



## Kan vi få et bedre miljø med smartere kloakker?

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Lektor Luca Vezzaro

København Ø, d. 29. april 2019

# Kan vi få et bedre miljø med smartere kloakker?

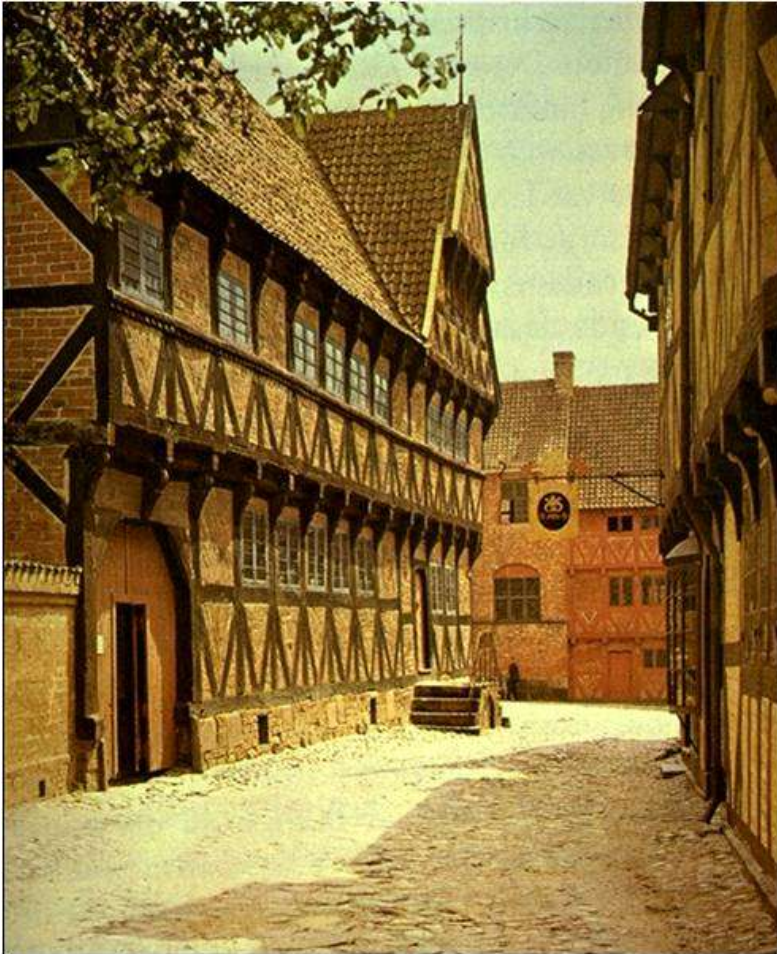
## Lidt om mig

- Født i Padova, tæt på Venedig
- Uddannet som miljøingeniør
- Kom til Danmark som udvekslingsstudent i 2005
- PhD om modellering af miljøfremmede stoffer i regnvand (2011)
- Arbejder på DTU Miljø med styring og modellering af afløbssystemer
- Deltid ansat hos Krüger Veolia A/S (jeg tager forskning ud i "den virkelige verden")

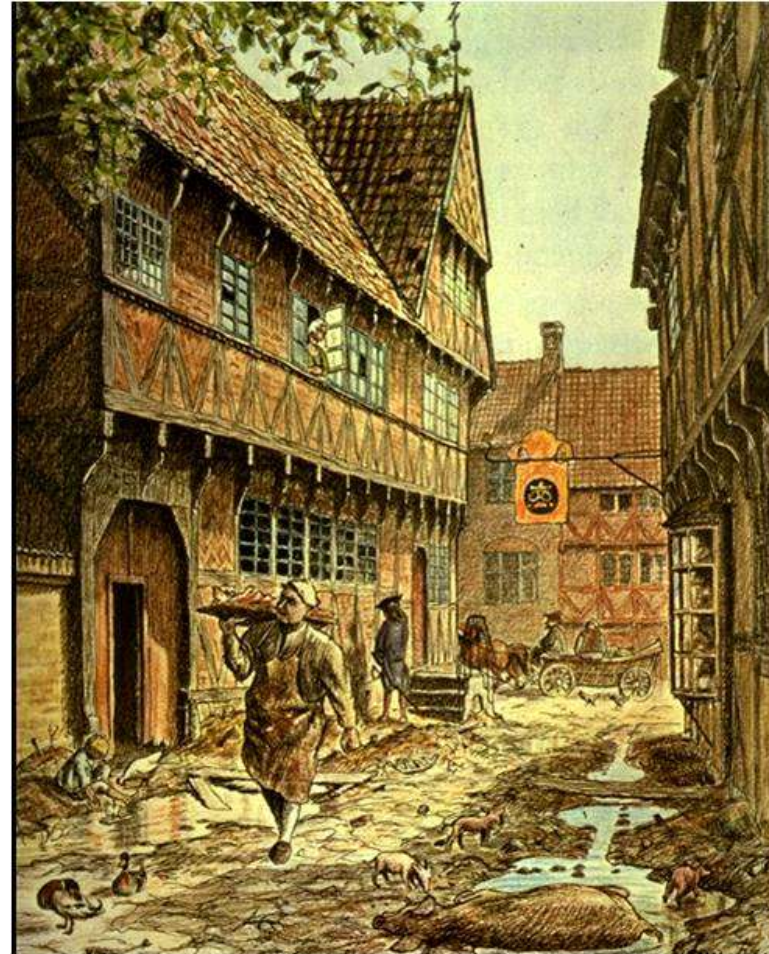


# Why do we have sewers?

# Aarhus "gamle by" – a living museum



Today



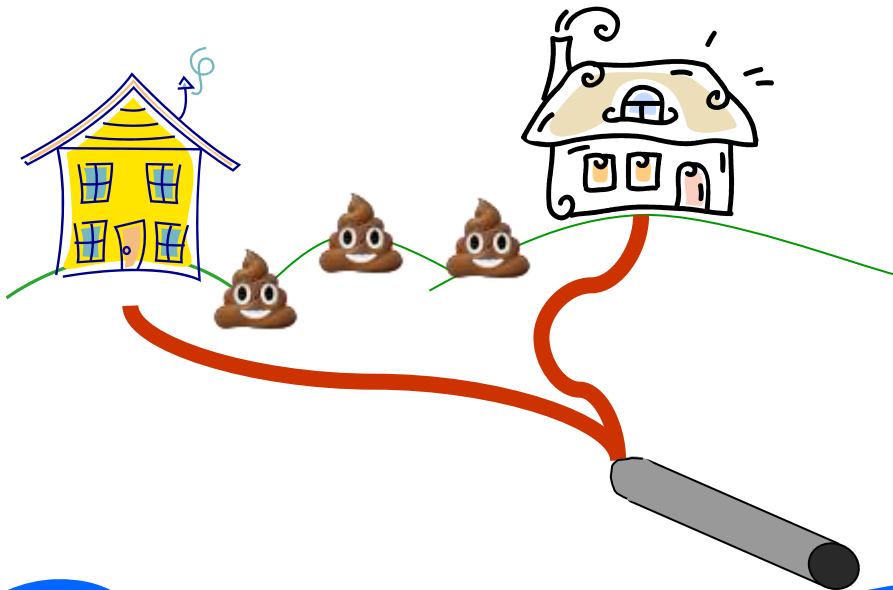
Around  
1850



# Why do we have sewers?



Before 1800  
(Western Cities)



**BMJ readers choose sanitation as greatest medical advance since 1840**

**Annabel Ferriman** *BMJ*

More than 11 300 readers of the *BMJ* chose the introduction of clean water and sewage disposal—"the sanitary revolution"—as the most important medical milestone since 1840, when the *BMJ* was first published. Readers were given 10 days to vote on a shortlist of 15 milestones, and sanitation topped the poll, followed closely by the discovery of antibiotics and the development of anaesthesia. The work of the 19th century lawyer Edwin Chadwick, who pioneered the introduction of piped water to people's homes and sewers rinsed by water, attracted 15.8% of the votes, while antibiotics took 15%, and anaesthesia took 14%. The next two most popular were the introduction of vaccines, with 12%, and the discovery of the structure of DNA (9%).

A total of 11 341 people voted on the shortlist, which was chosen by a panel of experts from a list nominated by readers. Almost a third of the voters were doctors, while a fifth were members of the general public, and one in seven were students. Another tenth were academic researchers. Almost two fifths of the voters were from the United Kingdom, and a fifth were from the United States.

Johan Mackenbach, professor of public health at Erasmus MC Medical Center, Rotterdam, who championed the cause of sanitation, said, "I'm delighted by so many people as such an important milestone. The general lesson which still holds is that passive protection against health hazards is often the best way to improve population health.

"The original champions of the sanitary revolution were John Snow, who showed that cholera was spread by water, and Edwin Chadwick, who came up with the idea of sewage disposal and piping water into homes.

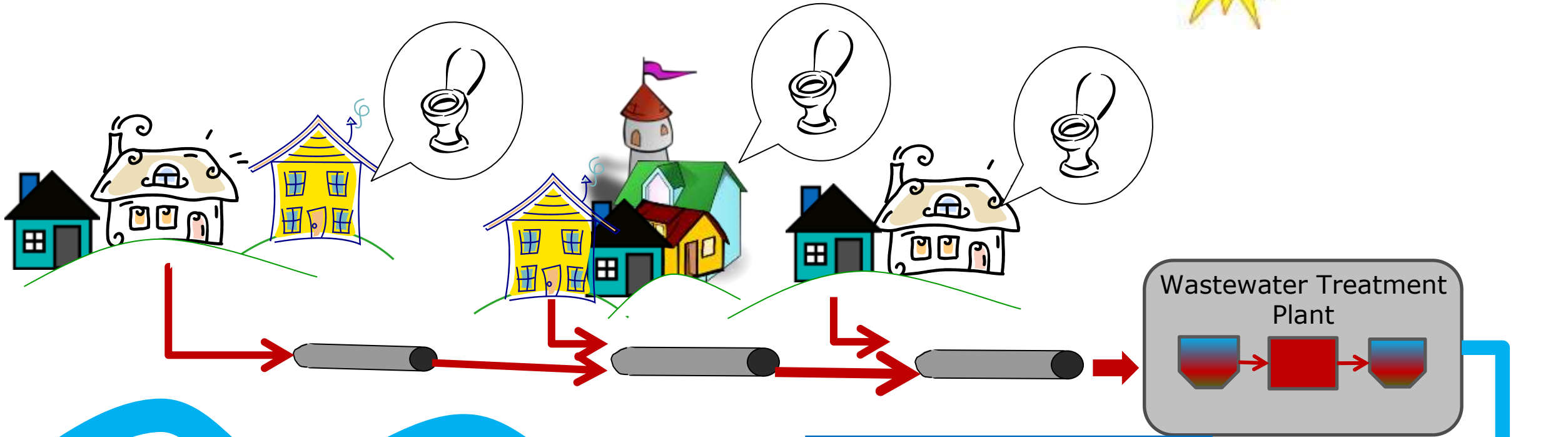
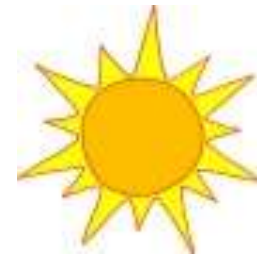
"Inadequate sanitation is still a major problem in the developing world."

The *Medical Milestones* supplement is distributed with this week's *BMJ*.

*BMJ* | 20 JANUARY 2007 | VOLUME 334

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# Our cities when sun is shining...



