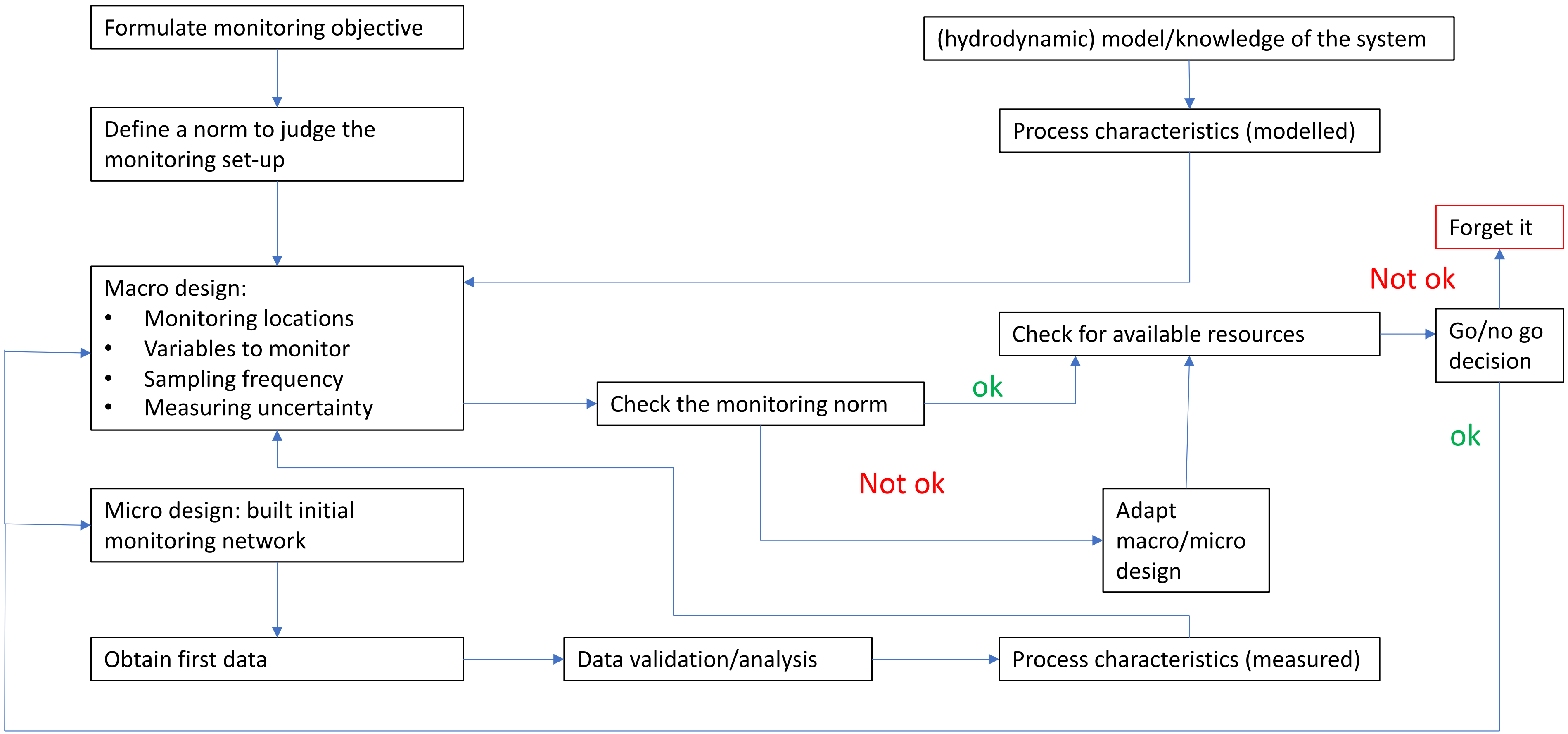

Definition of the monitoring objectives and means
Phase 1: Implementation and approval
- Data collection (GIS, maps, previous data etc.)
- Selection of monitoring sites
- Selection of sensors
- Implementation of monitoring equipment, including:
- Sensors calibration
- Uncertainty assessment and data validation
- Maintenance
check / complete
change adapt
change adapt
improve
Are the objectives reached?
no
yes
Phase 2: Operation
- Maintenance with metrology best practices and standards**
- Periodic sensor calibration and verification
- Uncertainty assessment and data validation
- Data storage and archiving
- use of data to produce information and knowledge
Are the objectives reached?
no
change / adapt
continue
yes
no
Need for new / revised objectives?
yes

Selection of measuring objectives

- An often used, but invalid, example:
  - Increase insight in the functioning of the system

- Some valid examples
  - Flooding frequency at location ‘x’
  - Hydraulic capacity of object ‘y’
  - Obtain data to calibrate some model ‘z’

Macro design



Macro design

- Measuring locations
- Parameters to monitor
- Sampling frequency
- Allowable uncertainty
- (Duration of the campaign)

Measuring locations

- Depends on the objective (e.g. flood frequency at location ‘x’)
- Safety (e.g. traffic)
- Accessibilty
- Presence of power/communication means
- Observability of the proces of interest at the location

Two Maintenance Workers Die After Inhaling Hydrogen Sulfide in Manhole

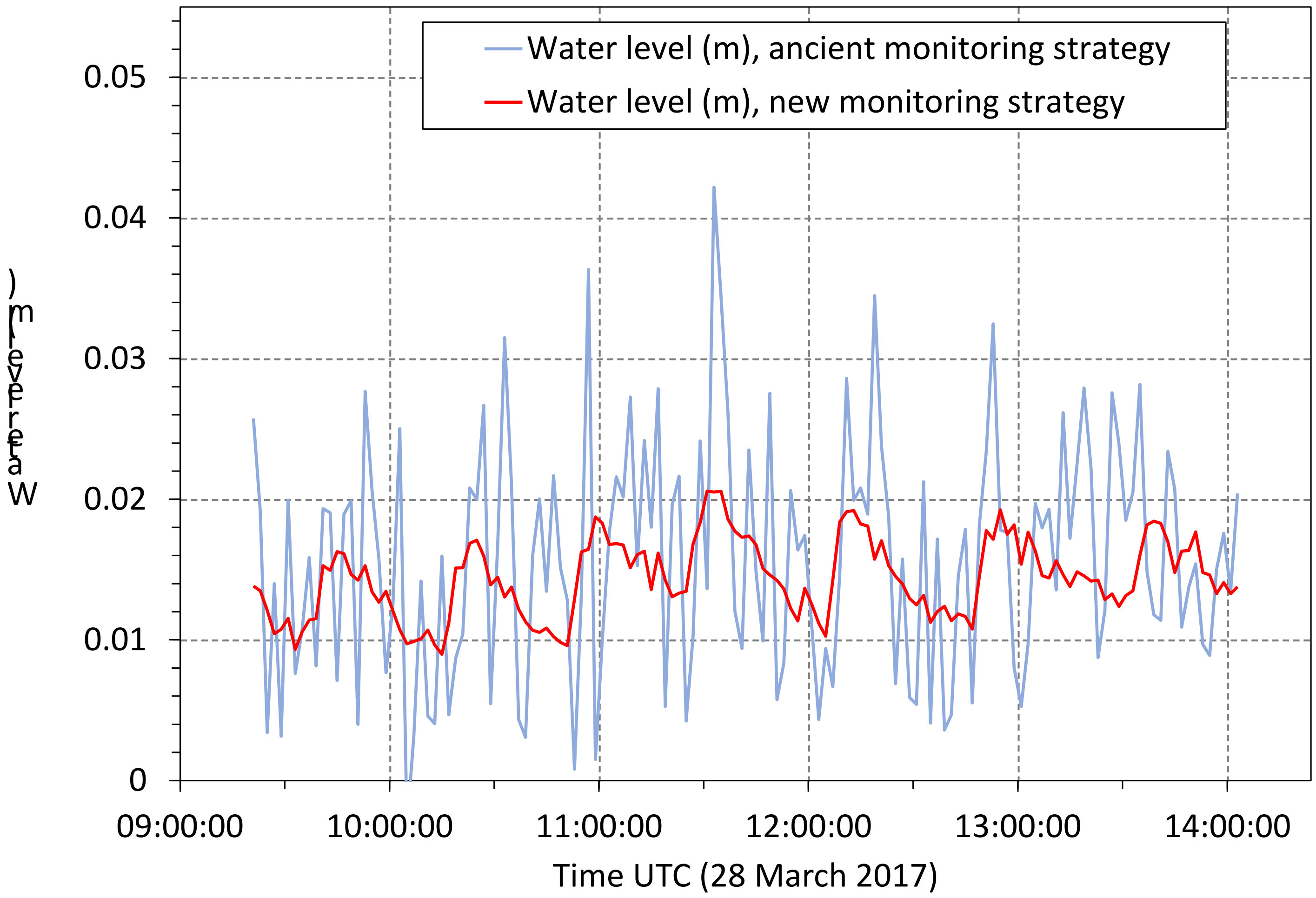
FACE 8928

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH), Division of Safety Research (DSR), performs Fatal Accident Circumstances and Epidemiology (FACE) investigations when a participating state reports an occupational fatality and requests technical assistance. The goal of these evaluations is to prevent fatal work injuries in the future by studying the working environment, the worker, the task the worker was performing, the tools the worker was using, the energy exchange resulting in fatal injury, and the role of management in controlling how these factors interact.

On January 31, 1989, a 29-year-old male maintenance worker (the victim) entered a sewer manhole to repair a pipe, and collapsed at the bottom. In a rescue attempt, a 43-year-old male maintenance worker (co-worker victim) entered the manhole and also collapsed. Both workers (hereinafter referred to as initial victim and co-worker victim) were pronounced dead at the scene.

Example of updating a monitoring setup (reduce dt, change of sensortype)



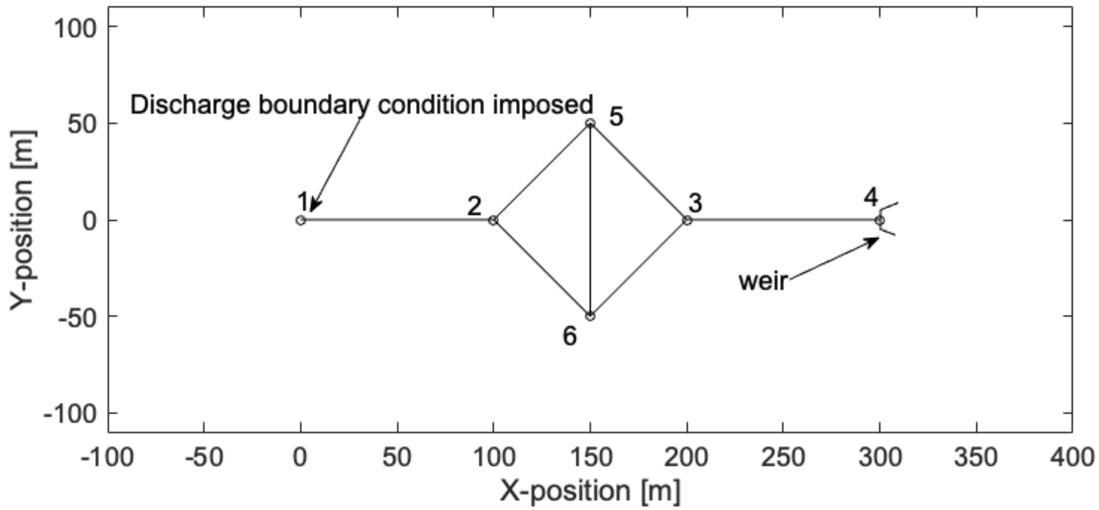
What if many possibilities exists?

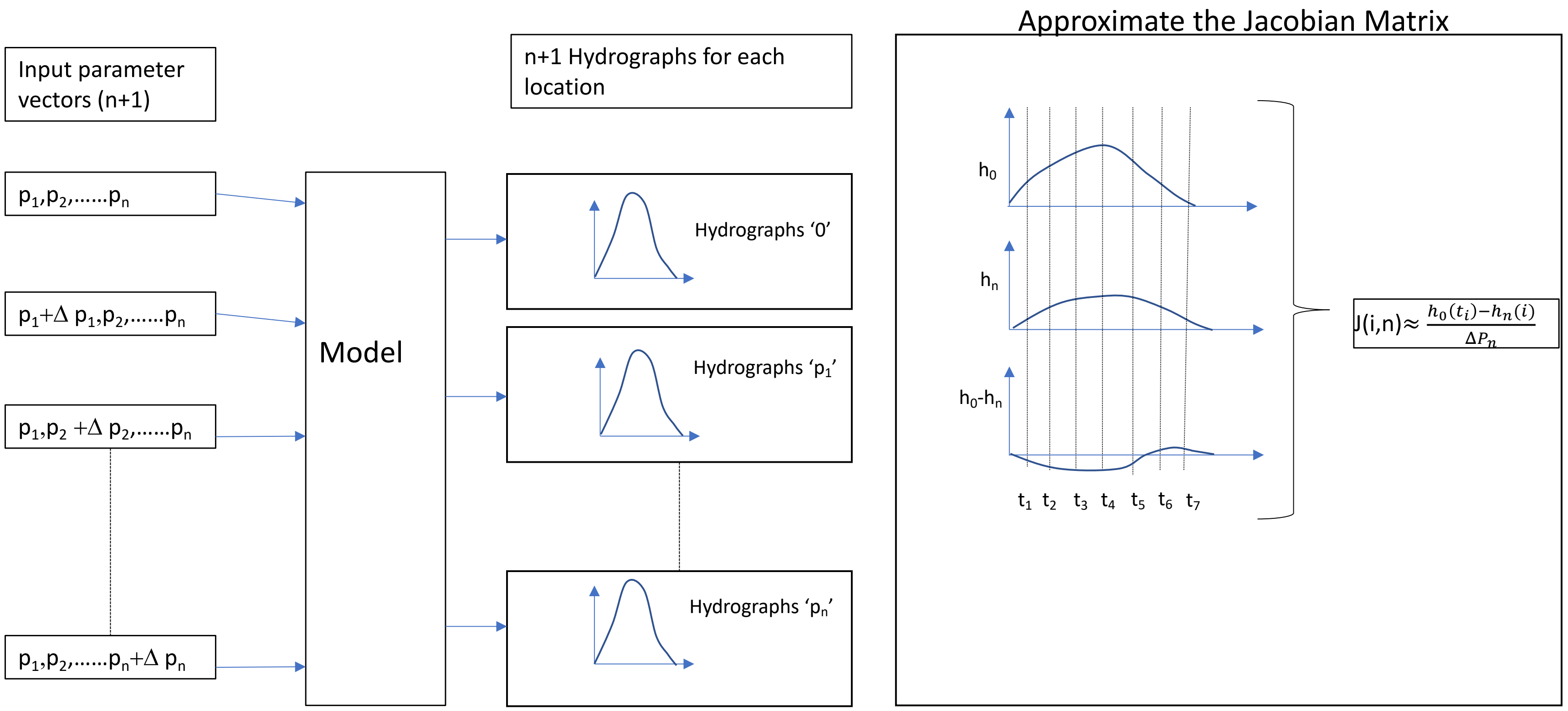
- Sometimes the locations are not directly clear from the objective: e.g. calibrate a hydrodynamic model
- There are ‘n’ locations and I have the budget for ’m’, n>>m
- So choose that combination that delivers the most ‘information’ for calibration.
- This is a very specialistic subject, I’ll give a brief outline of principles.