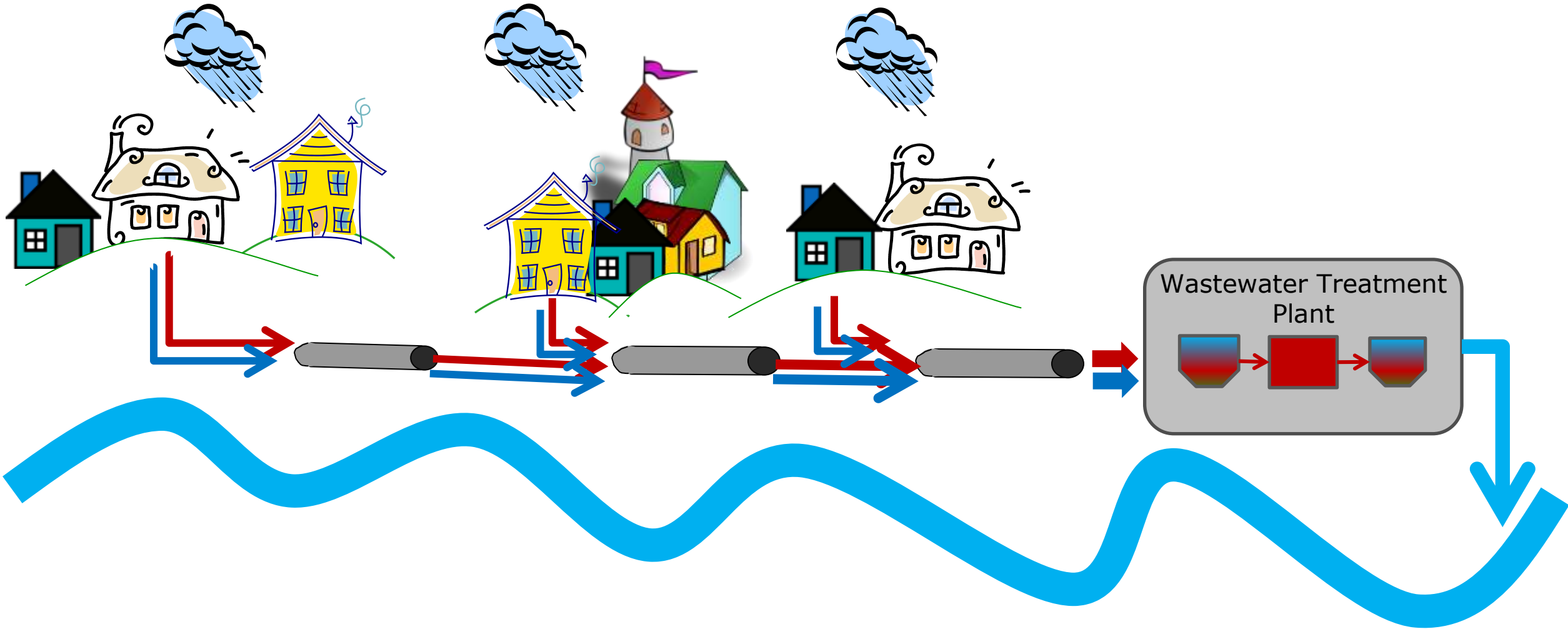
From [www.aldrigsur.dk/ved-stranden](http://www.aldrigsur.dk/ved-stranden)



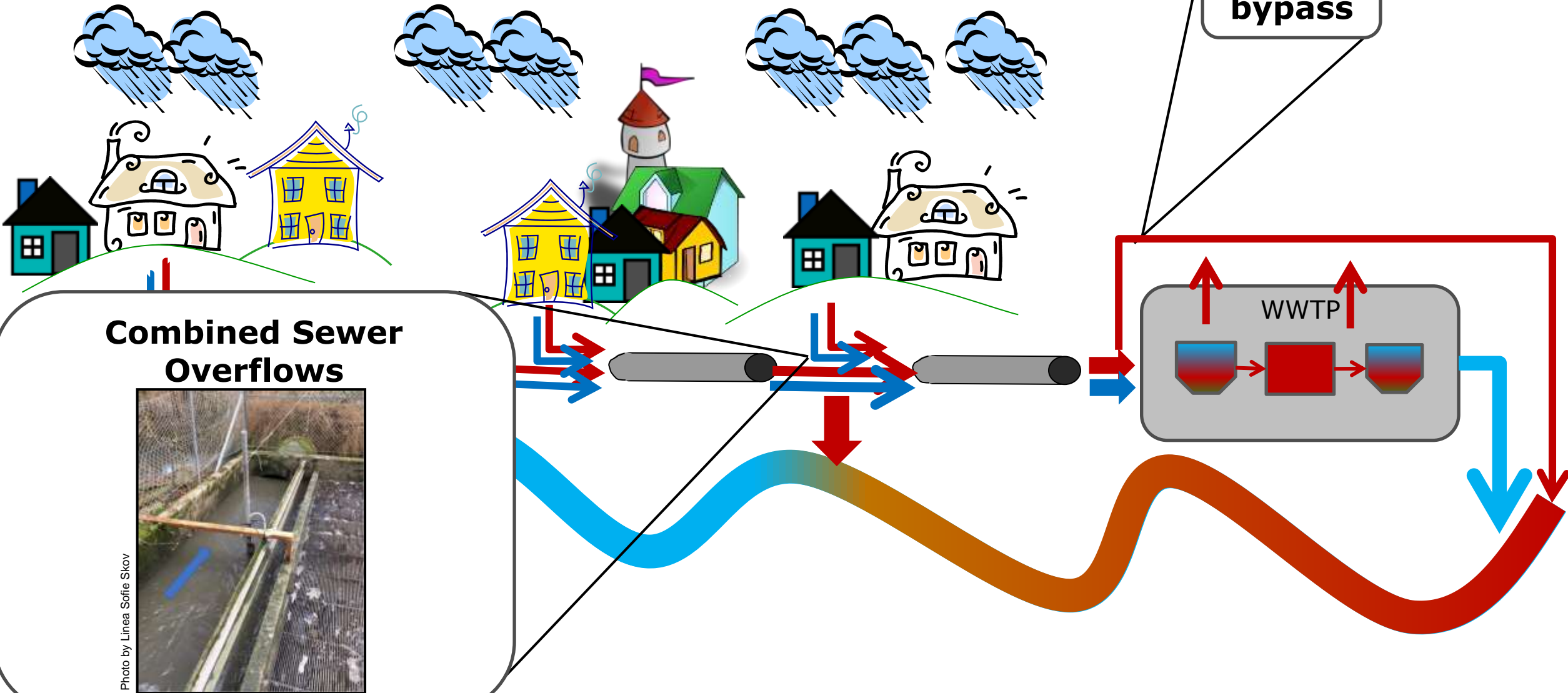
From <http://natmus.dk/museerne/brede-vaerk/>



# ...but sometimes it rains...



...and it rains more...



**Combined Sewer Overflows**



Photo by Linea Sofie Skov

# ...and it rains more...

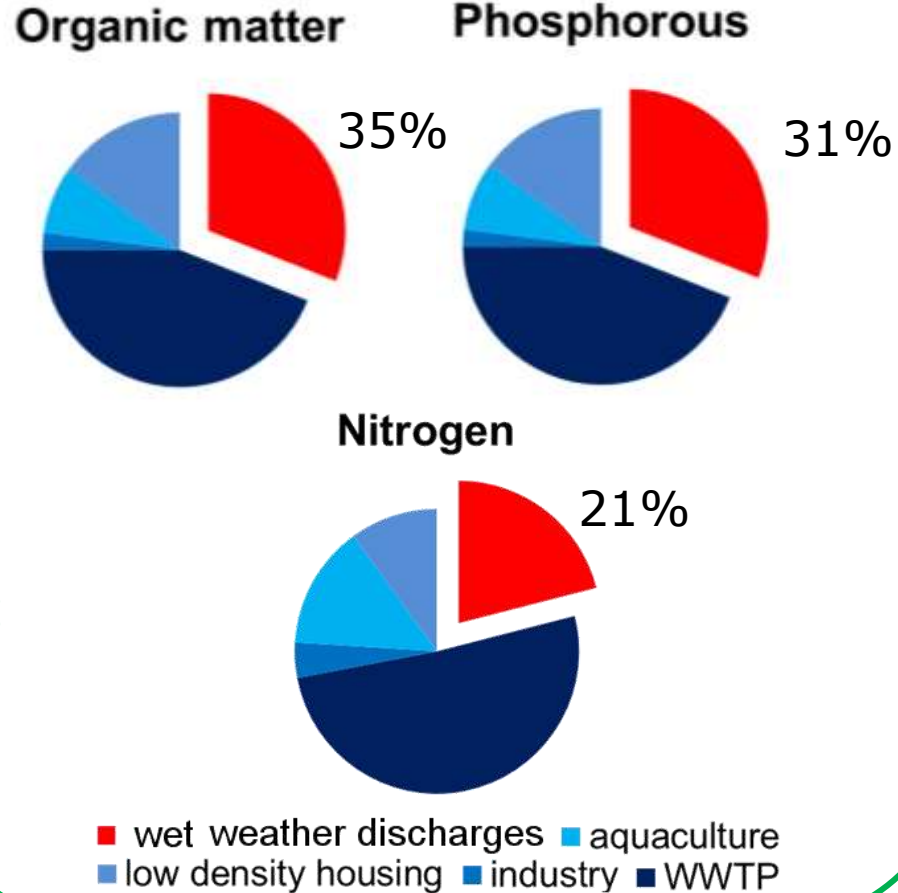


## Combined Sewer Overflows



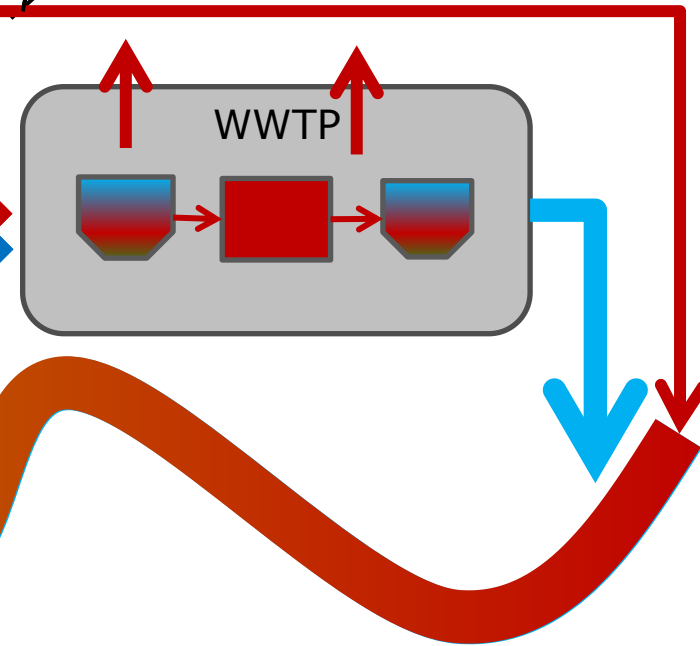
Photo by Linea Sofie Skov

### Pollutant contribution from point discharges in DK (2015)



Source: Miljø- og Fødevarerministeriet Styrelsen for Vand- og Naturforvaltning (2017). Punktkilder 2015

WWTP bypass



# ...and it rains more...



## Combined Sewer Overflows

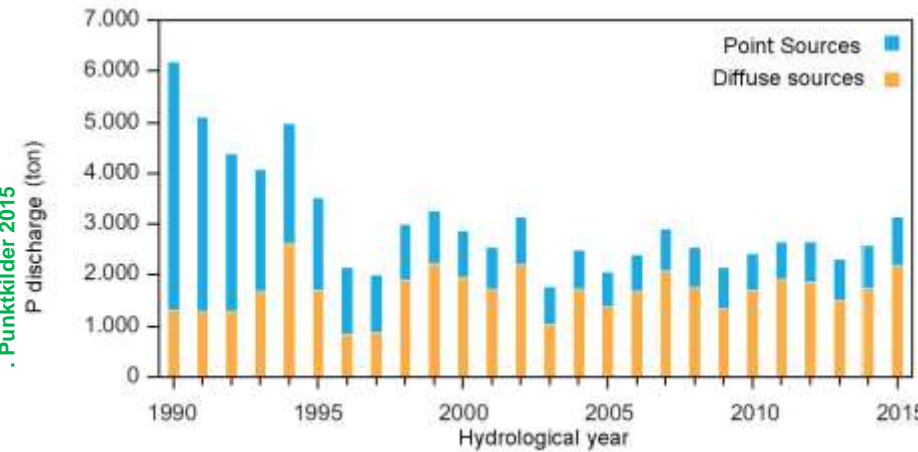
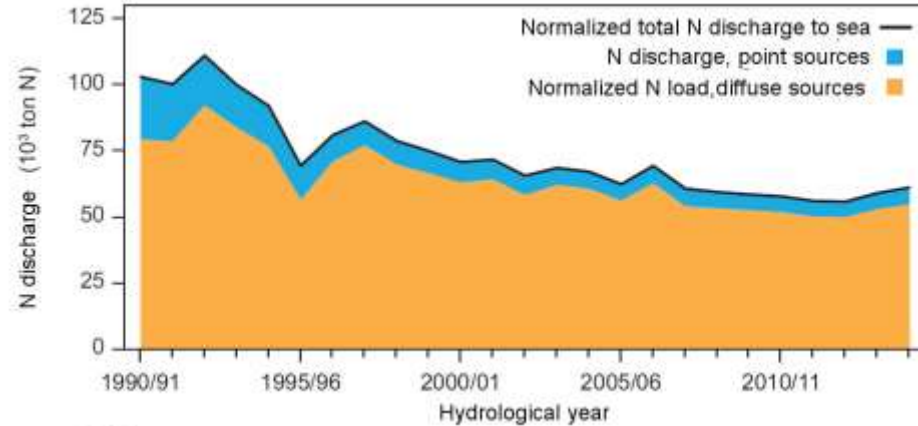


Photo by Linea Sofie Skov

Source: Miljø- og Fødevareministeriet Styrelsen for Vand- og Naturforvaltning (2017)

. Punktkilder 2015

## Pollutant contribution from point discharges in DK



WWTP bypass

Altinget

## Bæredygtigt Landbrug: Hvorfor må kommunen forurene uden konsekvenser?



DEBAT: I en aktuel sag på Fyn har det lokale spildevandsselskab beregnet, at der er løbet 12.000 m<sup>3</sup> urensset spildevand ud i åen. Hvorfor er kommunen ikke underlagt de samme regler som landmænd, spørger næstformand i Bæredygtigt Landbrug.