Information: sensitivity of the measured quantity to a change in model parameter

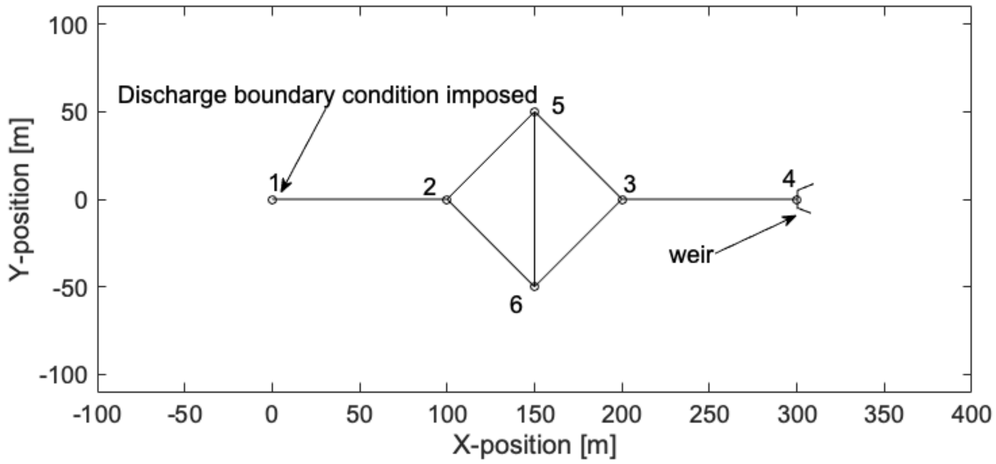
- $$J = \begin{bmatrix} \frac{dh_{t=1}^{loc=1}}{dp_1} & \cdots & \frac{dh_{t=1}^{loc=m}}{dp_2} \\ \vdots & & \vdots \\ \frac{dh_{t=n}^{loc=1}}{dp_1} & \cdots & \frac{dh_{t=n}^{loc=m}}{dp_2} \end{bmatrix} \approx \begin{bmatrix} \frac{\Delta h_{t=1}^{loc=1}}{\Delta p_1} & \cdots & \frac{\Delta h_{t=1}^{loc=m}}{\Delta p_2} \\ \vdots & & \vdots \\ \frac{\Delta h_{t=n}^{loc=1}}{\Delta p_1} & \cdots & \frac{\Delta h_{t=n}^{loc=m}}{\Delta p_2} \end{bmatrix}$$

e.g. p1=hydraulic roughness, p2= weir coefficient

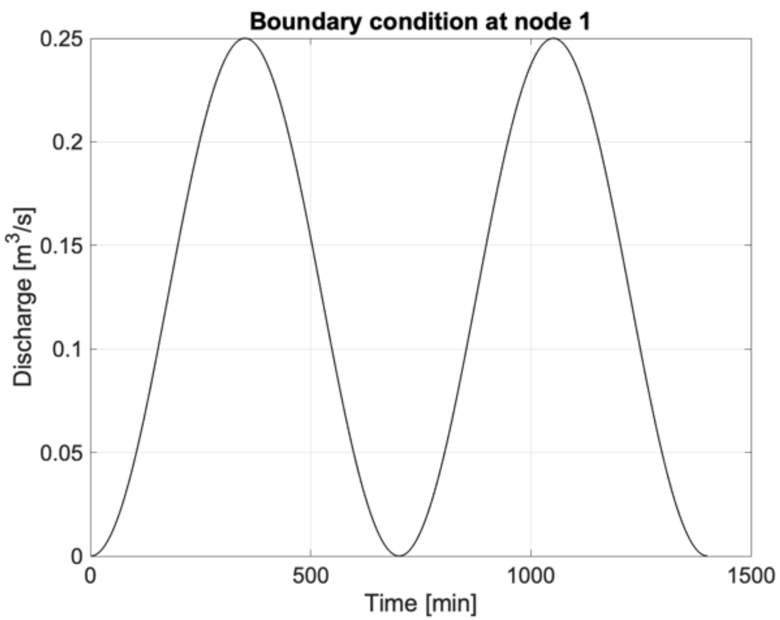



Input parameter vectors (n+1)
p1,p2,……pn
p1+Δ p1,p2,……pn
p1,p2 +Δ p2,……pn
p1,p2,……pn+Δ pn
Model
n+1 Hydrographs for each location
Hydrographs '0'
Hydrographs 'p1'
Hydrographs 'pn'
Approximate the Jacobian Matrix
h0
hn
h0-hn
t1 t2 t3 t4 t5 t6 t7
J(i,n)≈ (h0(ti)−hn(i))/ΔPn

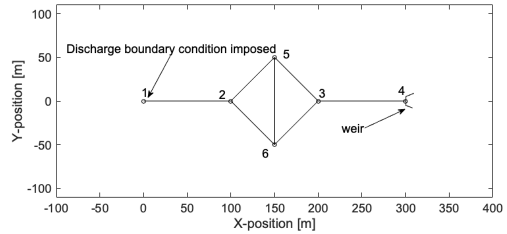
One example

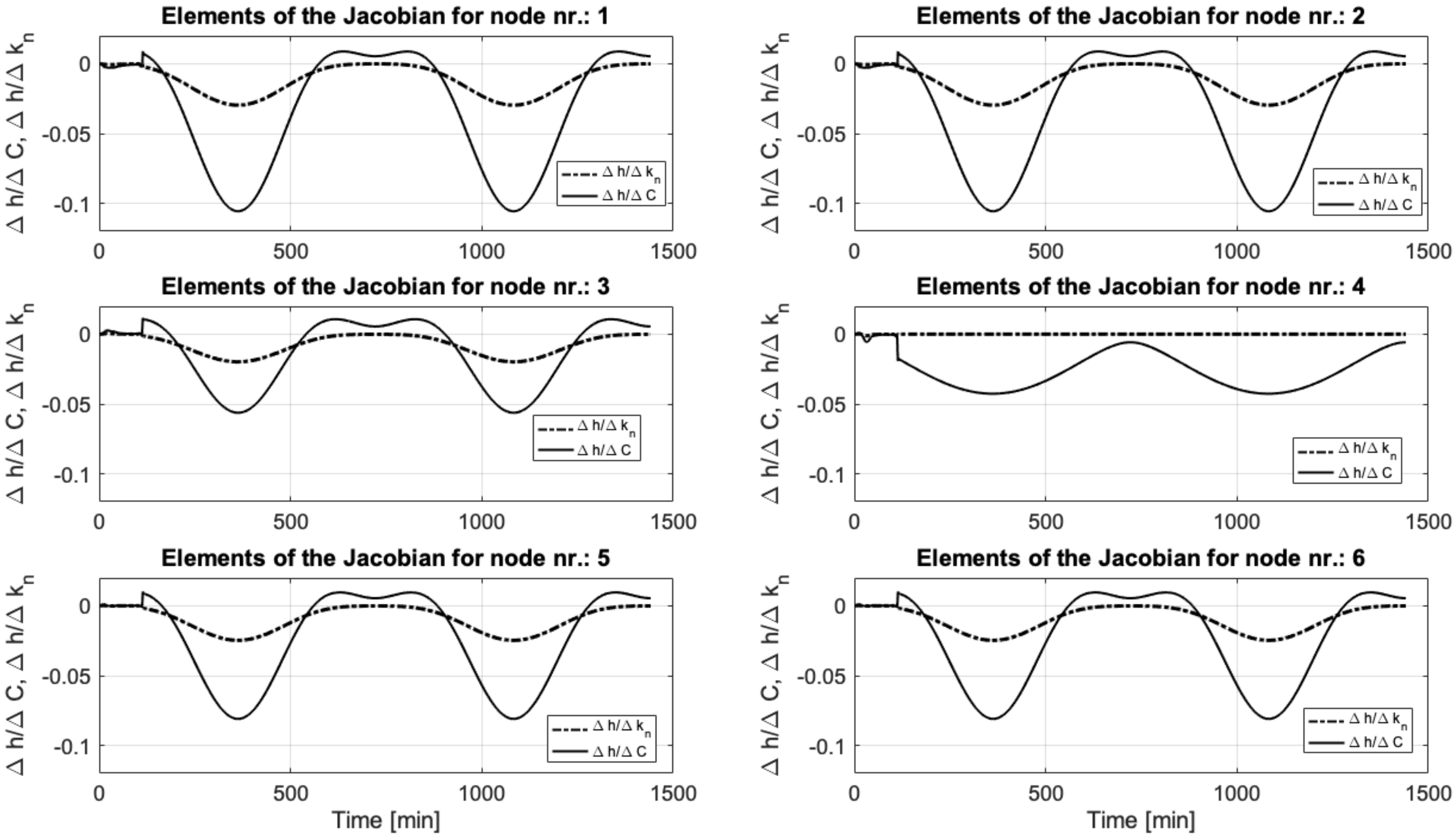


Discharge boundary condition imposed
1
2
3
4
5
6
weir
100
50
0
-50
-100
-100
-50
0
50
100
150
200
250
300
350
400
X-position [m]
Y-position [m]



Boundary condition at node 1
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
Time [min]
Discharge [m3/s]


Discharge boundary condition imposed
weir
1
2
3
4
5
6
X-position [m]
Y-position [m]

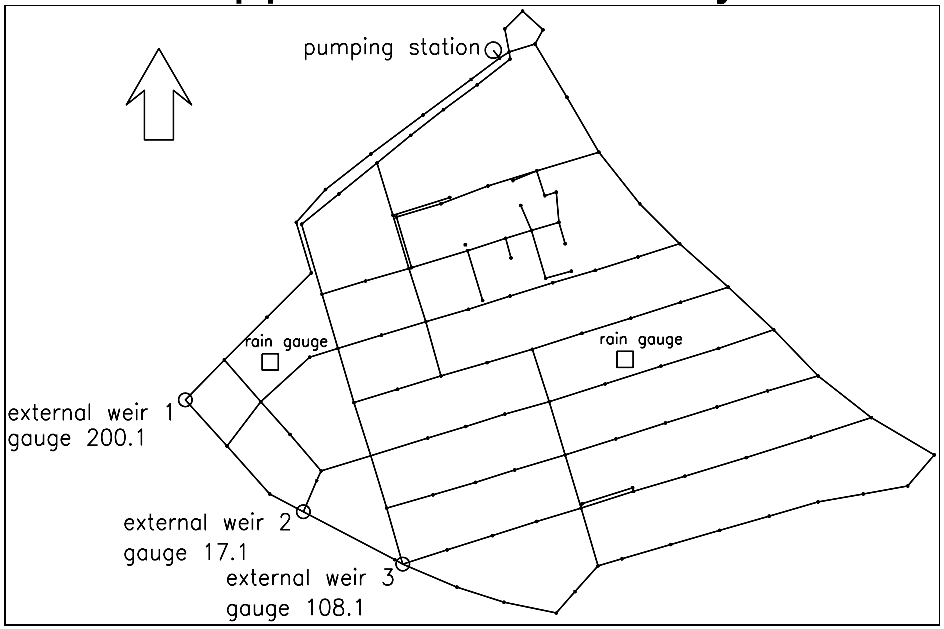

Elements of the Jacobian for node nr.: 1
Elements of the Jacobian for node nr.: 2
Elements of the Jacobian for node nr.: 3
Elements of the Jacobian for node nr.: 4
Elements of the Jacobian for node nr.: 5
Elements of the Jacobian for node nr.: 6
Δ h/Δ C, Δ h/Δ k_n
Δ h/Δ k_n
Δ h/Δ C
Time [min]

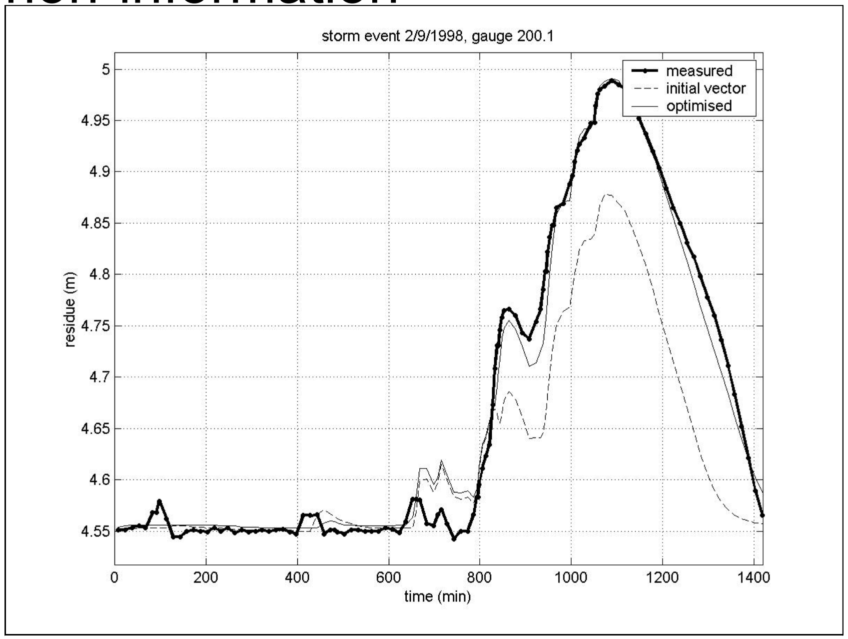
Procedure

- Identify those locations that are (combined) most sensitive to parameter changes (normally this is done through eigen-value analysis of the product of the Jacobian and its transpose)
- For this some optimisation algorithm is applied, e.g. some genetic agorithm as it is able to find a ’family’ of adequate solutions not ‘the’ optimal solution (but do we need that?)
- Many things to explore: how to deal with climate change, how robust is design to changes in the catchment
- How many storms should be used