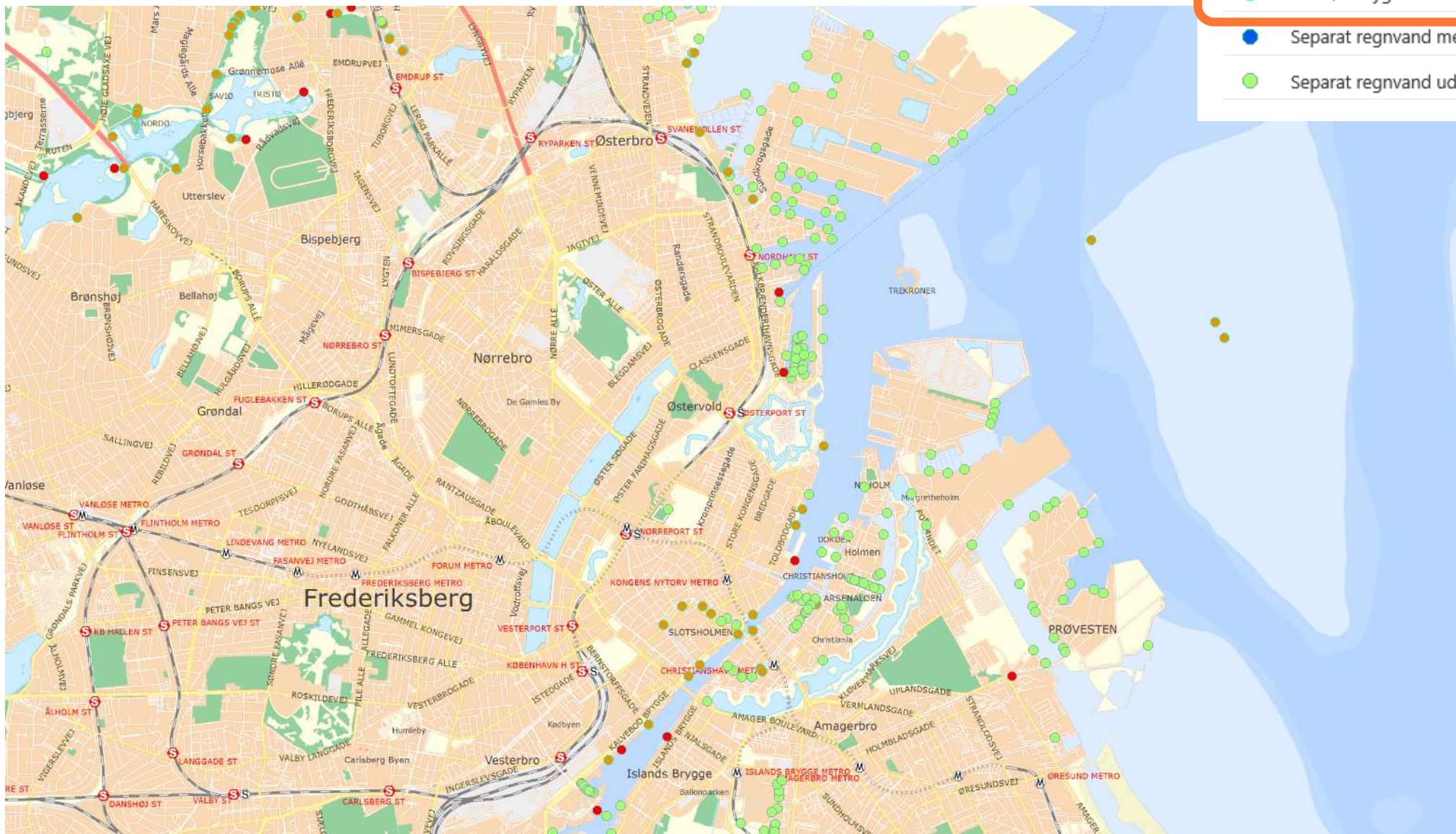
“En landmand har alarm på sin gylletank, han har ved overløb fra tank eller vogn pligt til at melde det til miljøvagten med det samme. Det er der fornuft i, så en forurening begrænses mest muligt.



# Kløakoverløb er overalt over 5,000 i hele Danmark

— Regnbetinget udledning, udledningspunkt

- Overløbsbygværk med bassin
- Overløbsbygværk uden bassin
- Separat regnvand med bassin
- Separat regnvand uden bassin





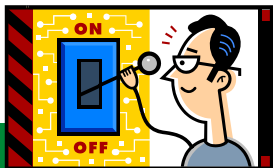
# Intermittent discharges – which problems they can cause?

Effect	Description	Type of effect
Physical changes	Flooding in urban and rural areas Erosion Resuspension of sediments	Acute (short time scale)
Aesthetical pollution	Toilet paper, condoms, cotton buds, etc. hanging or settled on beaches	
Hygienic pollution	Diseases for humans Diseases for animals	
Physical-chemical changes in the river	Oxygen depletion High concentration of ammonia	
Eutrophication	Organic pollutants (BOD, COD) Nutrients (N, P)	Accumulative (long time scale)
Changes in ecological status	-	
Toxic and/or xenobiotics	Toxicity (acute and chronic) Persistence Bioaccumulation	Acute/Accumulative

# Once upon a time in Denmark



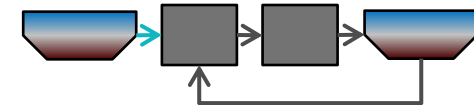
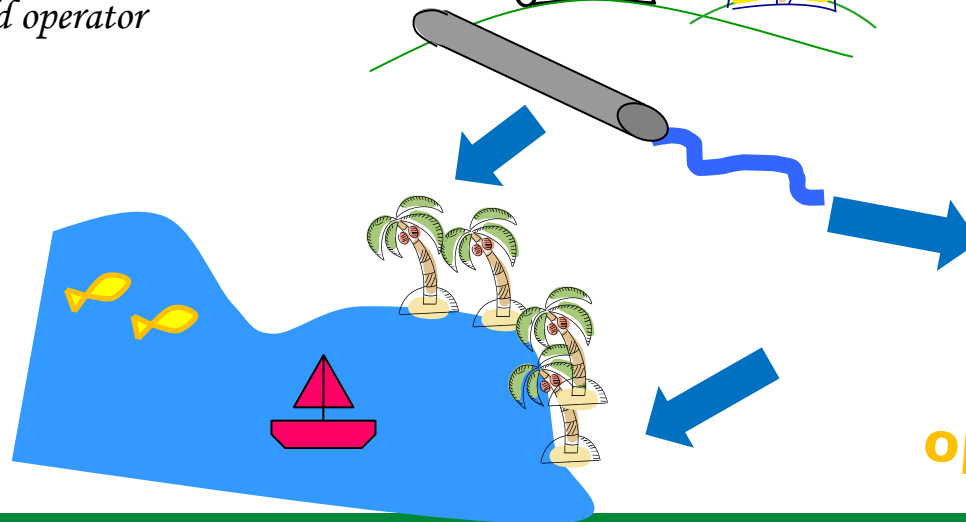
*The good old operator*



**WWTP  
overloading CSO**

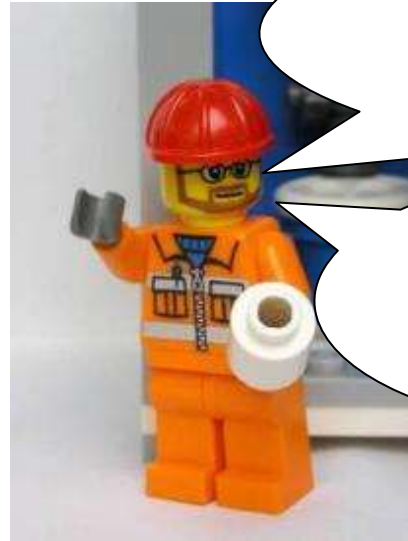
**Increased  
demand for  
recreational use**

**flooding**



**Energy  
optimization**

# Once upon a time in Denmark



*The good old operator*

I need to optimize the performance of my system  
(without building a lot of new expensive things)

Smart people from university, please help me!



# 2007-now ... a range of activities

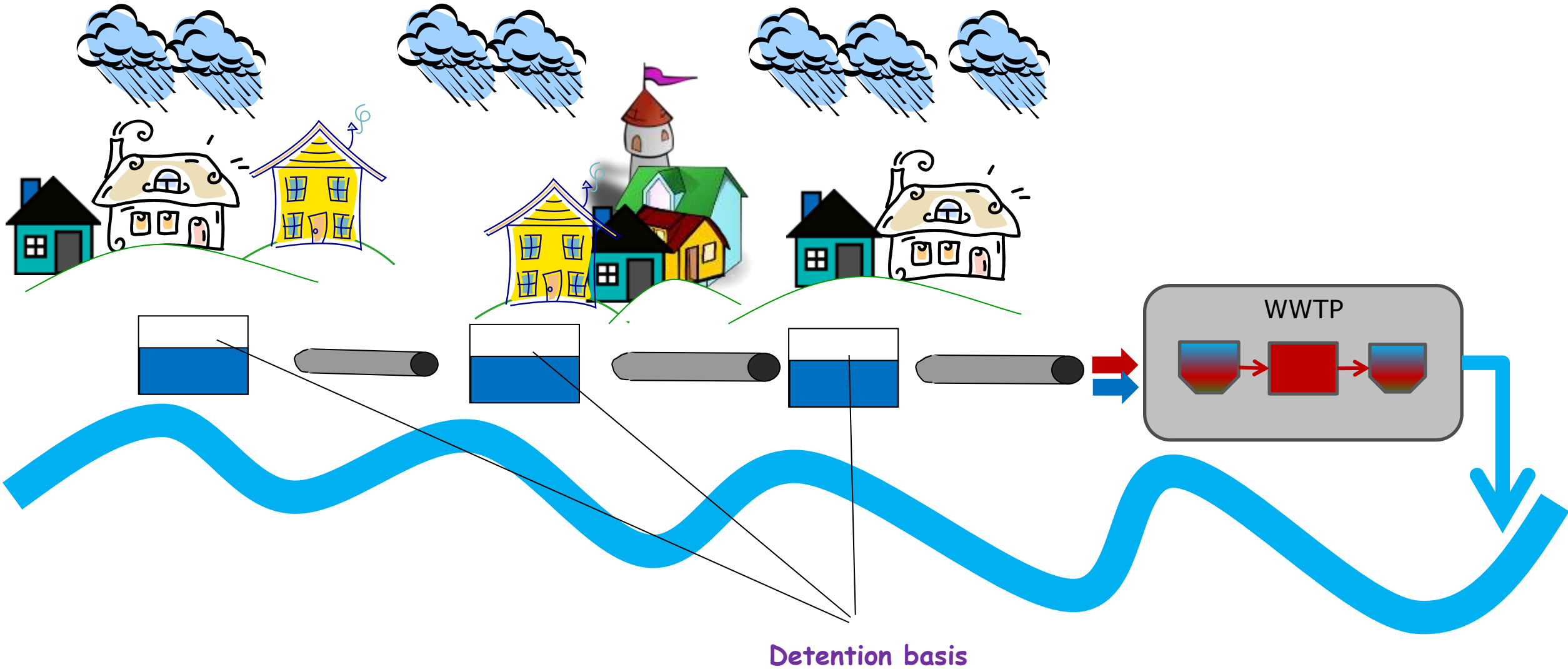


Universities + research institutions + water utilities + consultants

- Many projects
  - Storm- and Wastewater Informatics (SWI)
  - Klimaspring
  - Prepared
  - AMOK
  - Water Smart Cities
- Industrial PhDs
- Industrial postdocs
- Many MSc theses



# One option to avoid overflow...

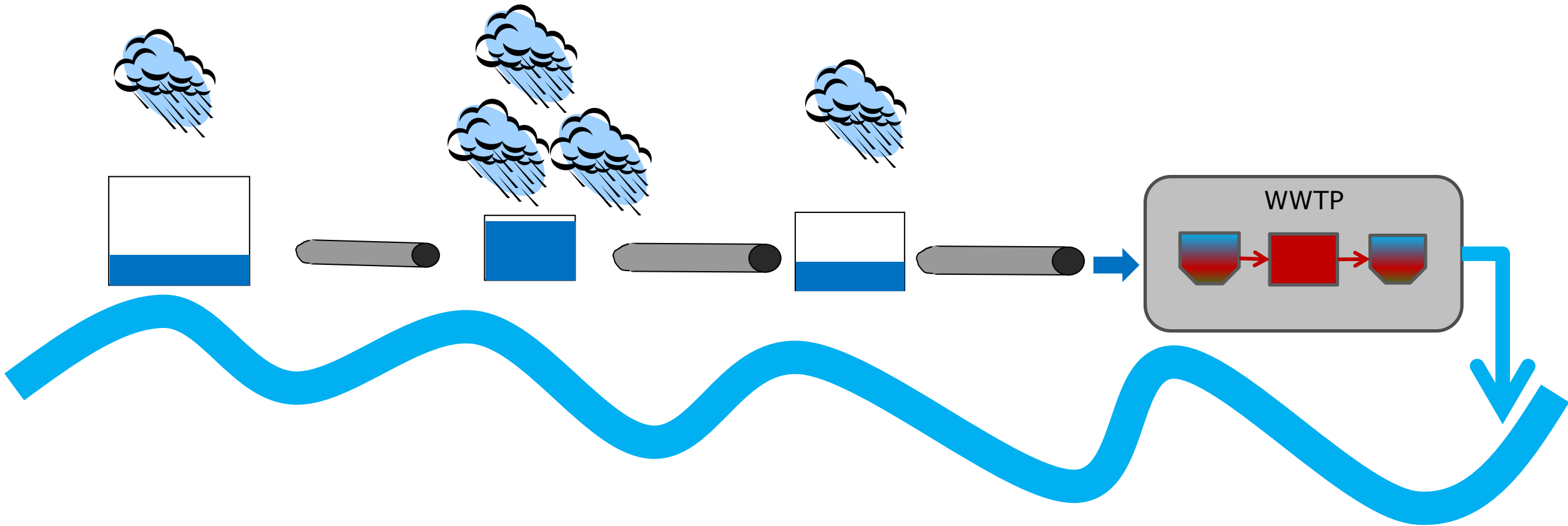






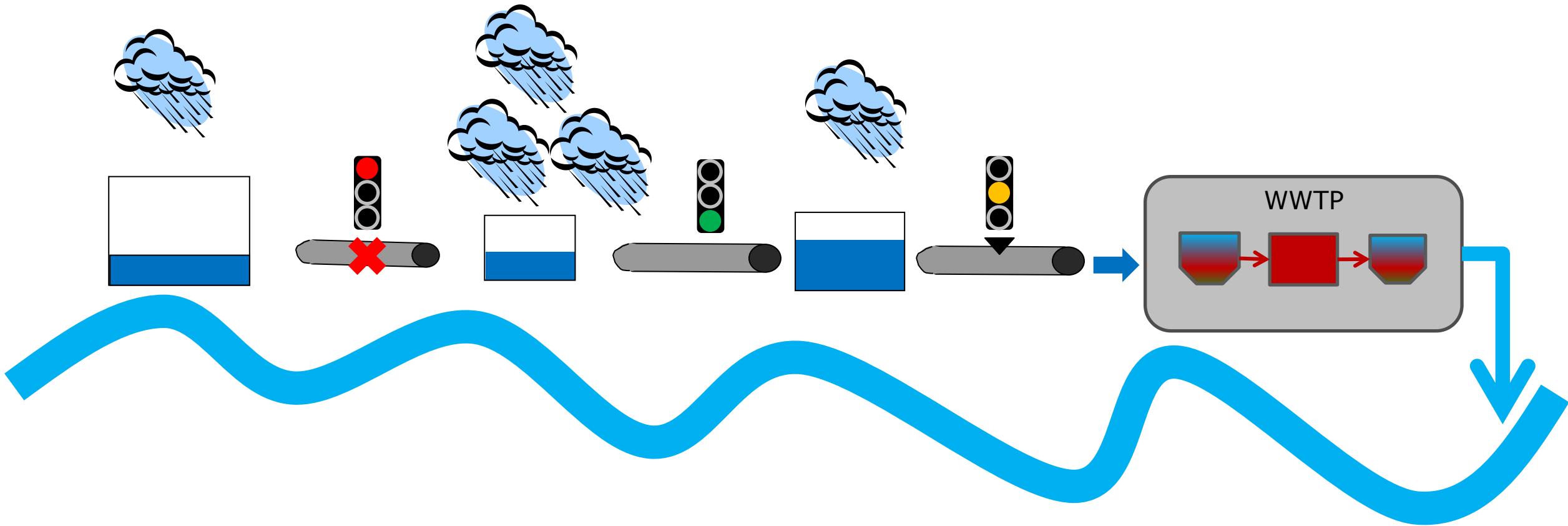
# Real Time Control of drainage network

- Rain is not uniform  $\longrightarrow$  we can optimize the storage across the system  $\longrightarrow$  less overflow
- WWTP doesn't like high flows  $\longrightarrow$  we can regulate the inlet flow to the WWTP  $\longrightarrow$  less bypass



# Real Time Control of drainage network

- Rain is not uniform  $\longrightarrow$  we can optimize the storage across the system  $\longrightarrow$  less overflow
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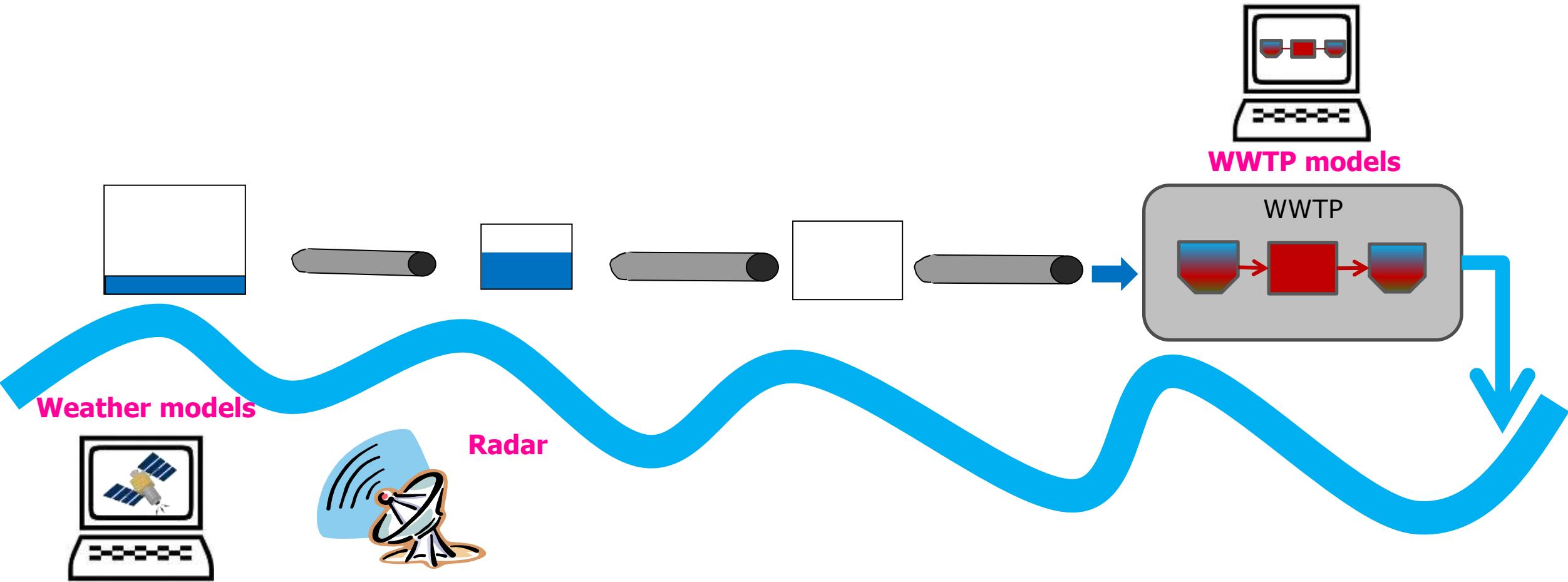




# Model Predictive Control



- We can forecast rainfall → where and how much is going to rain → even less CSO
- We can forecast WWTP status → how much water the WWTP can treat → even less bypass

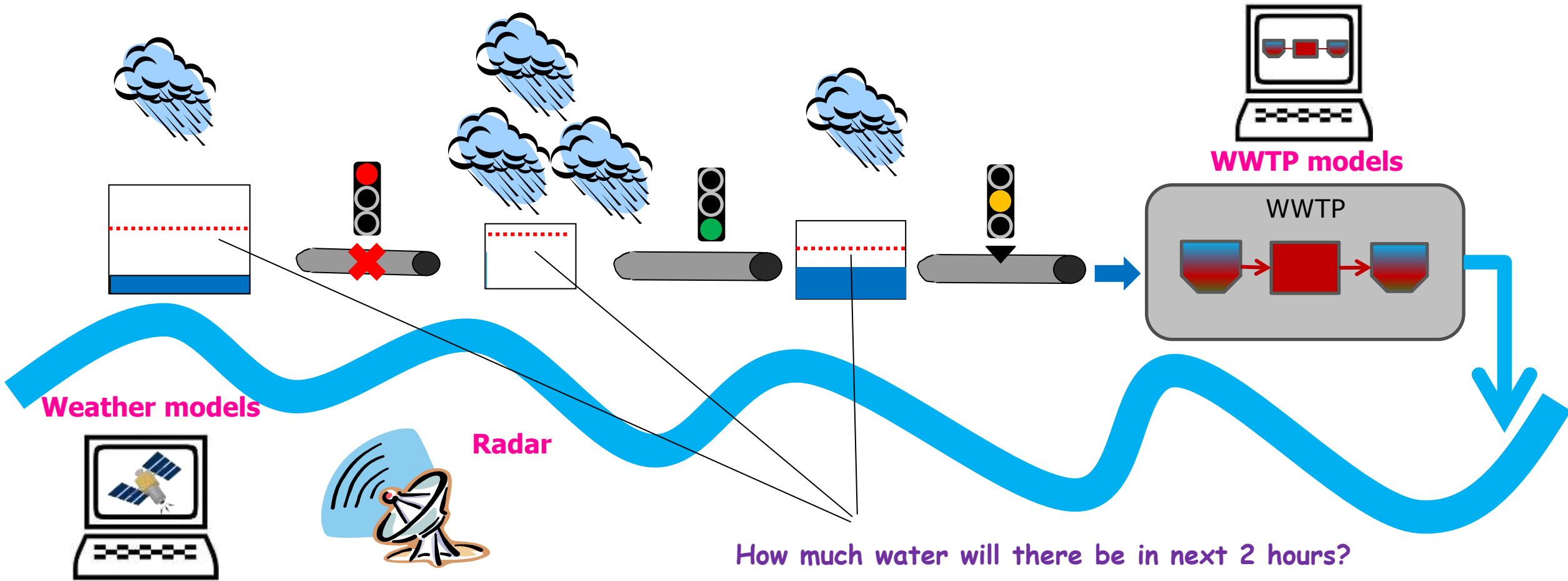




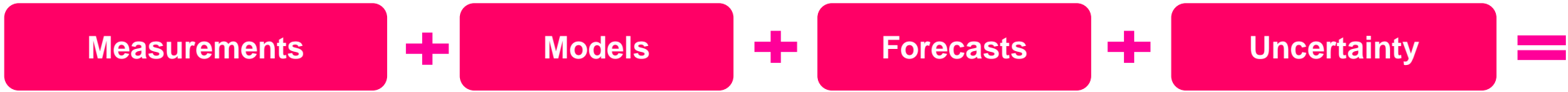
# Model Predictive Control



- We can forecast rainfall → where and how much is going to rain → even less CSO
- We can forecast WWTP status → how much water the WWTP can treat → even less bypass