Macro design, sampling freq and uncertainty

- Sampling frequency and choosen uncertainty are linked.
- Given a process and given an uncertainty, there are two limits on sampling frequency:
  - Lower limit defined by losing information
  - Upper limit defined by collecting non-information





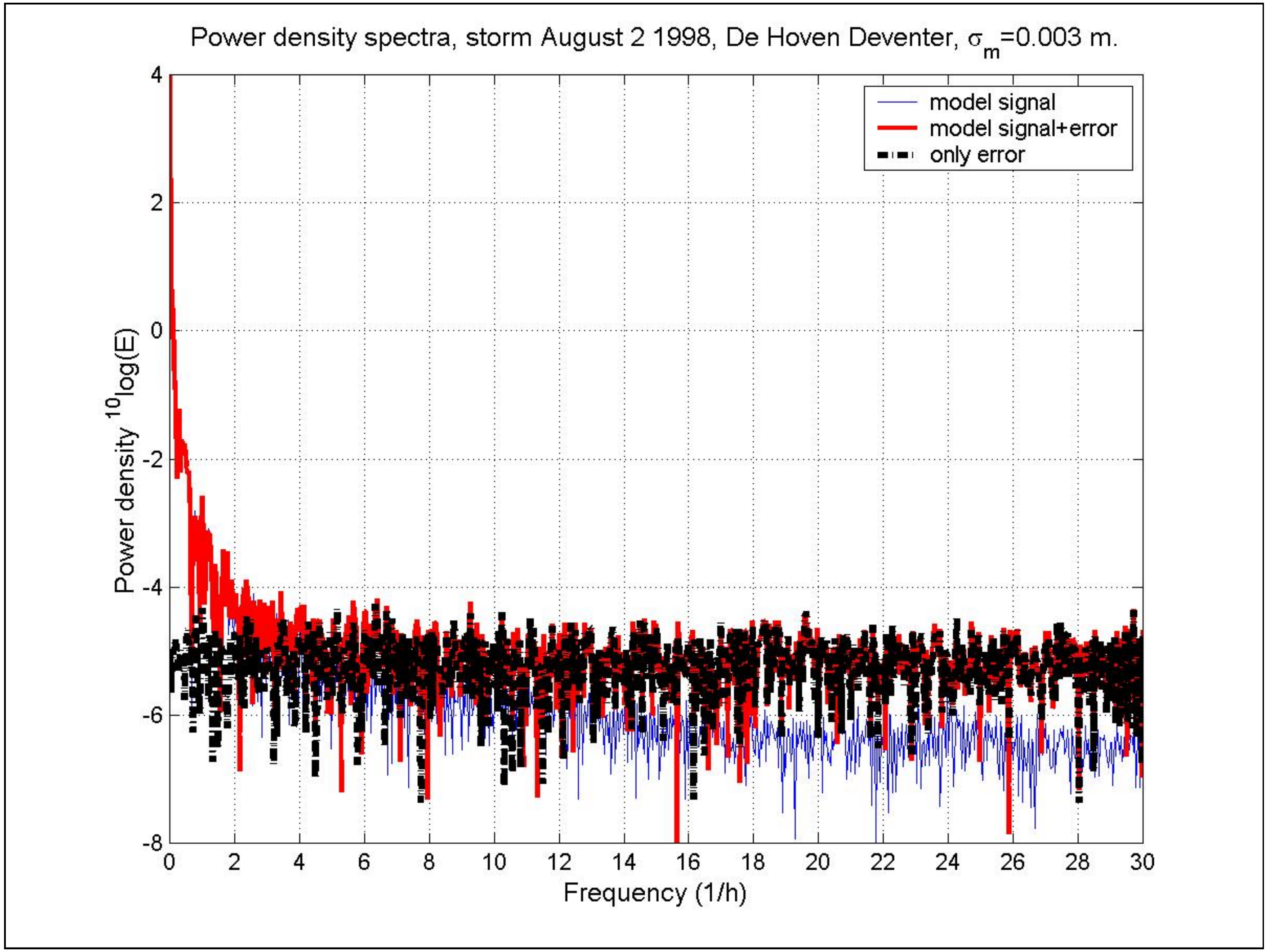
Frequency domain analysis (Fourier transform)

$$F(k) = \frac{1}{N}\sum_{j=1}^{j=N} f(j)\omega_N^{(j-1)(k-1)}$$

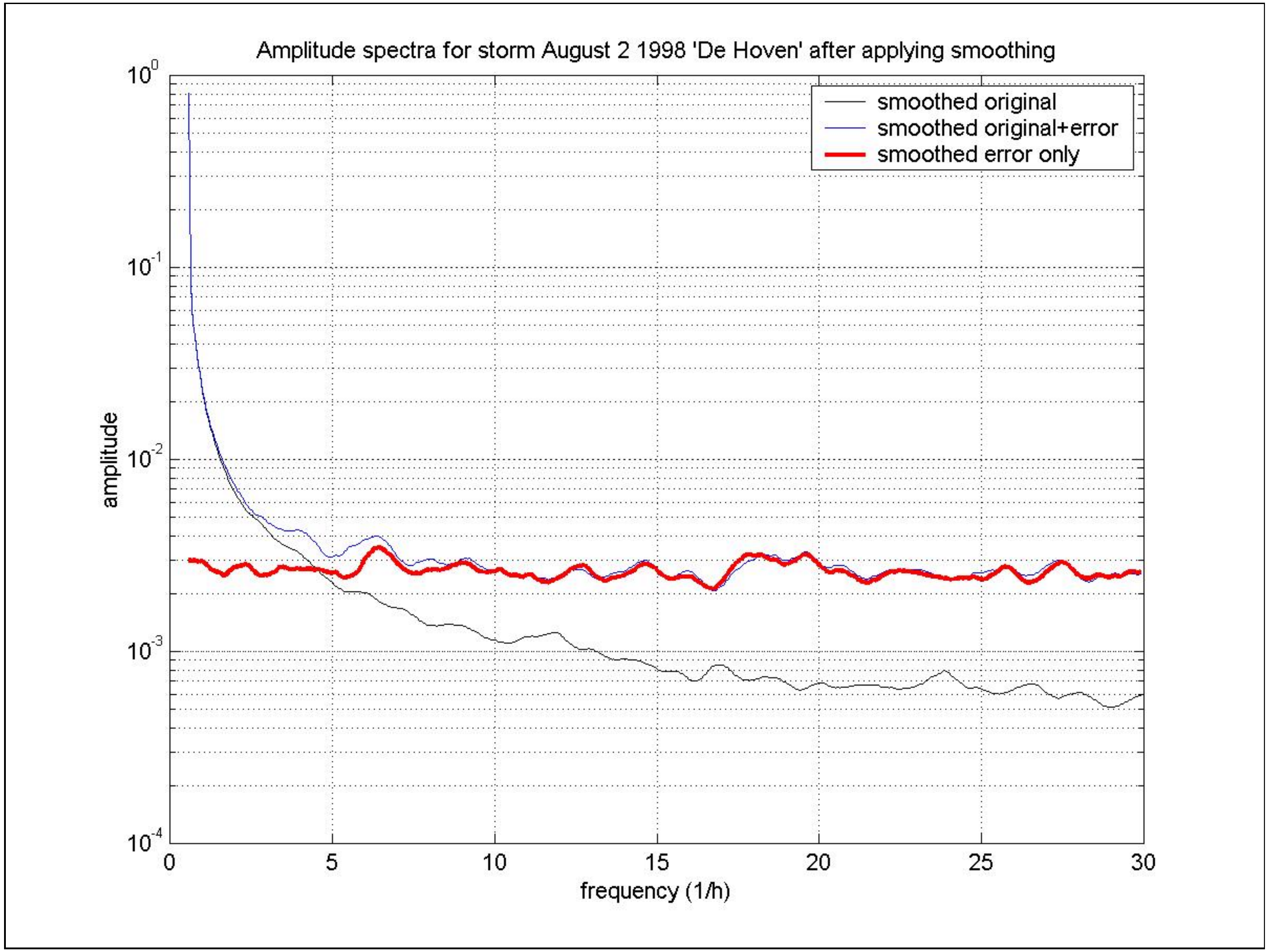
$$f(j) = \frac{1}{N}\sum_{k=1}^{k=N} F(k)\omega_N^{-(j-1)(k-1)}$$

$$\omega_N = e^{\frac{-2\pi i}{N}}$$

Rough energy density spectrum



‘Smoothing’



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Example

storm	remarks	δt (s) point 1	δt (s) point 2	δt (s) point 3
storm 01	Overflow	158	135	114
storm 02	Overflow	171	63	60
storm 03	Overflow	167	72	75
storm 04	Overflow	130	60	60
storm 05	Overflow	95	64	65
storm 06	Overflow	134	60	60
storm 07	Overflow	61	89	79
storm 08	Overflow	105	74	72
storm 09	Overflow	60	60	60
storm 10	Overflow	60	60	60
August 25 1998	Overflow	199	280	375
September 2 1998	No overflow	654	675	686
October 7 1998	No overflow	1196	658	1082
October 9-13 1998	No overflow	469	527	505
October 24 1998	Overflow	329	300	146

Time-domain analysis

- goal is to keep the interpolation error due to discretisation in time within limits.
- This is related to the accuracy of the measuring device the process characteristics (dynamics) and the demands in the monitoring programme.

Time-domain analysis

Interpolation error

$$mse = \frac{1}{2}\sigma_p^2\left(3 + \rho(t_{i-1}, t_i) - 4\rho(t_{i-1}, t_\tau)\right)$$

A reasonable demand would be:

$$mse \leq \sigma_m^2$$

Example

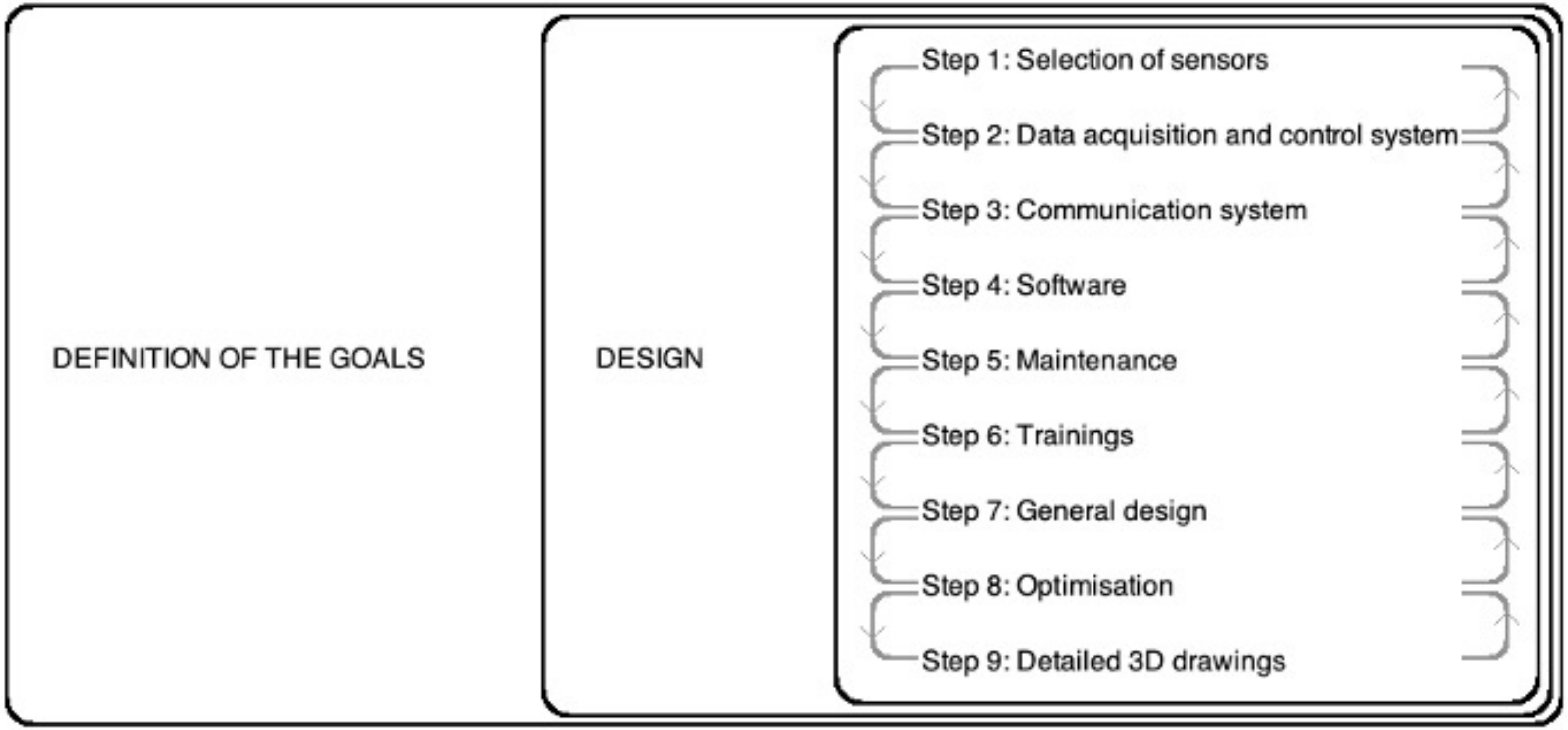
storm	Δt (s) minimal maximum	Δt (s) maximal minimum	range char time
01	394	158	7730-111
02	**303**	171	7730-101
03	339	167	5526-88
04	331	130	5526-81
05	394	95	4260-82
06	336	134	4260-77
07	365	89	3468-72
08	345	105	3468-74
09	327	**60**	2366-70
10	324	60	1795-68
August 25 1998	739	375	7014-90
September 2 1998	1414	686	34664-23800
October 7 1998	2096	1196	34664-18850
October 9-13 1998	1422	527	9950-5360
October 24 1998	1046	329	13222-127

In conclusion

- Without prior knowledge (a model, rules of the thumb, old monitoring data) no estimates for sampling frequency and/or/ allowable uncertainty can be made.
- Strategy: start with a sampling freq. as high as feasible and adjust (or obtain prior information ☺) when needed. (increasing the frequency cannot be done based on low frequency data!!!!!).
- Many things to consider: uncertainty is not only defined by the instrument! As we've seen the local geometry has an influence -> relation location, sampling freq. and uncertainty-> typical engineering problem).