# Our new concept

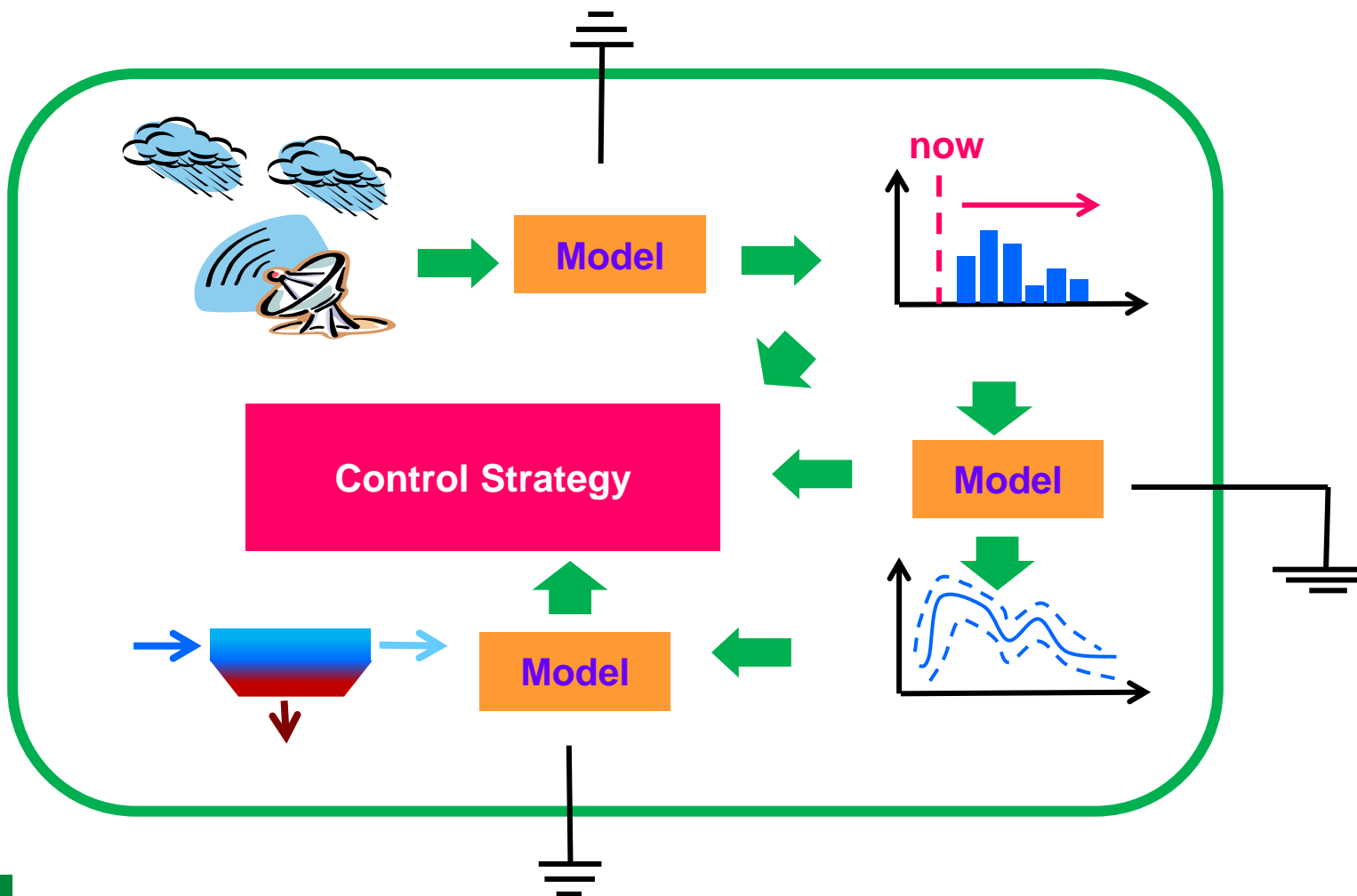


*The happy operator*



*The happy operator*

Measurements
+
Models
+
Forecasts
+
Uncertainty
=

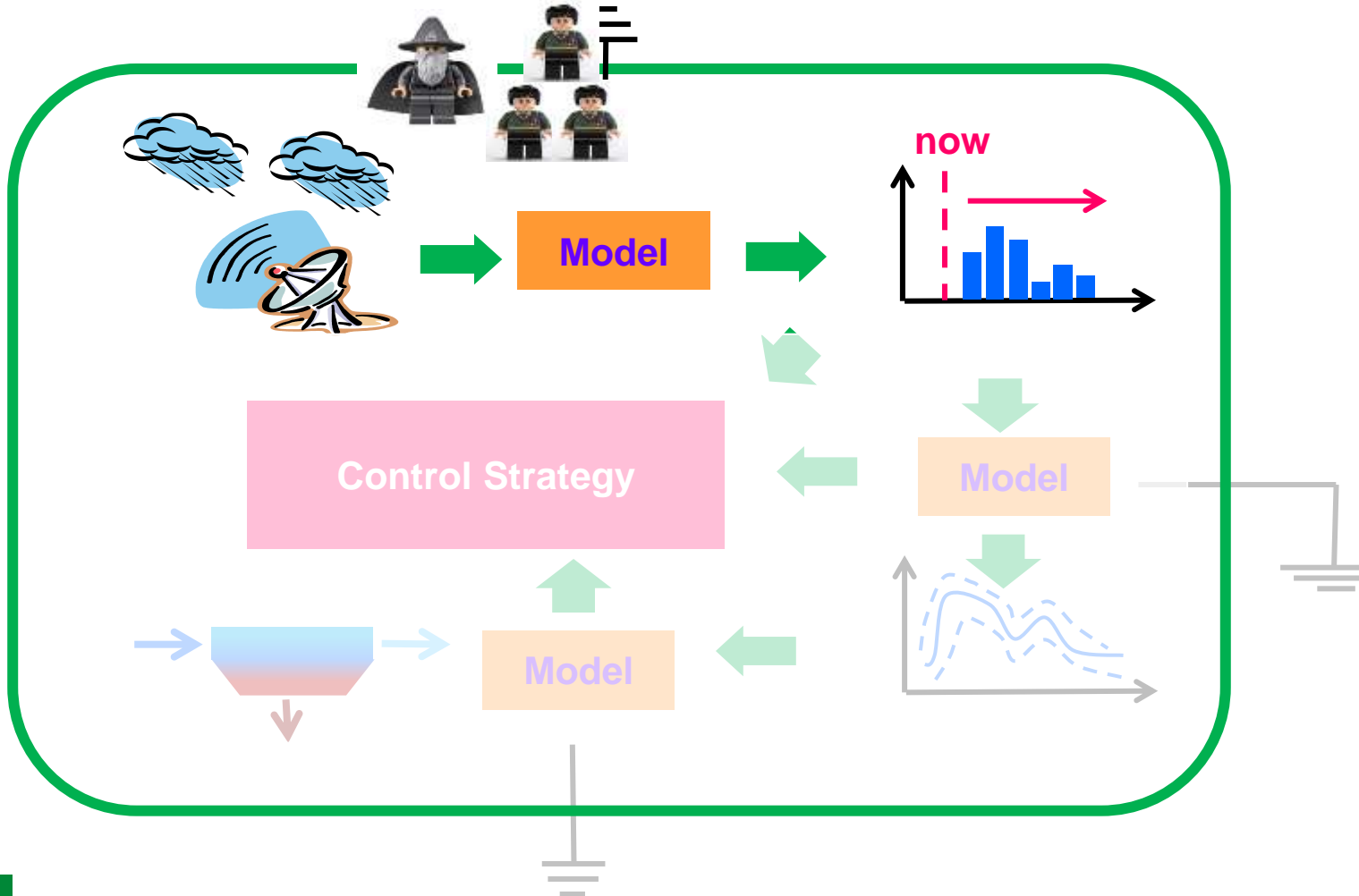


- Rainfall measurements  
*is it going to rain?*
- Short-term rainfall forecasts  
*how much is it going to rain?*
- Continuously updated hydrodynamic models  
*how much water am I getting?*
- Stochastic rainfall-runoff forecast  
*how much can I trust those forecasts?*
- WWTP forecast models  
*can the plant take so much water?*
- MPC strategy addressing uncertainty  
*what should I do?*

# The fellowship of SWI – the long journey



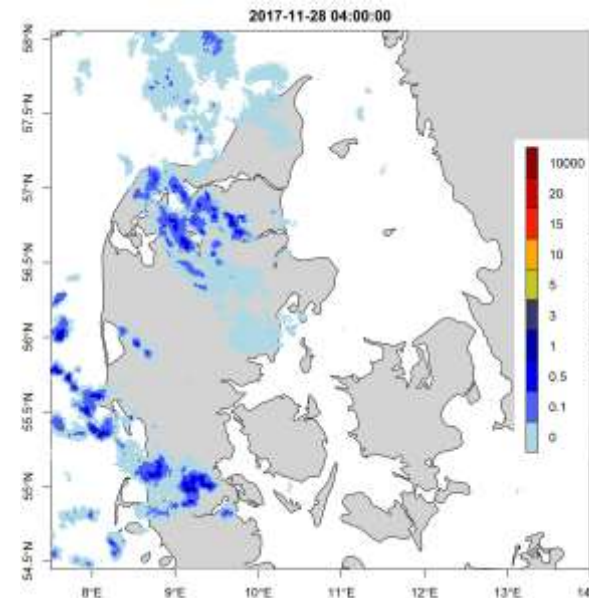
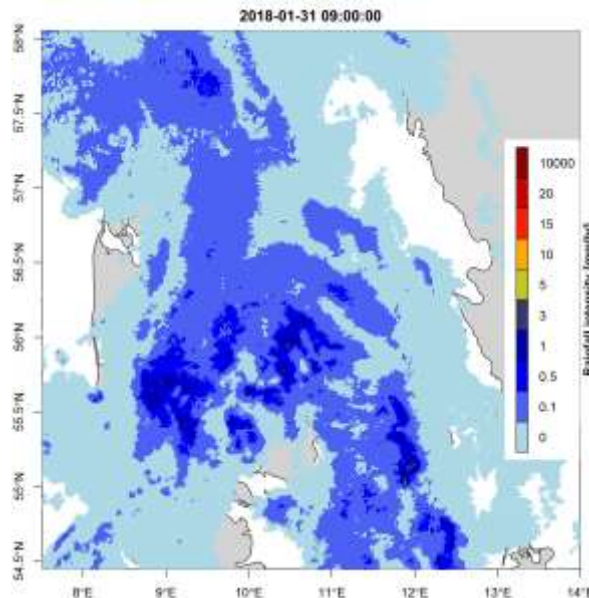
*The happy operator*



- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

# Rainfall input

Where is it raining?  
And how much?



- Rainfall is not easy to measure

Rain gauge

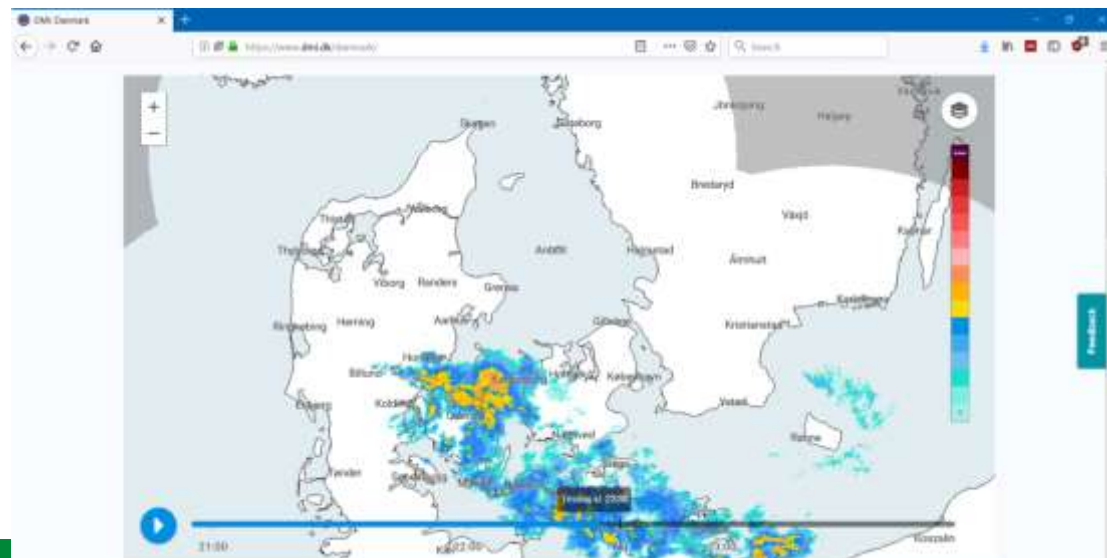


Lygten (5725)



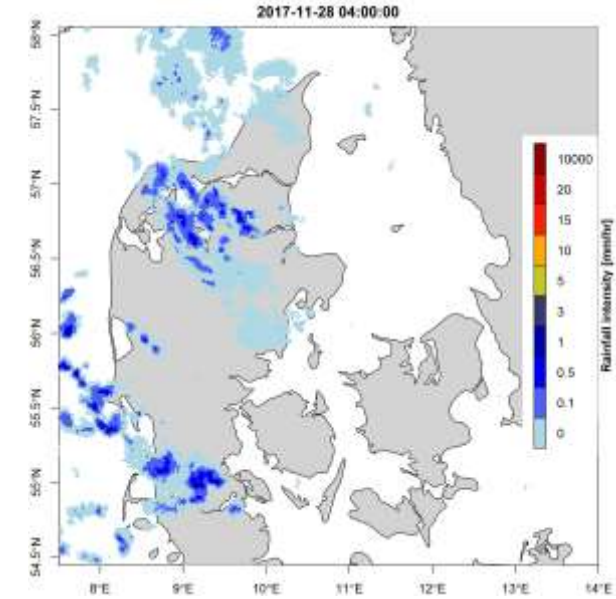
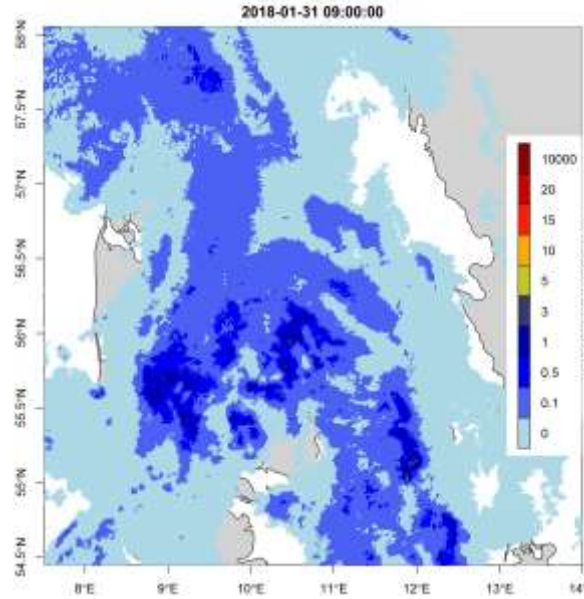
Hellerup Kirkegård (5690)

Radar



# Rainfall input

Where is it raining?  
And how much?



- Rainfall is not easy to measure

	Volume
● Rain gauges	✓
● Radar	✗
● Flow measurements	?

	Spatial distribution
● Rain gauges	✗
● Radar	✓
● Flow measurements	?

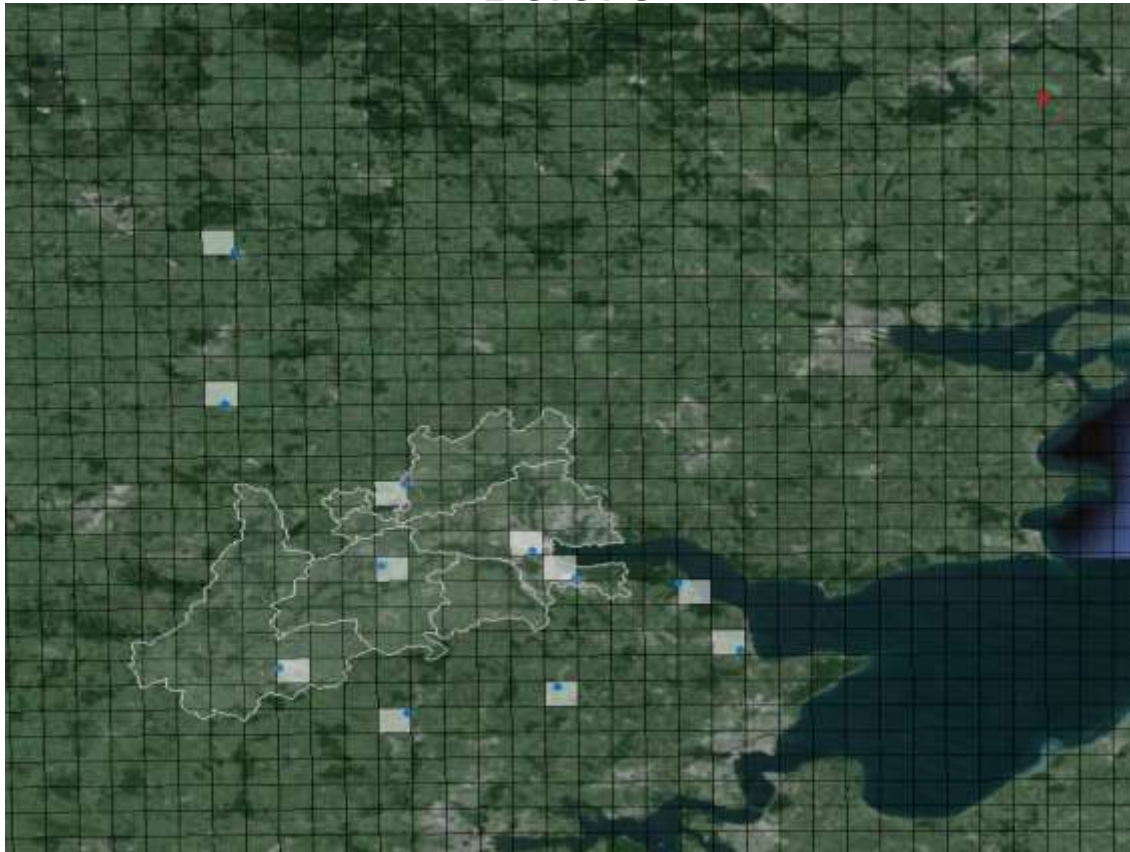
- But you can combine them!



# The new AAU Nowcaster

The spatial resolution is 16 times higher than before  
(500x500m vs 2000x2000m)

Before

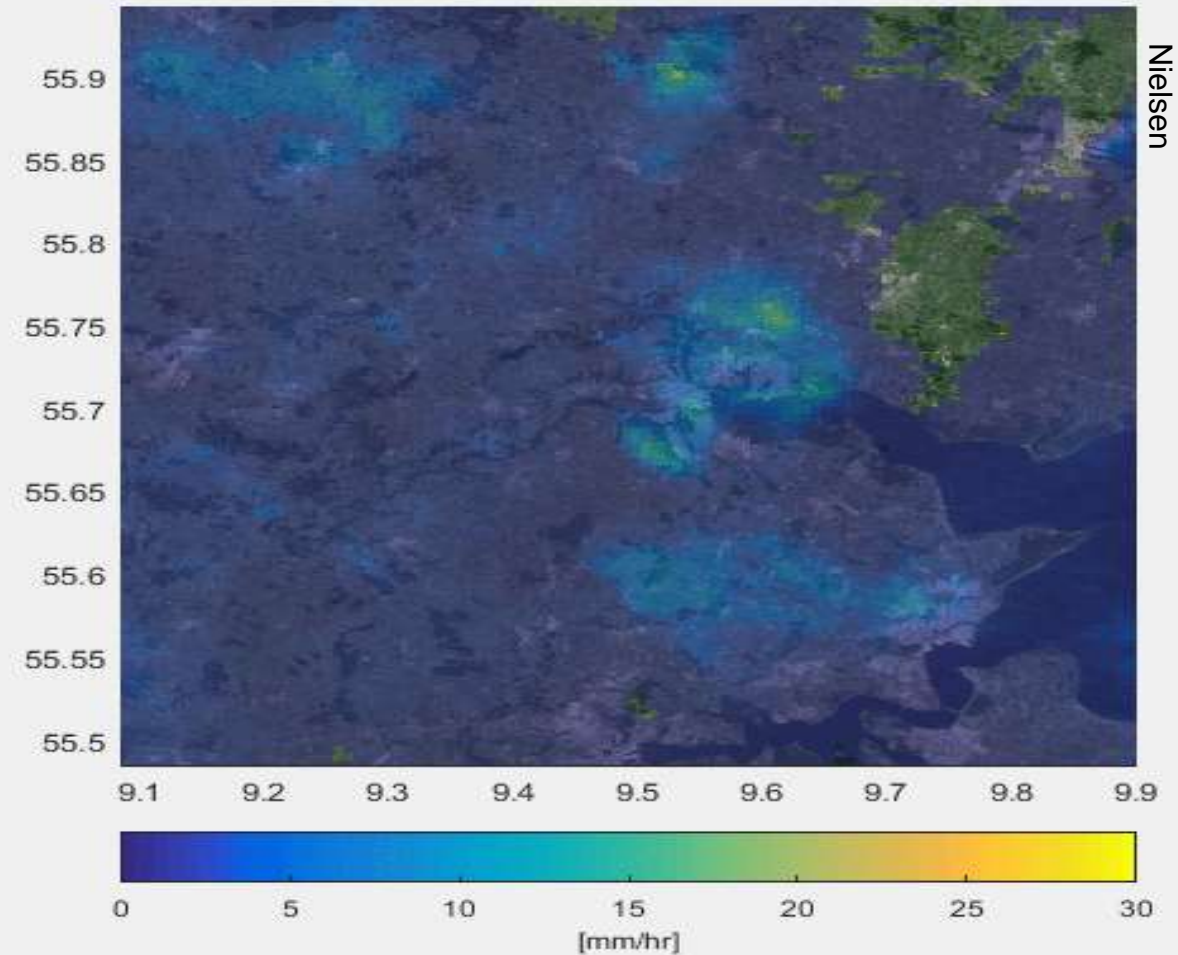
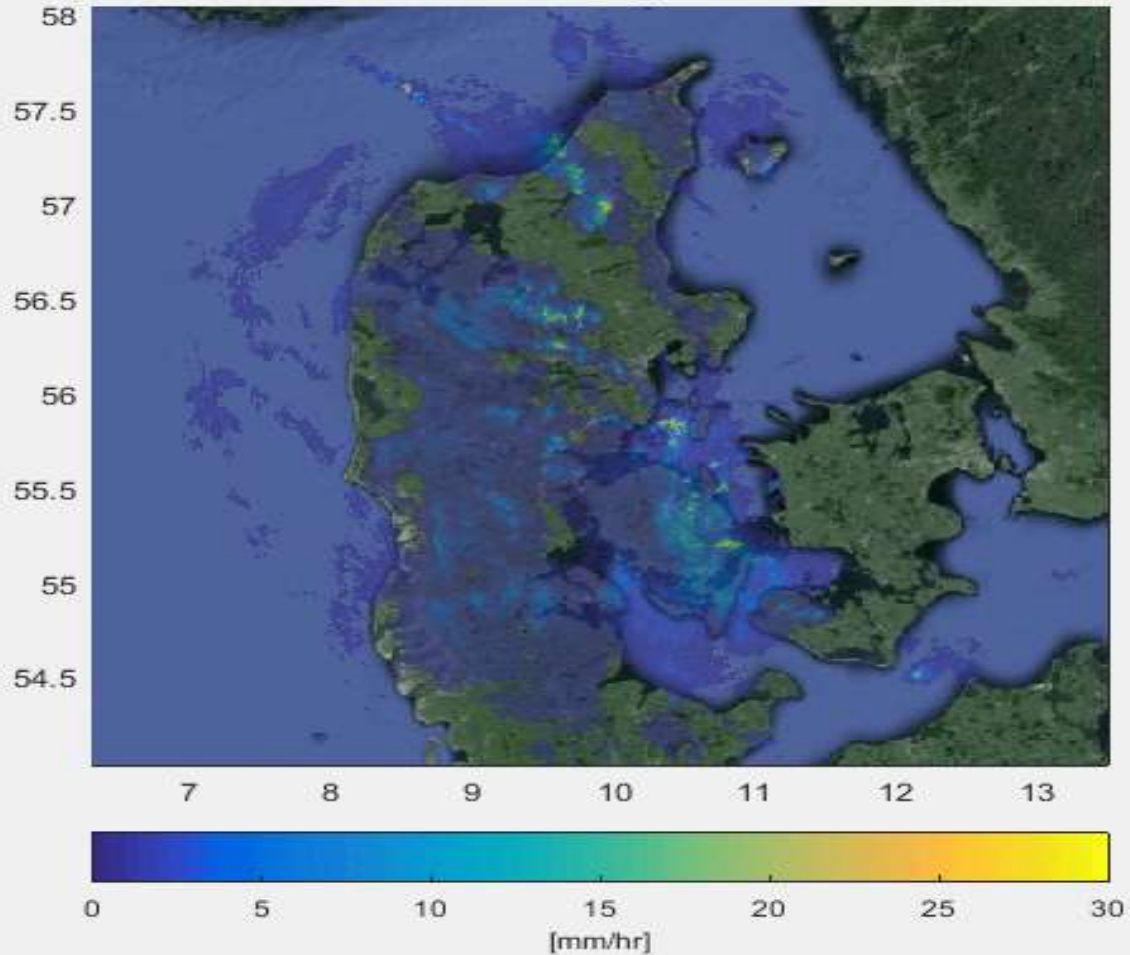