Micro design

		Type of monitoring stations	
		24/7	Event sampling
Life expectancy	Short term	- Robust components - Stability of the power supply	- Detection of events - Robustness regarding the start/stop procedures
	Long term	- Same as above + quality of the components - Scalability of hardware and software	- Same as above + quality of the components



Propagation of uncertainties

- In many cases one is interested in a not measured quantity based on measured quantities (e.g. velocity-area method for discharge)
- In many cases ‘’hidden variables” are present in the measurement. (can somebody give an example?)
- Sometimes extensive postprocessing is involved (e.g. PIV or PTV)
- How to quantity the uncertainty in the parameter of interest?

Repeated measurements:

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$$

Unbiassed standarddeviation of the measurements:

$$s(y) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y}\,)^2}$$

Unbiassed standarddeviation of the mean:

$$s(\bar{y}) = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(y_i - \bar{y}\,)^2} = \frac{s(y)}{\sqrt{n}}$$

Coverage interval:

$$[\bar{y} - ku(\bar{y}), \bar{y} + ku(\bar{y})]$$

$u(\bar{y}) \sim s(\bar{y})$ (standarduncertainty)

For now we take k=1.96, resulting in a 95% coverage interval

Propagation of uncertainties

$$u(y)^2 = \sum_{i=1}^{N} u(x_i)^2 \left(\frac{\partial f}{\partial x_i}\right)^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} u(x_i, x_j)\left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right)$$

Covariant terms

Example: Manning-Strickler in a rectangular channel (B,h)

$$Q = f(K, I, B, h) = KI^{\frac{1}{2}}(Bh)\left(\frac{Bh}{B+2h}\right)^{\frac{2}{3}} = KI^{\frac{1}{2}}(Bh)^{\frac{5}{3}}(B+2h)^{-\frac{2}{3}}$$

- K (Manning-Strickler coefficient)
- I (bed slope of the channel)
- B (width of the channel)
- H (water level)

Under what conditions are these parameters independent? (i.e. no covariant terms)

Example: Manning-Strickler

$$Q = f(K, I, B, h) = KI^{\frac{1}{2}}(Bh)\left(\frac{Bh}{B + 2h}\right)^{\frac{2}{3}} = KI^{\frac{1}{2}}(Bh)^{\frac{5}{3}}(B + 2h)^{-\frac{2}{3}}$$

$$u(Q)^2 = \sum_{i=1}^{4}(u(x_i)^2\left(\frac{\partial Q}{\partial x_i}\right)^2$$

$$= u(K)^2\left(\frac{\partial Q}{\partial K}\right)^2 + u(I)^2\left(\frac{\partial Q}{\partial I}\right)^2 + u(B)^2\left(\frac{\partial Q}{\partial B}\right)^2 + u(h)^2\left(\frac{\partial Q}{\partial h}\right)^2$$

parameter	value	U(parameter)
K	[70,80]	$10/(2*3^{0.5})$
I	0.0032 m/m	6×10^{-6} m/m
B	0.805 m	0.002 m
H	0.32 m	0.0015

Example: Manning-Strickler

$$Q = f(K, I, B, h) = KI^{\frac{1}{2}}(h)\left(\frac{Bh}{B+2h}\right)^{\frac{2}{3}} = KI^{\frac{1}{2}}(Bh)^{\frac{5}{3}}(B+2h)^{-\frac{2}{3}}$$

$$\frac{\partial Q}{\partial K} = I^{\frac{1}{2}}(Bh)^{\frac{5}{3}}(B+2h)^{-\frac{2}{3}} = \frac{Q}{K} = 0.004615$$

$$\frac{\partial Q}{\partial I} = \frac{1}{2}KI^{-\frac{1}{2}}(Bh)^{\frac{5}{3}}(B+2h)^{-\frac{2}{3}} = \frac{Q}{2I} = 54.090477$$

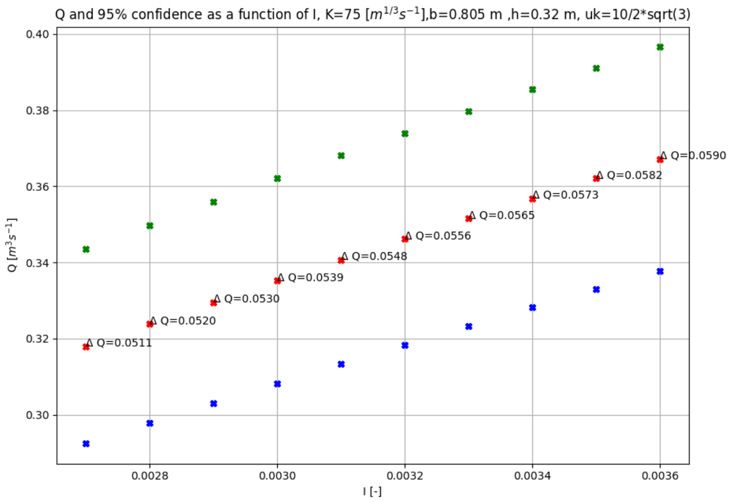
$$\frac{\partial Q}{\partial B} = \frac{5}{3}hKI^{\frac{1}{2}}(Bh)^{\frac{2}{3}}(B+2h)^{-\frac{2}{3}} - \frac{2}{3}KI^{\frac{1}{2}}(Bh)^{\frac{5}{3}}(B+2h)^{-\frac{5}{3}} = \frac{Q}{3}\left(\frac{5}{B} - \frac{2}{B+2h}\right) = 0.557013$$

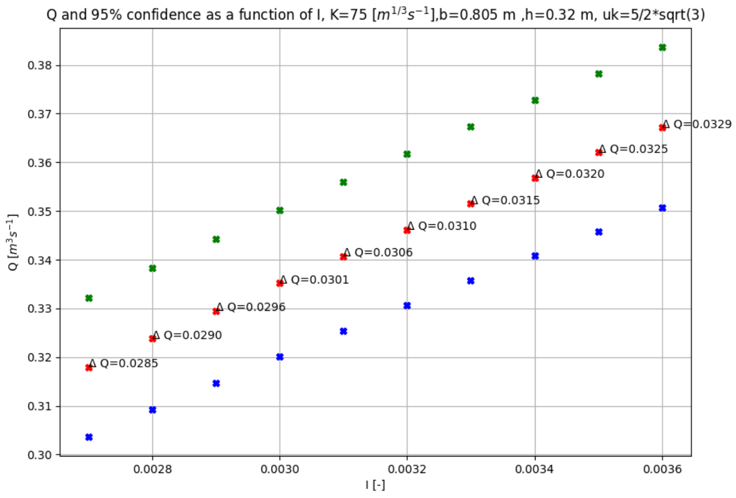
$$\frac{\partial Q}{\partial h} = \frac{5}{3}BKI^{\frac{1}{2}}(Bh)^{\frac{2}{3}}(B+2h)^{-\frac{2}{3}} - \frac{4}{3}KI^{\frac{1}{2}}(Bh)^{\frac{5}{3}}(B+2h)^{-\frac{5}{3}} = \frac{Q}{3}\left(\frac{5}{h} - \frac{4}{B+2h}\right) = 1.483588$$

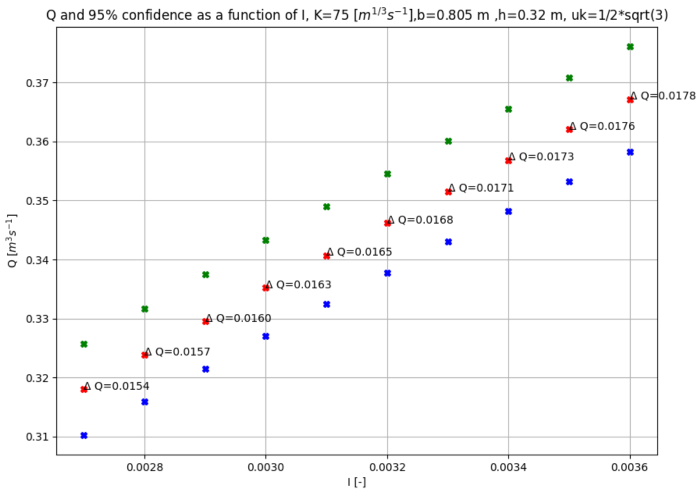
Example Manning-Strickler

- Result is that with 95% probability the discharge is in the interval [0.320, 0.373] m^3/s with an expected value of $Q = 0.346\ m^3/s$
- Relative contribution from individual terms (for this set of measuring data:
  - Uncertainty in K: 96,55% !
  - Uncertainty in I: 0.05 %
  - Uncertainty in B: 0.7 %
  - Uncertainty in H: 2.7 %

Effect of decreasing uncertainty in K







Example weir field calibration

Calibrate a model

- The model is: $Q = \alpha h^{\beta}$

$$\underline{\underline{\text{cov}}} = \sigma_r^2 \left(\underline{\underline{J}}^T \underline{\underline{J}} \right)^{-1}$$

$$\sigma_r = \sqrt{\frac{\sum_{i=1}^{i=n} \left(r_i - \mu_r \right)^2}{n-1}}$$

$$\underline{\underline{J}} = \begin{bmatrix} \frac{\partial r_i}{\partial \alpha} & \frac{\partial r_i}{\partial \beta} \\ . & . \\ . & . \\ . & . \\ \frac{\partial r_n}{\partial \alpha} & \frac{\partial r_n}{\partial \beta} \end{bmatrix}$$

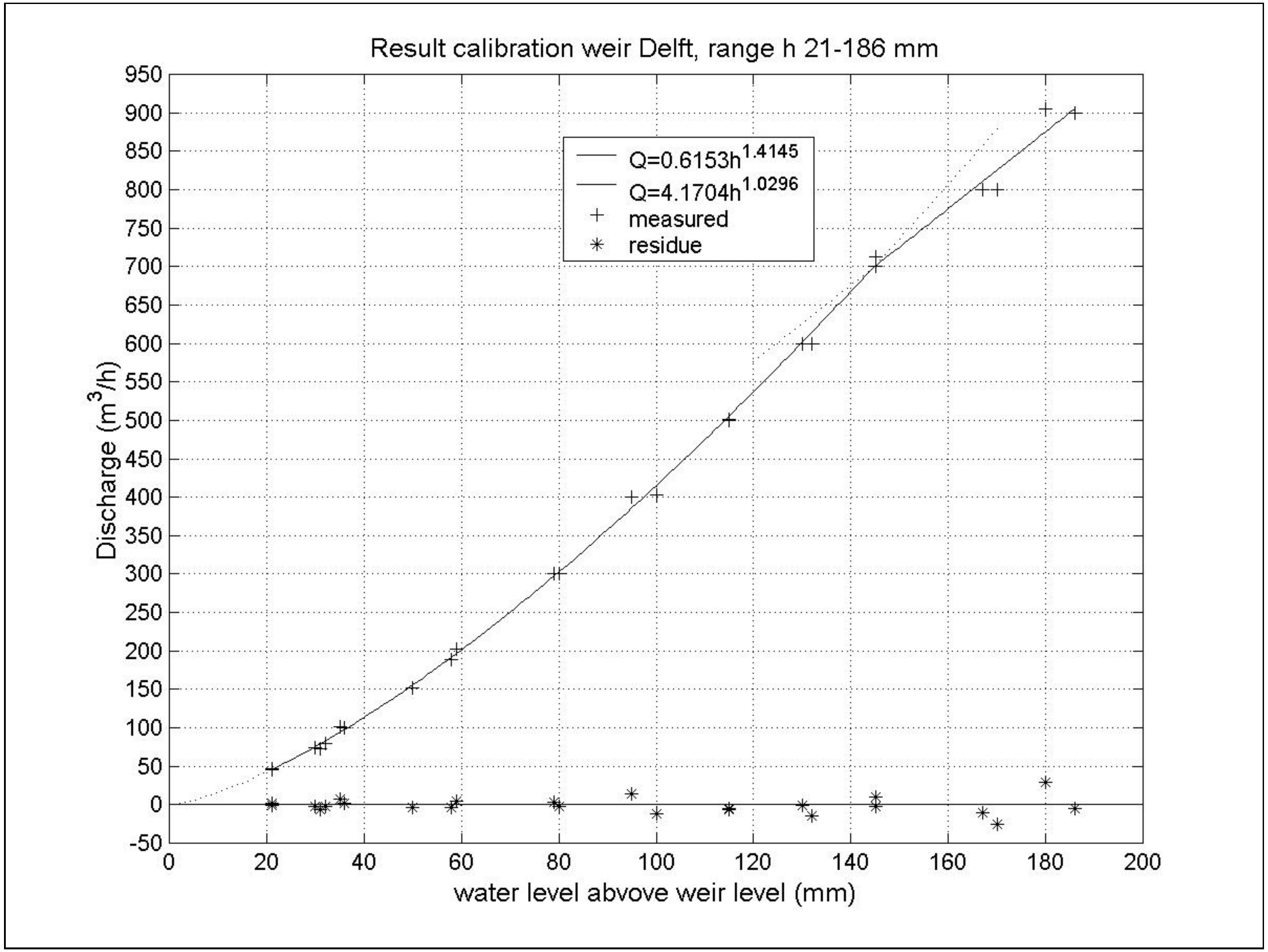
Example Delft

	Range for h	α	β	σ_α^2	σ_β^2	$\rho_{\alpha\beta}$
Q-h_1	21-145 (mm)	0.6153	1.4145	0.0016	$1.8509*10^{-4}$	$-5.4539*10^{-4}$
Q-h_2	145-186 (mm)	4.1704	1.0296	4.8637	0.0107	-0.2277
Q-h_3	21-186 (mm)	0.9542	1.3183	0.0130	$5.7667*10^{-4}$	-0.0270