After



# Demonstration af online nowcaster (WP-3)

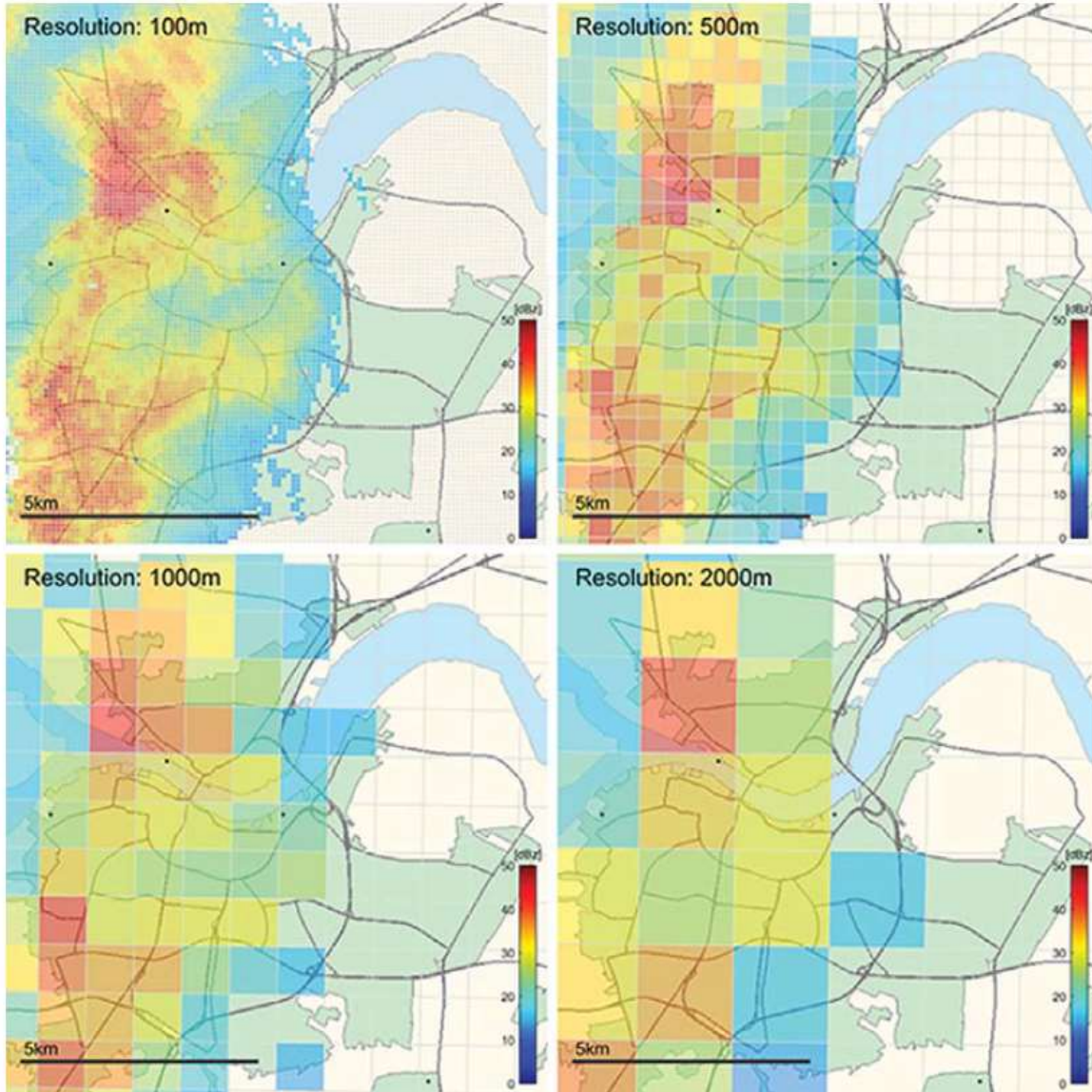
Observation: 04-Aug-2015 16:51:00



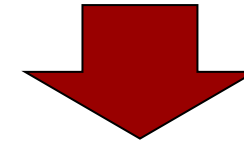
Slide courtesy of Jesper Ellerbaek Nielsen



# Radar resolution



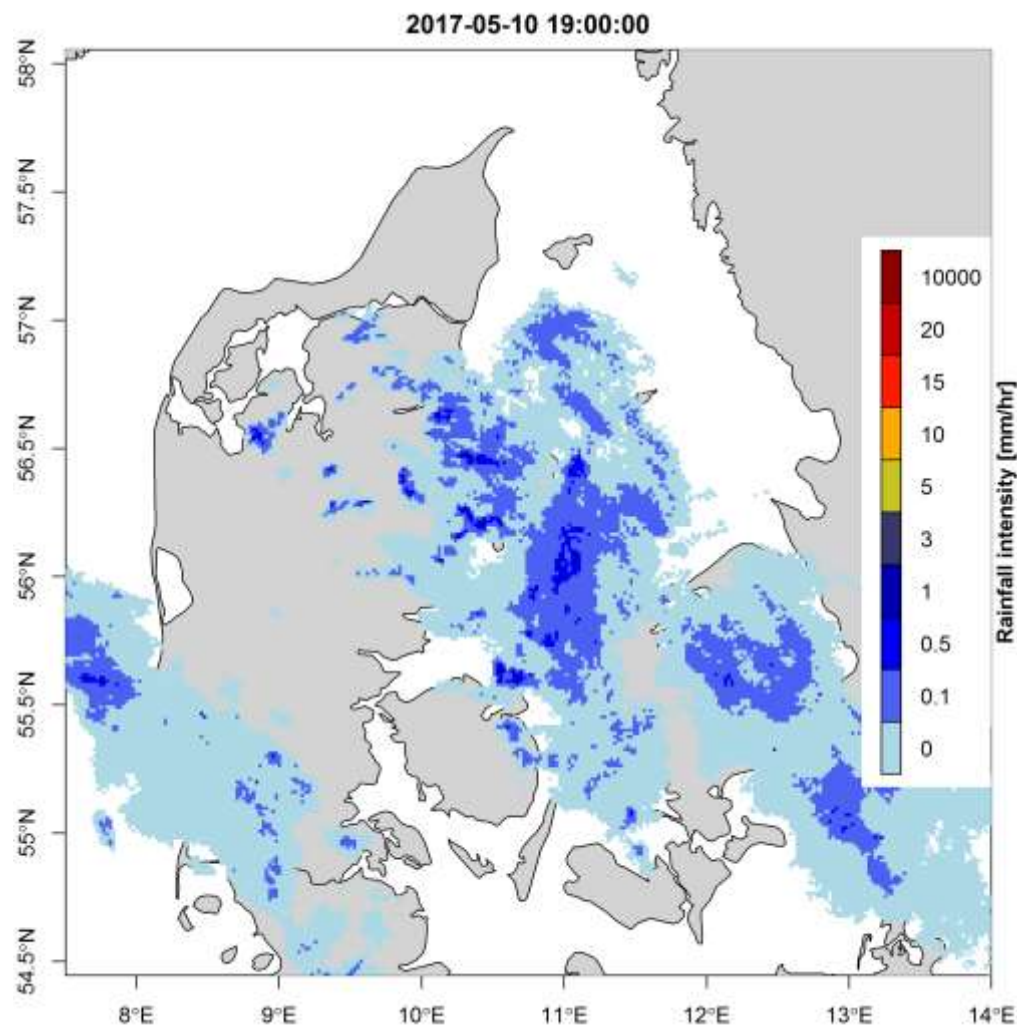
- Which one is the good one for the urban scale?
- Radar can are only useful to predict up to 2 hrs in the future
- What about longer horizons?



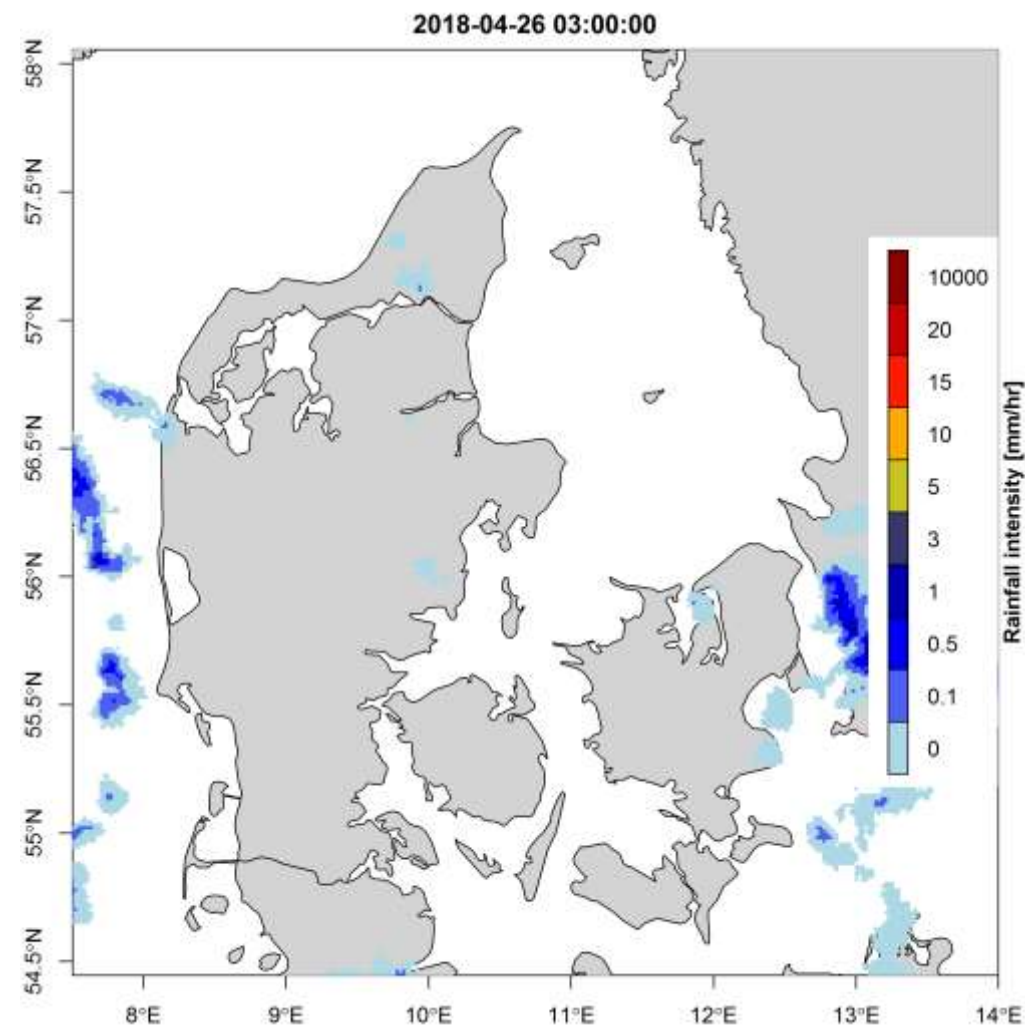
- Numerical Weather Prediction (NWP) models

Thorndahl, S., Einfalt, T., Willems, P., Nielsen, J. E., ten Veldhuis, M.-C., Arnbjerg-Nielsen, K., ... Molnar, P. (2017). Weather radar rainfall data in urban hydrology. *Hydrology and Earth System Sciences*, 21(3), 1359–1380.