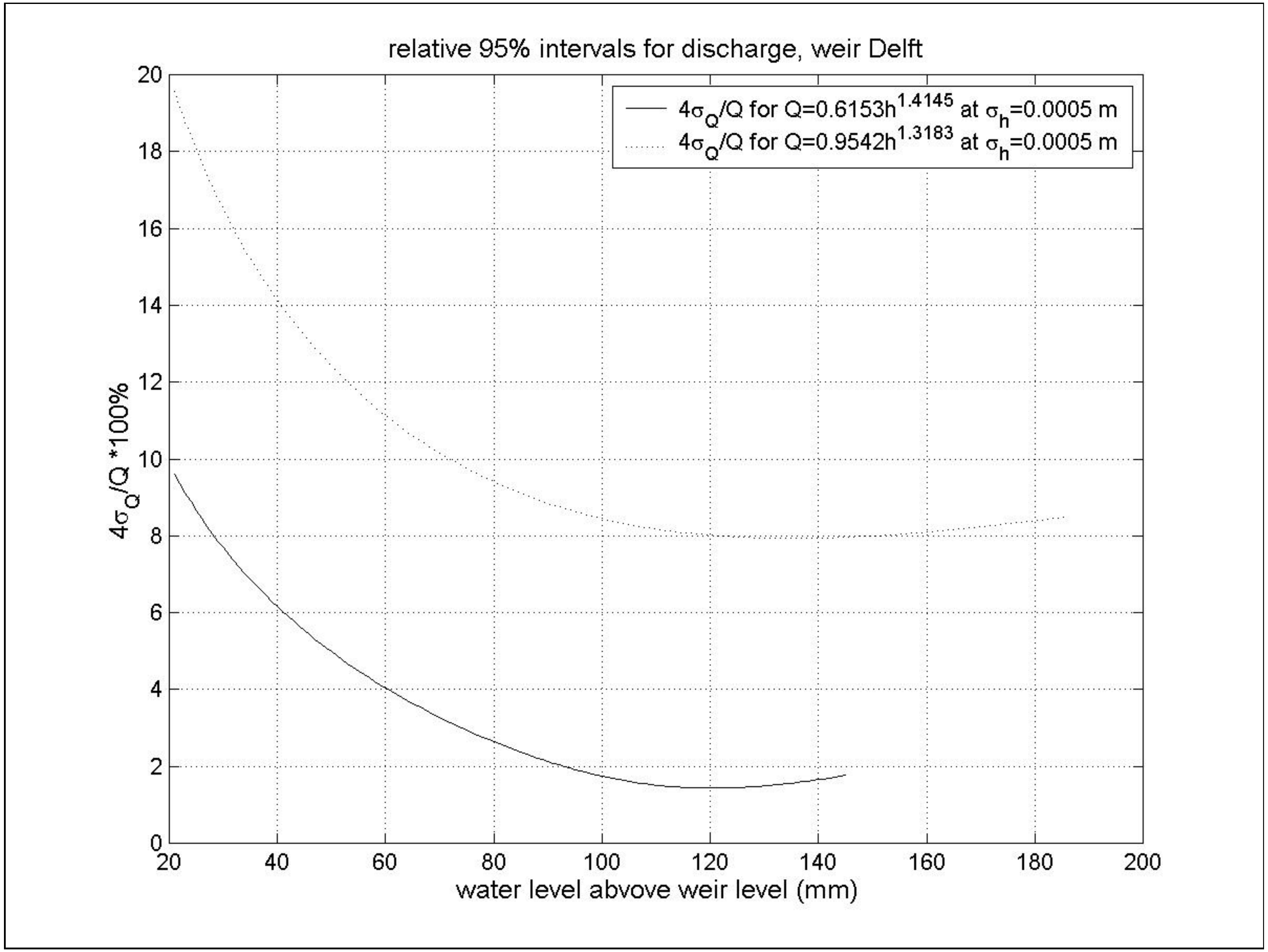
$$\sigma_Q^2 = \left(\alpha\beta h^{(\beta-1)}\right)^2 \sigma_h^2 + \left(h^\beta\right)^2 \sigma_\alpha^2 + \left(\alpha h^\beta \ln(h)\right)^2 \sigma_\beta^2 + 2\left(h^\beta \alpha h^\beta \ln(h)\right)^2 \rho_{\alpha\beta}$$

$$u(y)^2 = \sum_{i=1}^{N} u(x_i)^2 \left(\frac{\partial f}{\partial x_i}\right)^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} u(x_i, x_j)\left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right)$$

Example Delft



Example Delft



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Data validation

- Murphy was an optimist!
- Causes of corrupted data:
  - Power dip
  - Loss of communication
  - Water + electronics are not best friends
  - Weird conditions

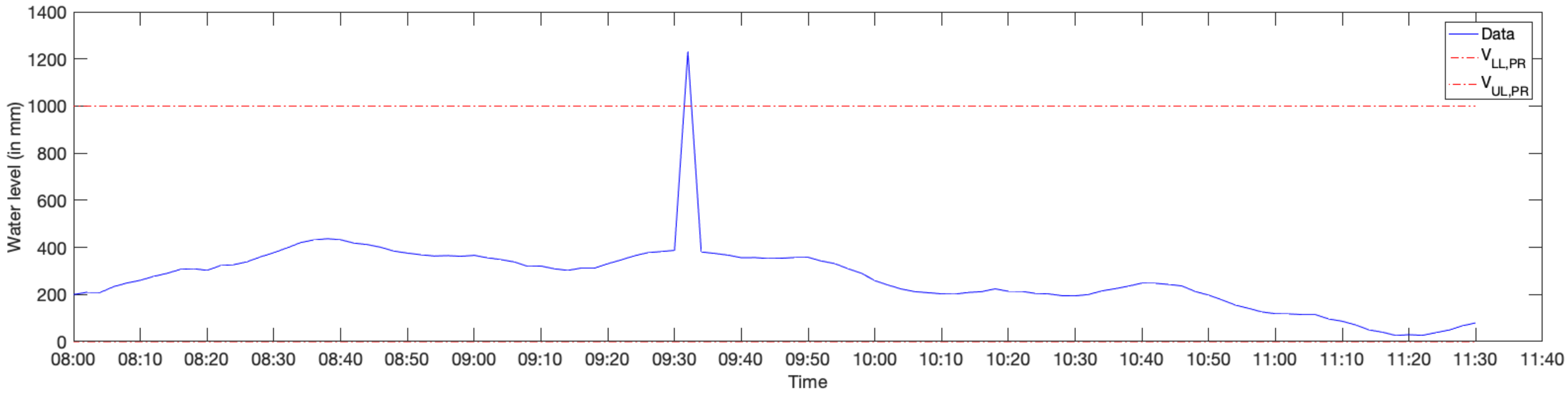
Quality of measuring data

- **Consistency**: there are no internal inconsistencies in the data, e.g. no data beyond the physical defined window of allowed values.
- **Plausibility**: data points seem consistent with the expected conditions.
- **Accuracy**: data points are too inaccurate and, therefore, meaningless.
- **Auditability**: this refers to the ability for users of the data set to obtain knowledge on the 'history' of the data*, i.e.* information e.g. correction, interpolations, *etc*. being done on the data and the availability of meta-data on e.g. calibration and maintenance of sensors.
- **Synchronicity**: timestamps of measured data should be correct in relation to different global time systems, e.g. UTC (Coordinated Universal Time) and, again depending on the purpose the data is collected for, synchronized with associated sensor applications in the same network.

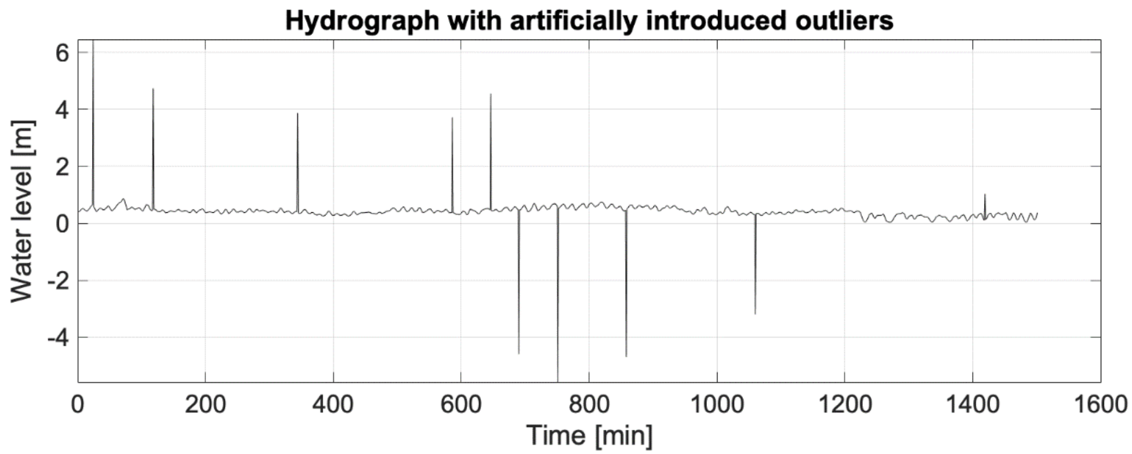
- **Key messages on data validation**
  - KM 9.1: Data validation is mandatory – never use the data without a careful check.
  - KM 9.2: Data validation based on the separation of concerns: Two steps – *i)* pre-validation (unified basic checks), *ii)* goal-driven validation.
  - KM 9.3: Purpose dependency: The results of the data validation depends on the anticipated use of the data.
  - KM 9.4: Subjectivity and reproducibility: Despite there are numerous methods and protocols, data validation remains a subjective process. Keep track of tasks performed.

Pre-check

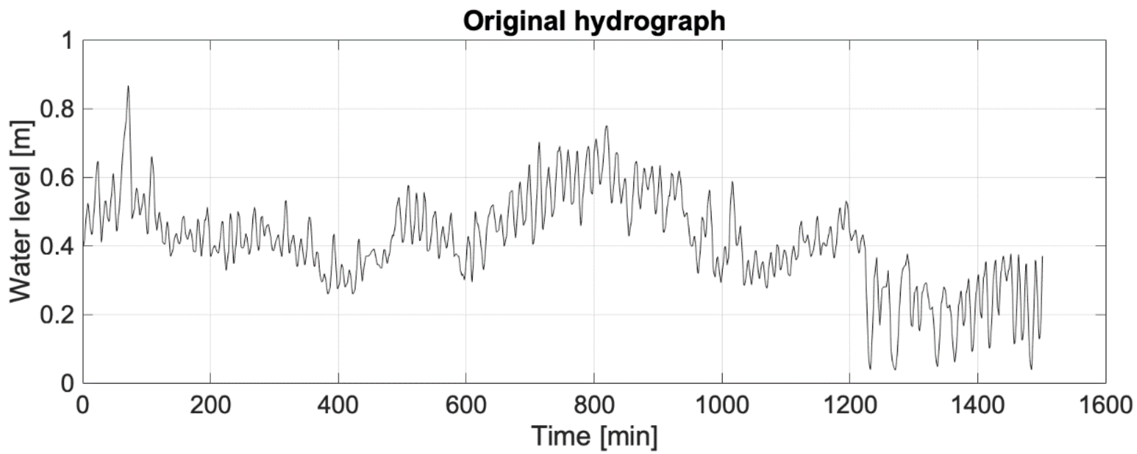
- Is the data point there?
- Is the data point within the expected range?



example

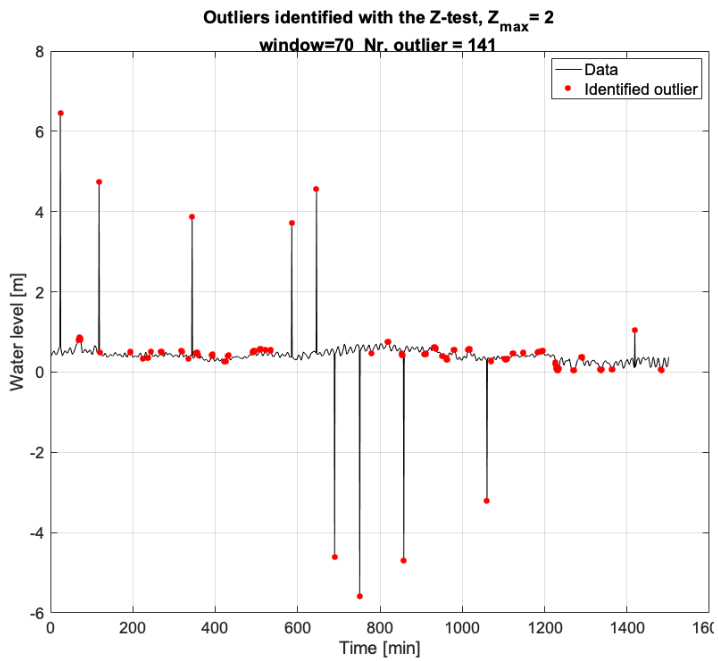


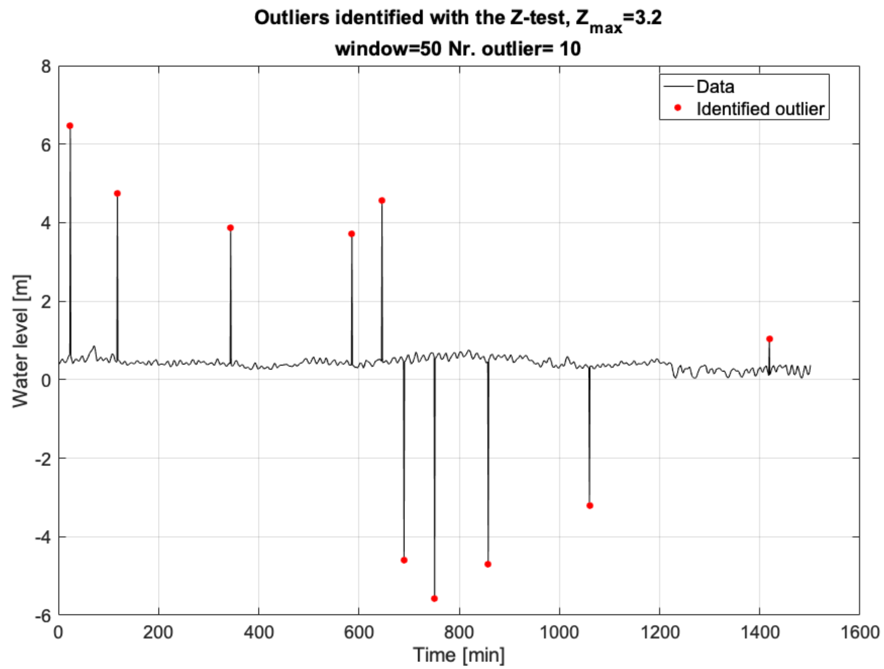
Hydrograph with artificially introduced outliers
Water level [m]
6
4
2
0
-2
-4
0
200
400
600
800
1000
1200
1400
1600
Time [min]



Original hydrograph
Water level [m]
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
1200
1400
1600
Time [min]

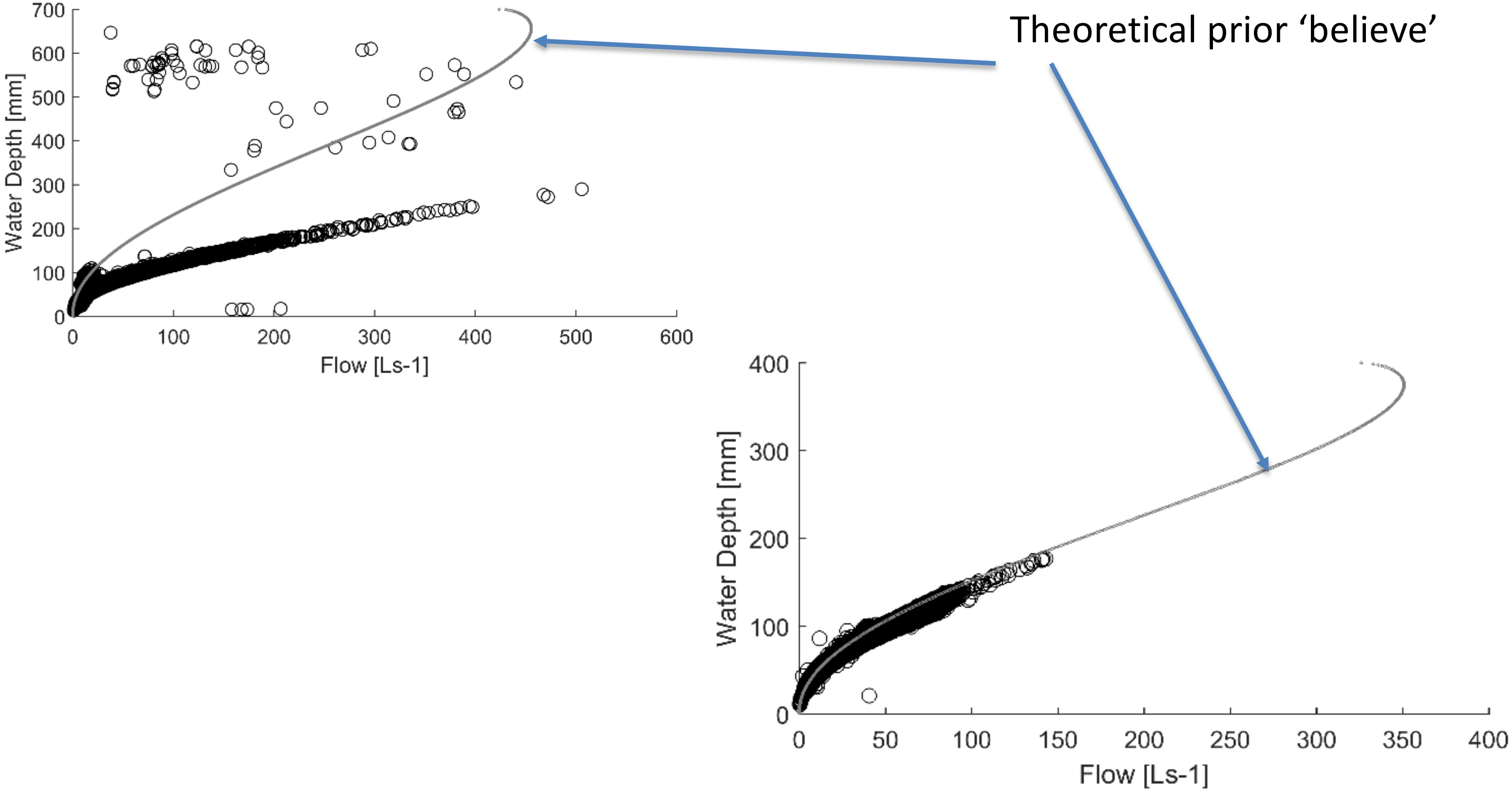
More advanced (ex. Z-test)





Choice for Z_{max} is subjective !!!!!!!

Data or model driven approach



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communicate dataquality

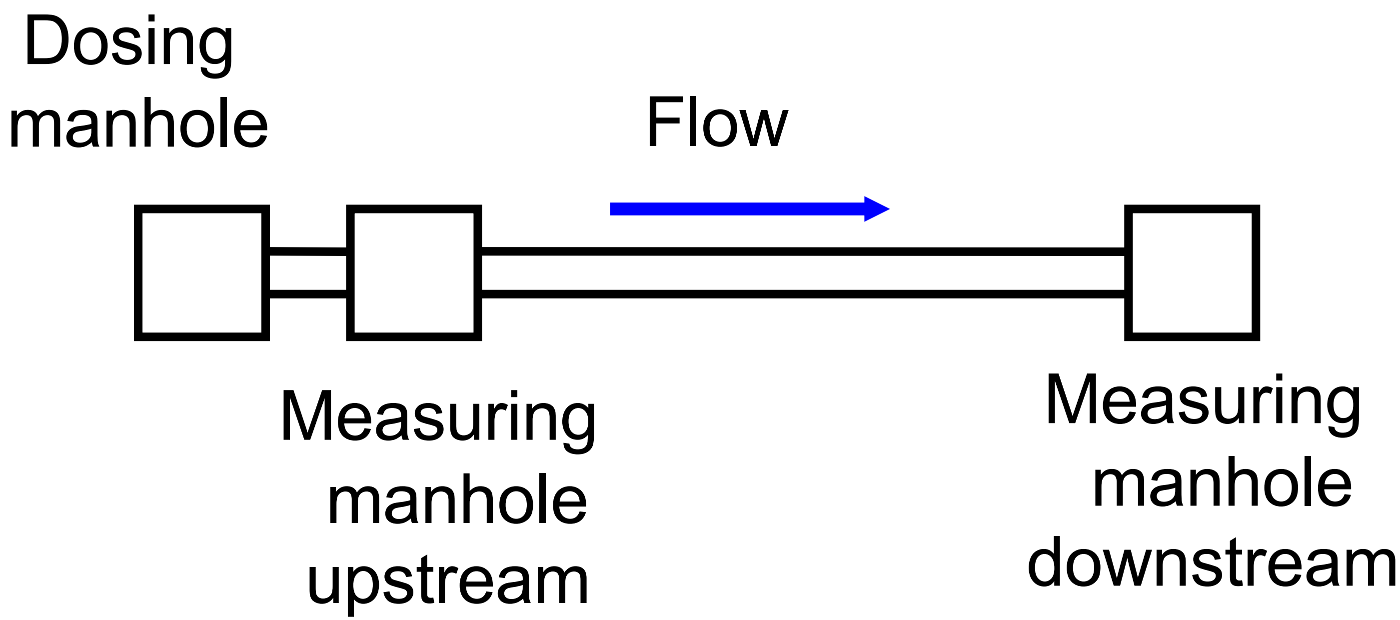
- ’traffic light’ representation

Conclusion

- Monitoring is not really straight forward
- Murphy always wins (but we should keep putting up the fight!)
- Monitoring is becoming more and more important, because:
  - There is need to optimise the operation of UD systems (e.g. by RTC
  - Environmental regulation demand more and more reporting on e.g. CSO events
  - Model validation/calibration to enhance (re)design
  - Developments in IT and sensor technology allow for doing monitoring

Tracer experiments

Tracer: concentrated (200 g/l) NaCl solution
Measuring conductivity

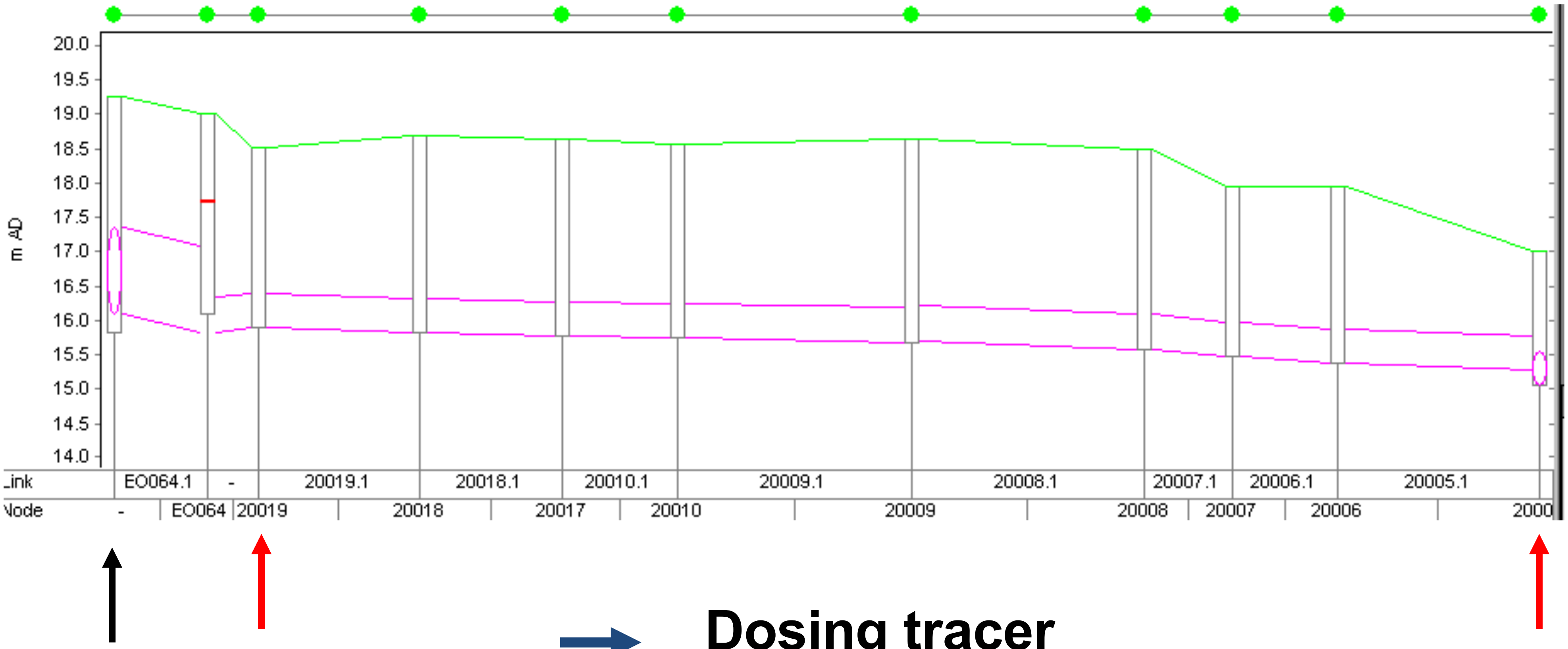


Available models

- Hydroworks/infoworks: only advection
- SOBEK: advection and dispersion, several numerical solvers
- Mouse: advection and dispersion

- Literature reports high numerical dispersion, although studies including a fully calibrated hydrodynamic model are rare

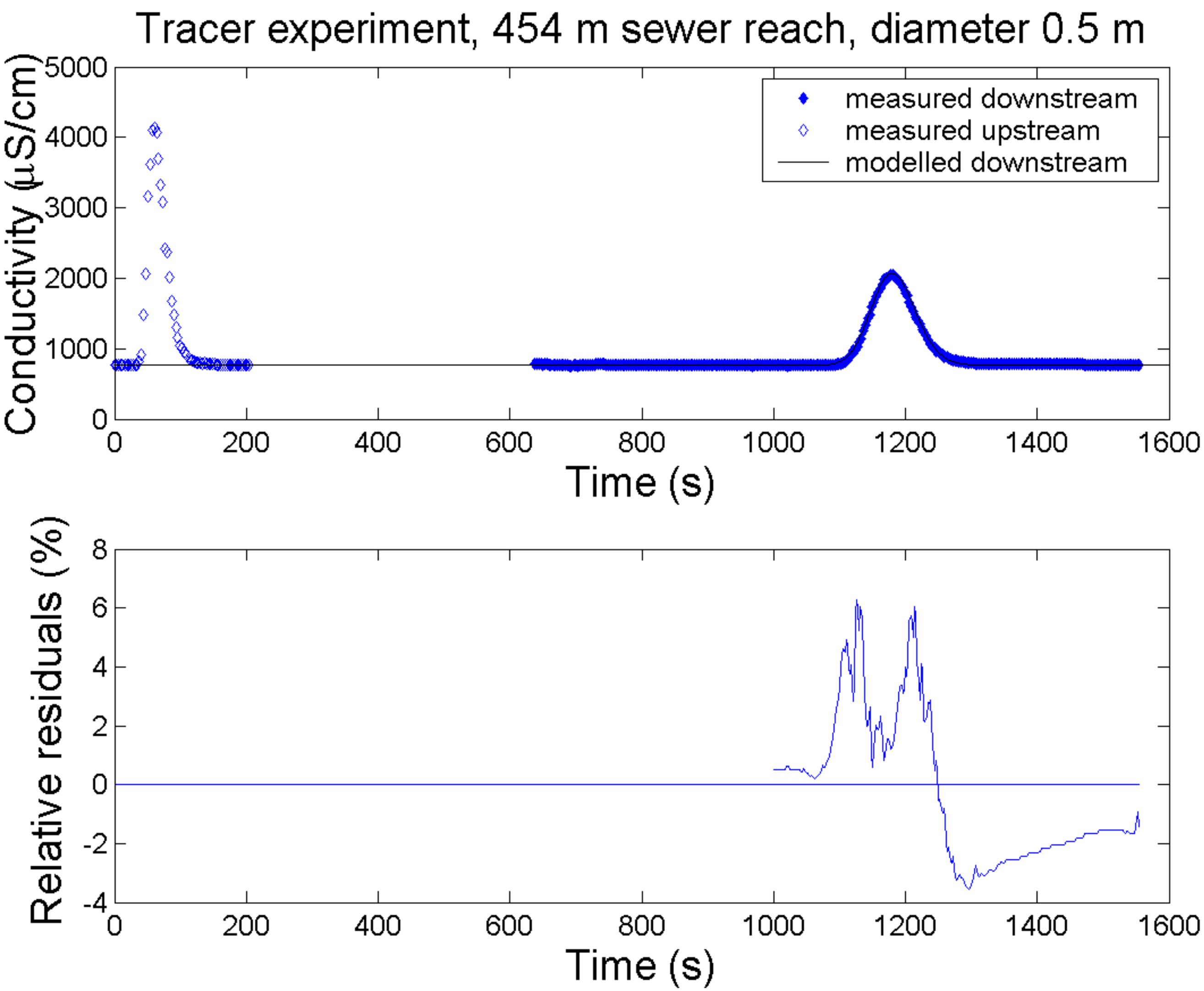
Loenen, 454 m reach, 0.5 m



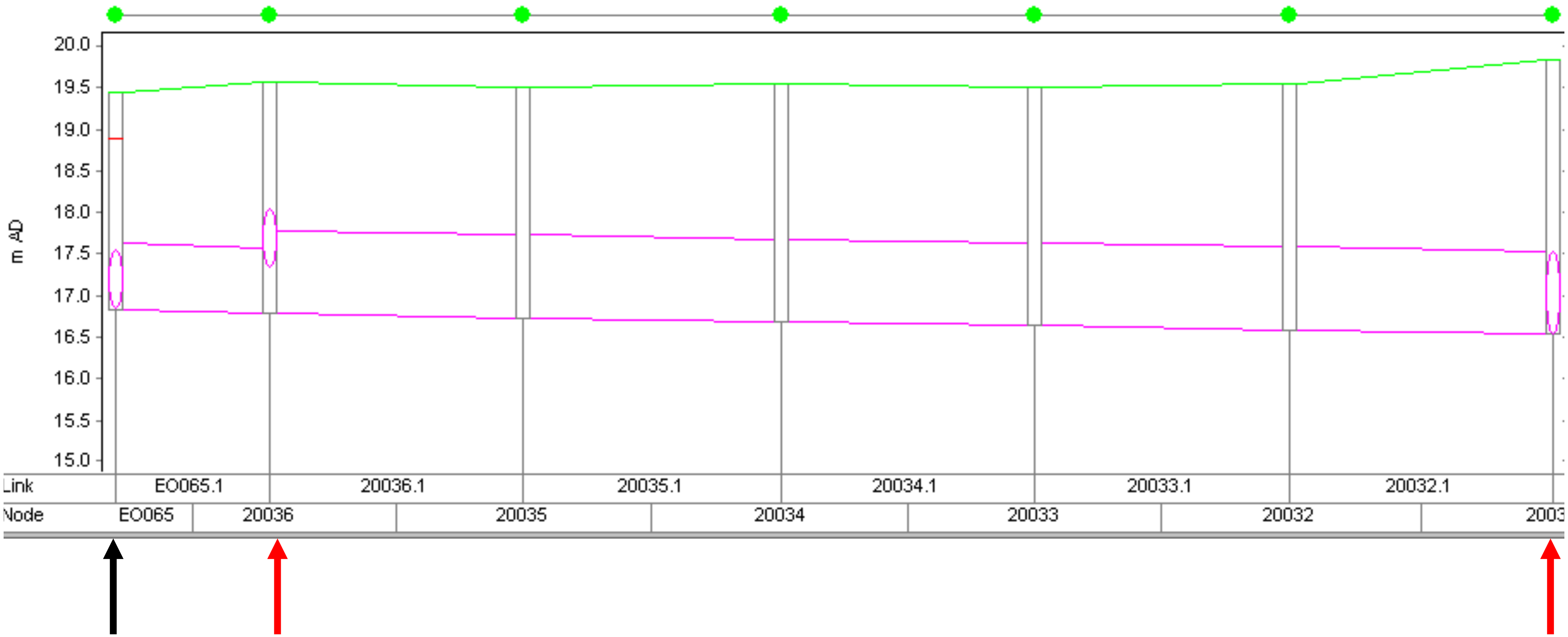
Dosing tracer

Measuring conductivity

Results matlab model



Loenen, 233 m reach, 1 m

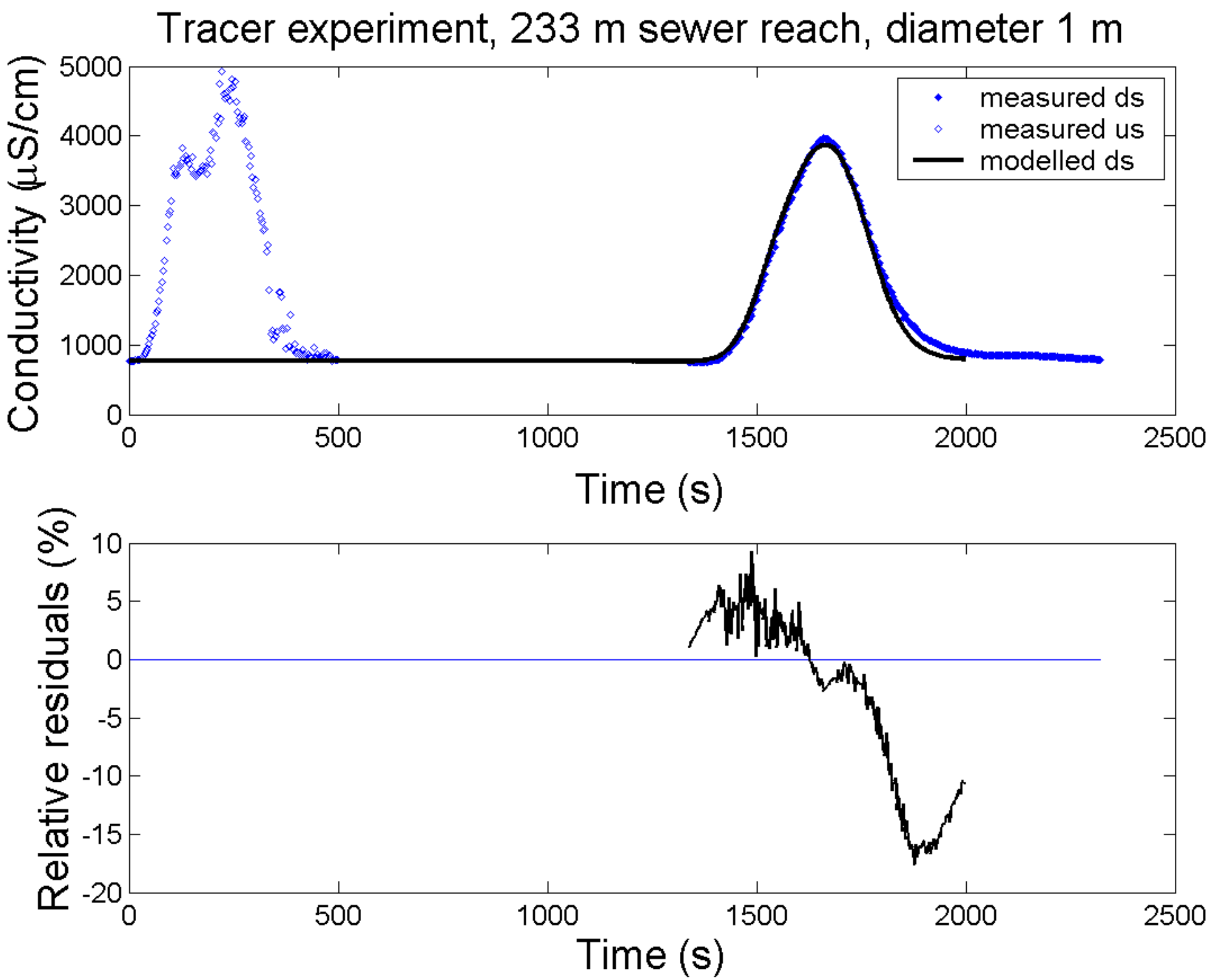


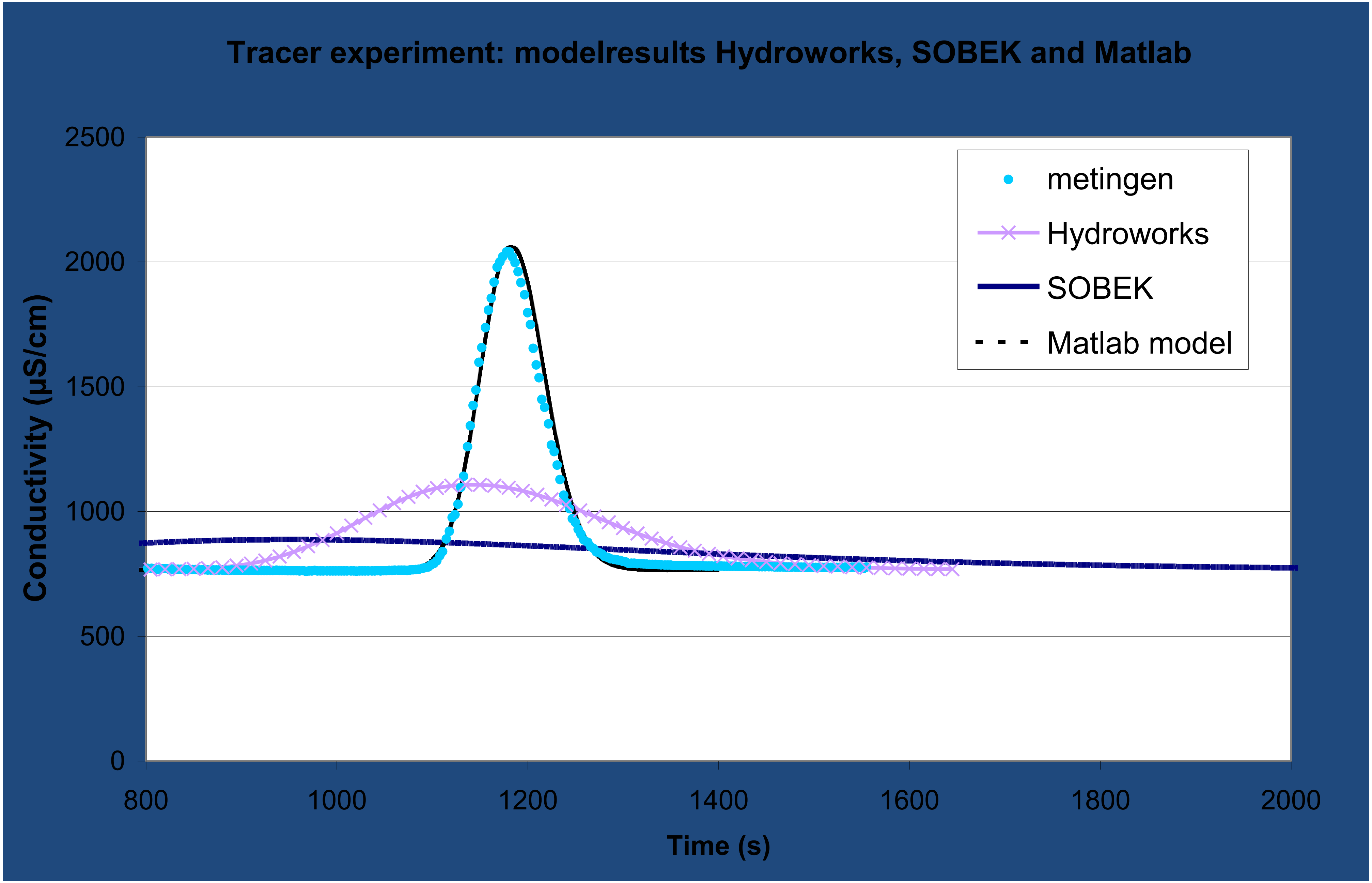
Dosing tracer

Measuring conductivity

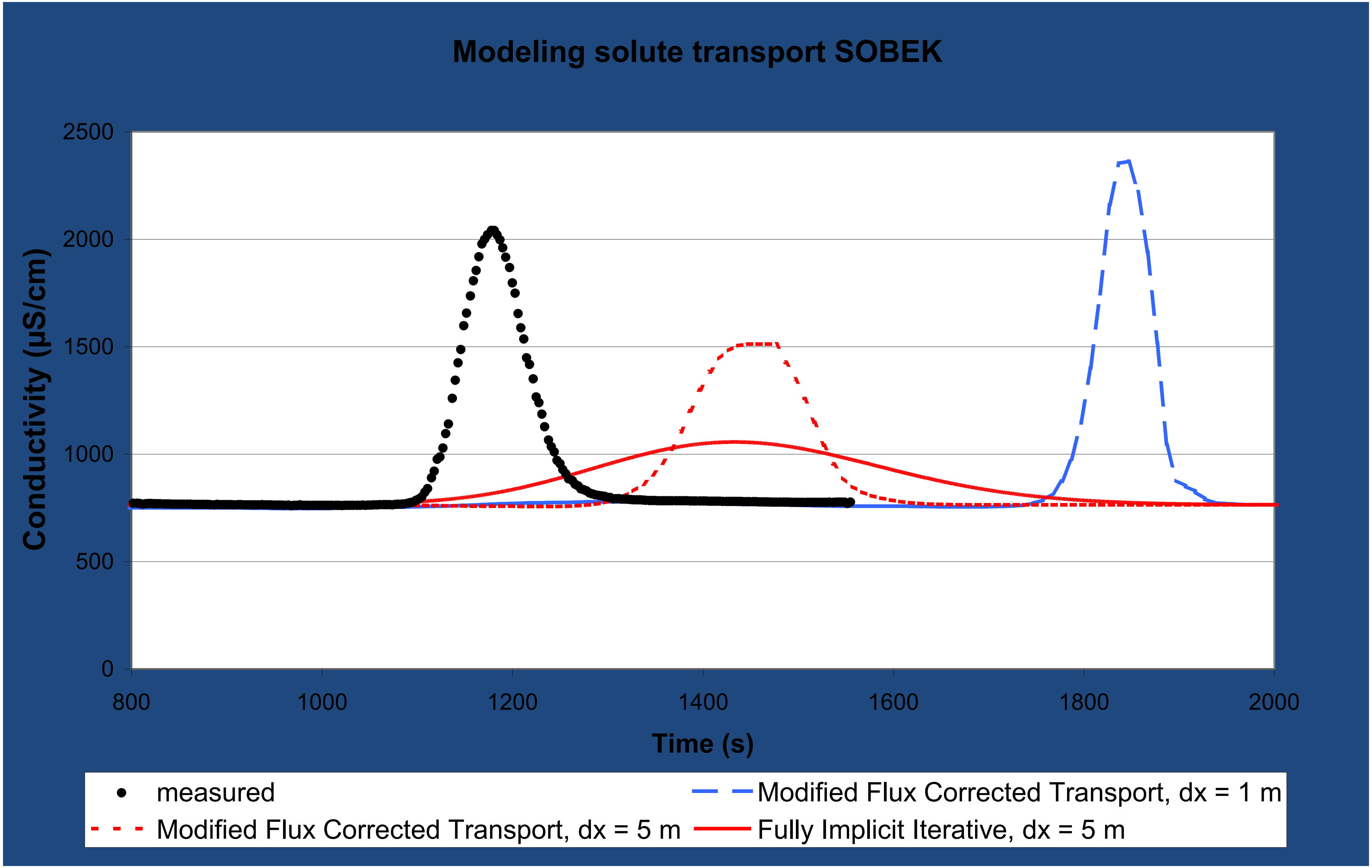
Results matlab model

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} - K\frac{\partial^2 c}{\partial x^2} = 0$$

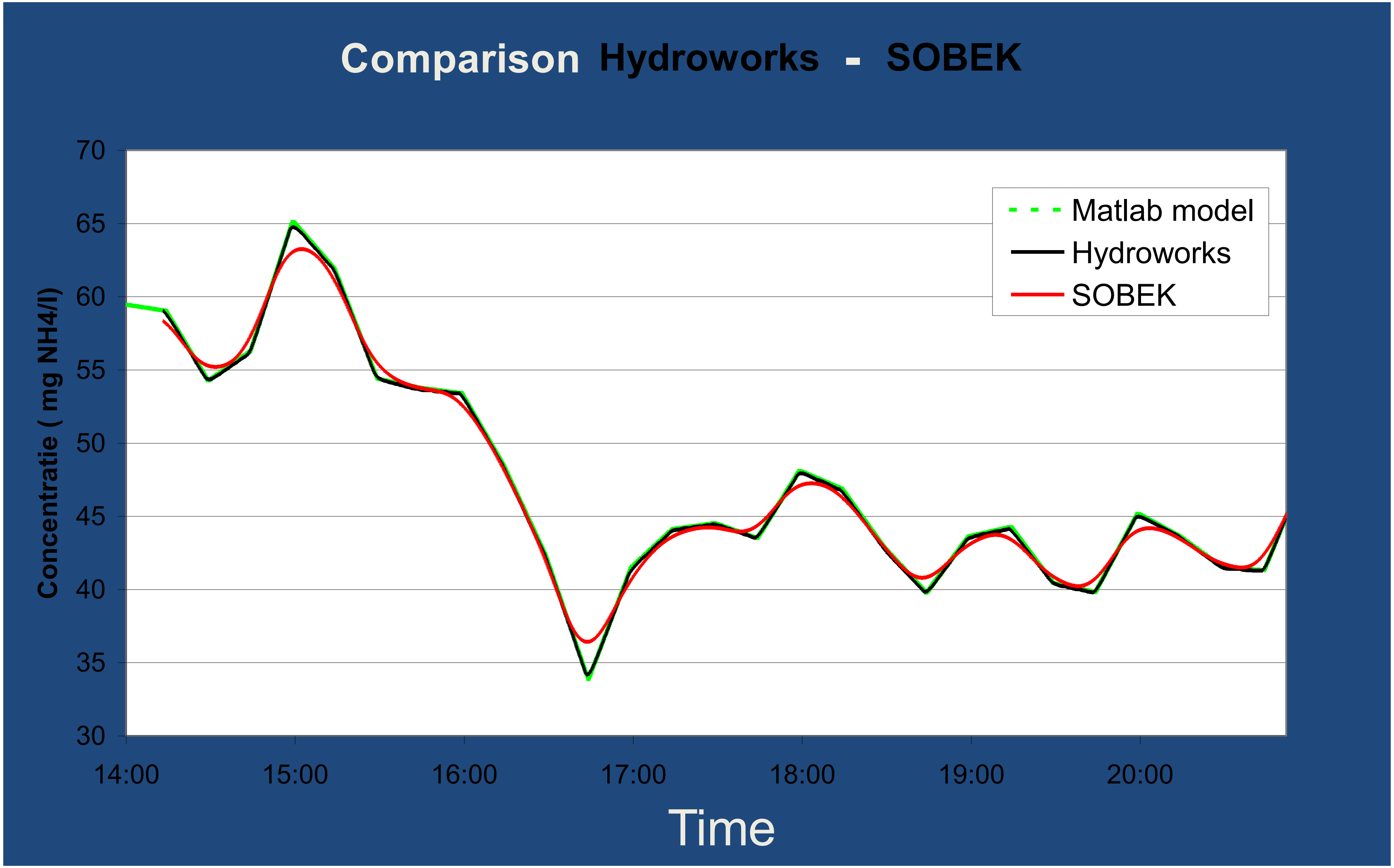




Tracer experiment: modelresults Hydroworks, SOBEK and Matlab
Conductivity (µS/cm)
Time (s)
0
500
1000
1500
2000
2500
800
1000
1200
1400
1600
1800
2000
metingen
Hydroworks
SOBEK
Matlab model



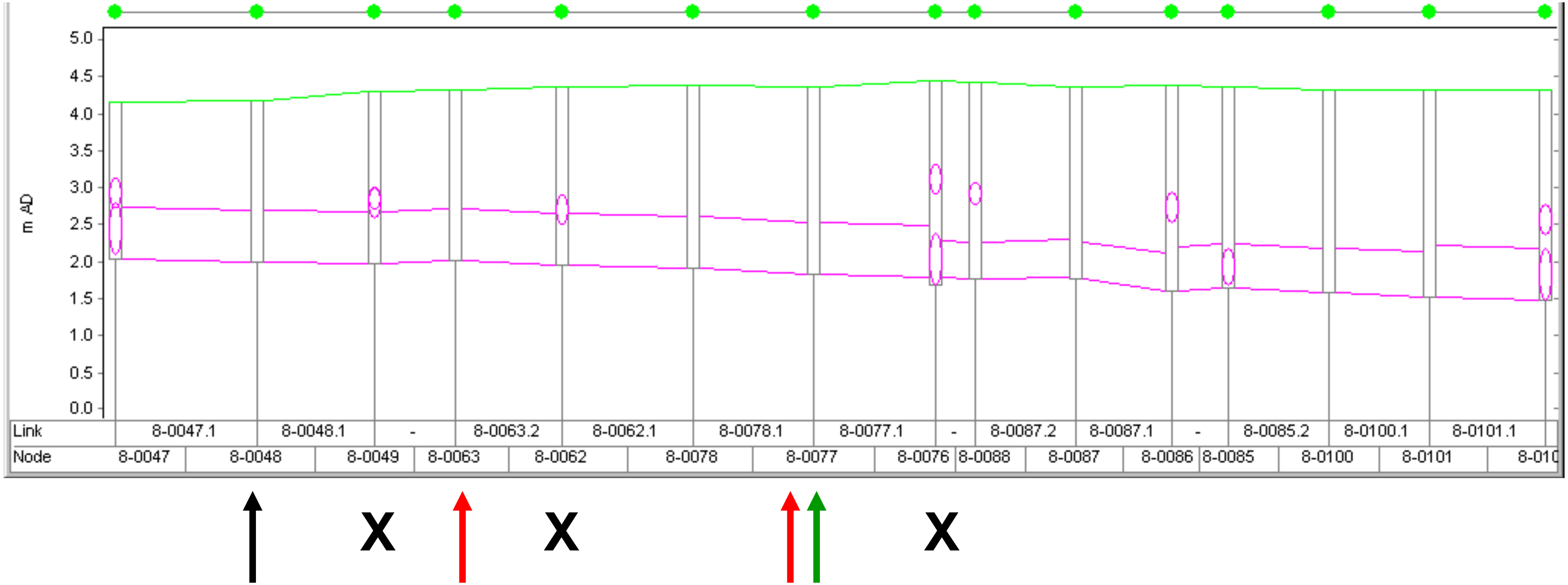
Modeling solute transport SOBEK
Conductivity (µS/cm)
0
500
1000
1500
2000
2500
800
1000
1200
1400
1600
1800
2000
Time (s)
measured
Modified Flux Corrected Transport, dx = 1 m
Modified Flux Corrected Transport, dx = 5 m
Fully Implicit Iterative, dx = 5 m



Comparison Hydroworks - SOBEK
Matlab model
Hydroworks
SOBEK
Concentratie (mg NH4/l)
70
65
60
55
50
45
40
35
30
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Time

NTNU

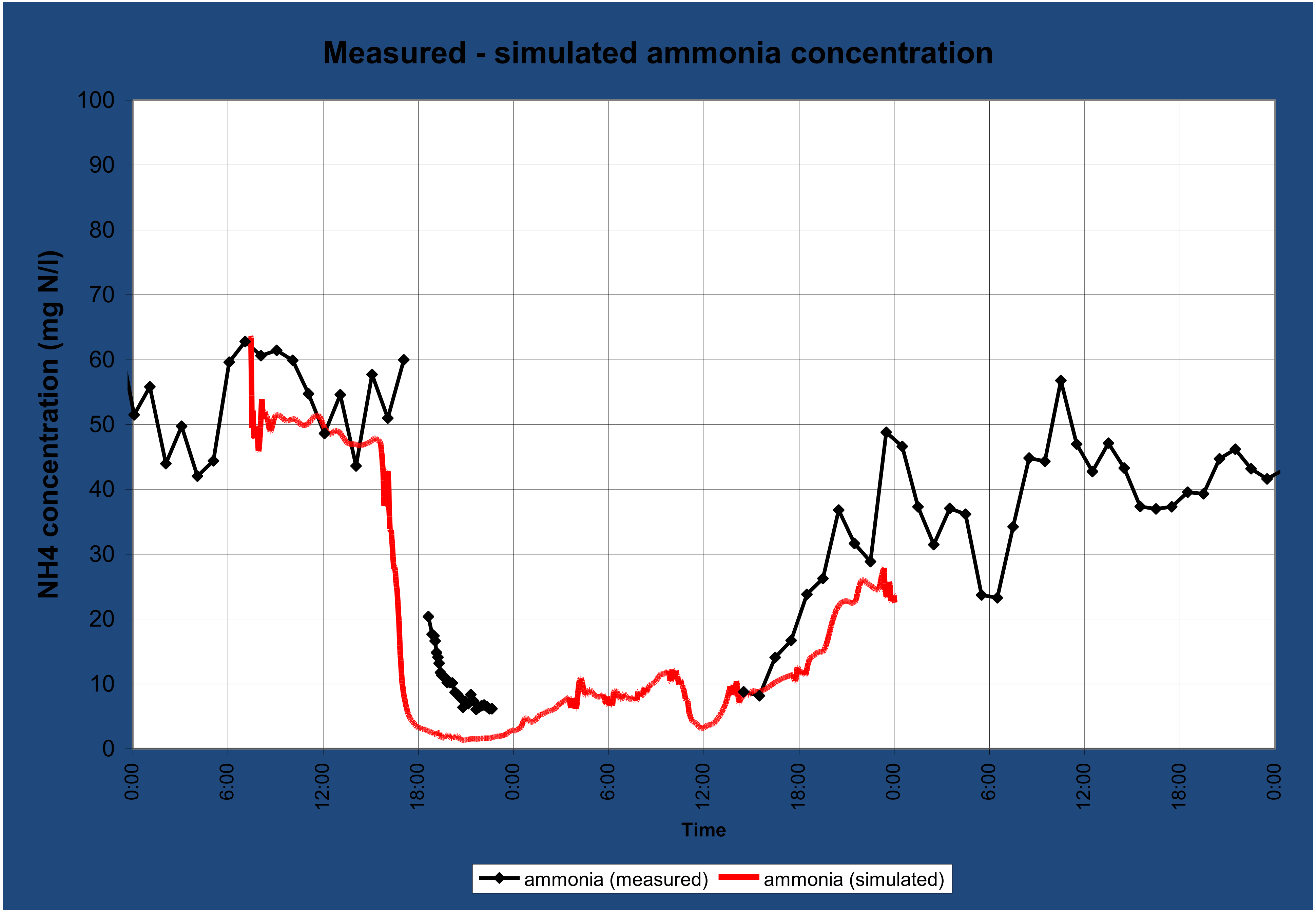
Ulvenhout (wwf), 142 m, 0.7 m



Dosing tracer

Conductivity

Sampling NH_4


Measured - simulated ammonia concentration
NH4 concentration (mg N/l)
100
90
80
70
60
50
40
30
20
10
0
0:00
6:00
12:00
18:00
0:00
6:00
12:00
18:00
0:00
6:00
12:00
18:00
0:00
Time
ammonia (measured)
ammonia (simulated)

Conclusion

– Advection-dispersion in sewers can be described with the well-known equation

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} - K \frac{\partial^2 c}{\partial x^2} = 0$$

– Today's models show significant numerical dispersion, however, modeling of influent concentrations in terms of NH_4 seems to be possible