# What the radar can see

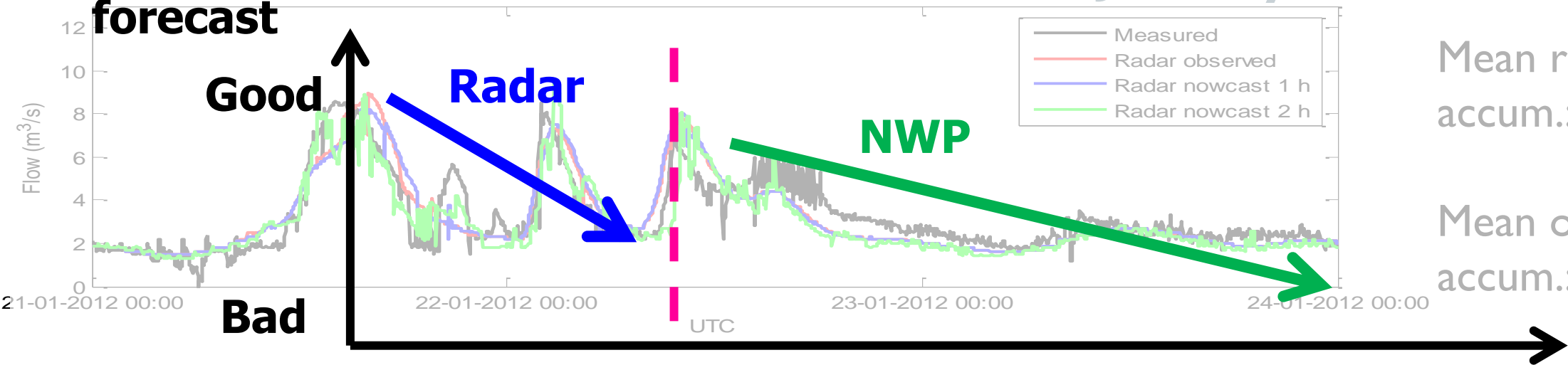


**Radar is fine**



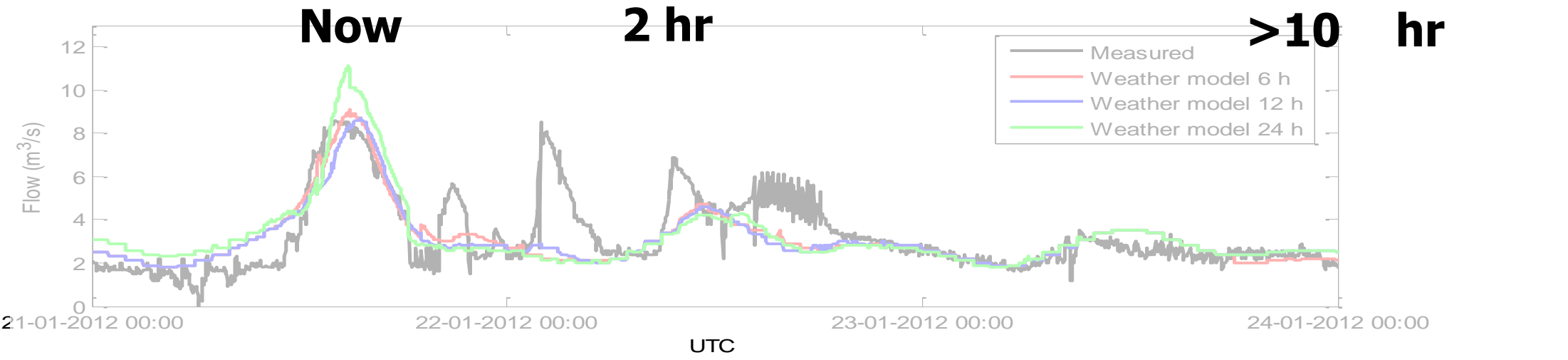
**not so good for the radar**

# Goodness of forecast results - Event 6: 21 - 24 January 2012



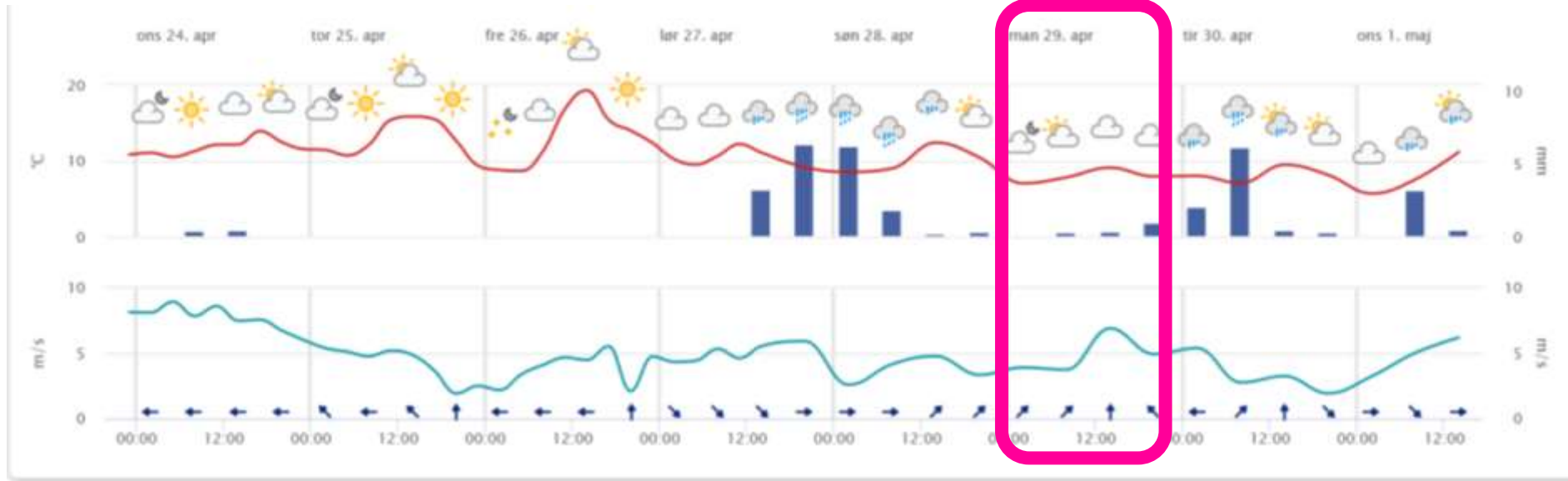
Mean rain gauge accum.: 8.6 mm

Mean obs. radar accum.: 7.3 mm

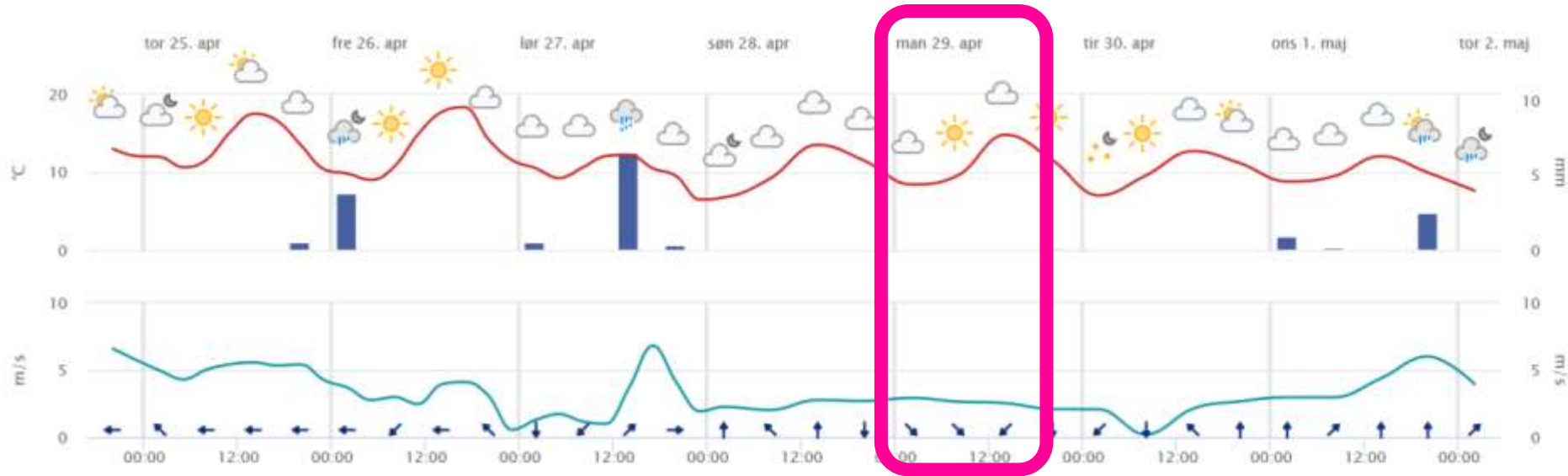


# Hvordan er vejret i dag?

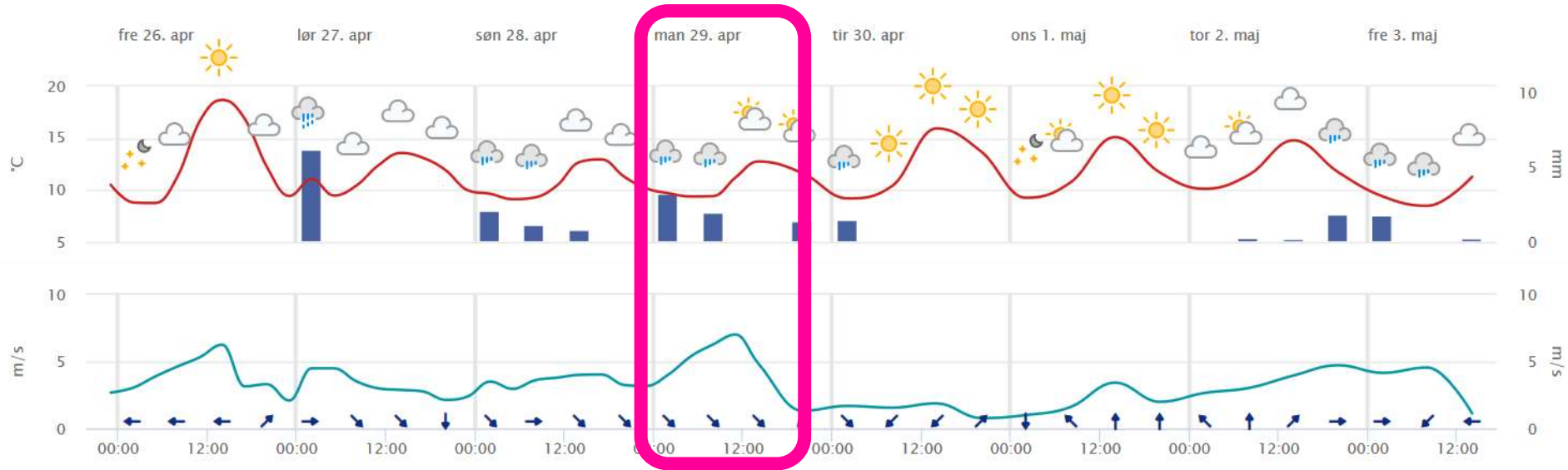




Tomorrow 22/04/2019	Tuesday 23/04/2019	Wednesday 24/04/2019	Thursday 25/04/2019	Friday 26/04/2019	Saturday 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	Tuesday 30/04/2019
16°	16°	10°	14°	13°	13°	10°	12°	11°
Clear sky. Gentle breeze, 5 m/s from southeast. 0 mm precipitation.	Clear sky. Fresh breeze, 8 m/s from east-southeast. 0 mm precipitation.	Partly cloudy. Fresh breeze, 8 m/s from east. 0 mm precipitation.	Clear sky. Moderate breeze, 6 m/s from southeast. 0 mm precipitation.	Cloudy. Moderate breeze, 7 m/s from south-southwest. 0 mm precipitation.	Fair. Moderate breeze, 6 m/s from south-southwest. 0 mm precipitation.	Clear sky. Fresh breeze, 9 m/s from west-southwest. 0 mm precipitation.	Rain showers. Moderate breeze, 7 m/s from south. 2.5 mm precipitation.	Partly cloudy. Moderate breeze, 7 m/s from west. 0 mm precipitation.

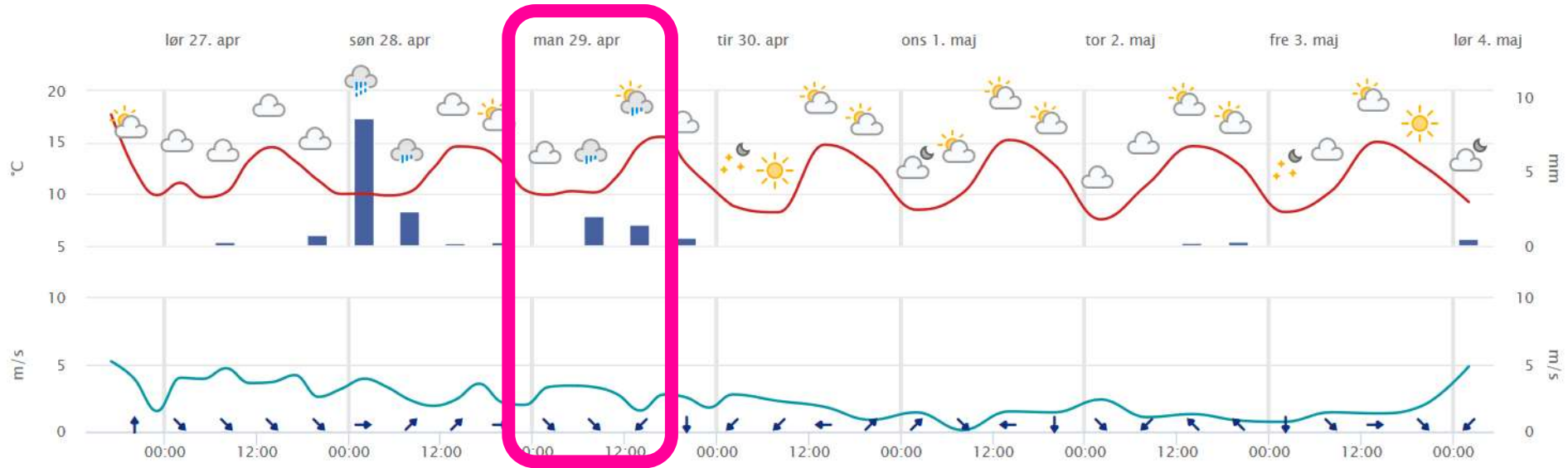


Tomorrow 23/04/2019	Wednesday 24/04/2019	Thursday 25/04/2019	Friday 26/04/2019	Saturday 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	Tuesday 30/04/2019	Wednesday 01/05/2019
16°	14°	16°	16°	12°	12°	13°	12°	11°
Clear sky. Fresh breeze, 8 m/s from east- southeast. 0 mm precipitation.	Clear sky. Moderate breeze, 7 m/s from east- southeast. 0 mm precipitation.	Partly cloudy. Moderate breeze, 6 m/s from east. 0 mm precipitation.	Partly cloudy. Gentle breeze, 4 m/s from east. 0 mm precipitation.	Partly cloudy. Light breeze, 3 m/s from southwest. 0 mm precipitation.	Cloudy. Gentle breeze, 4 m/s from south. 0 mm precipitation.	Clear sky. Gentle breeze, 4 m/s from north- northeast. 0 mm precipitation.	Partly cloudy. Light breeze, 3 m/s from southeast. 0 mm precipitation.	Rain showers. Gentle breeze, 5 m/s from south- southeast. 2.1 mm precipitation.

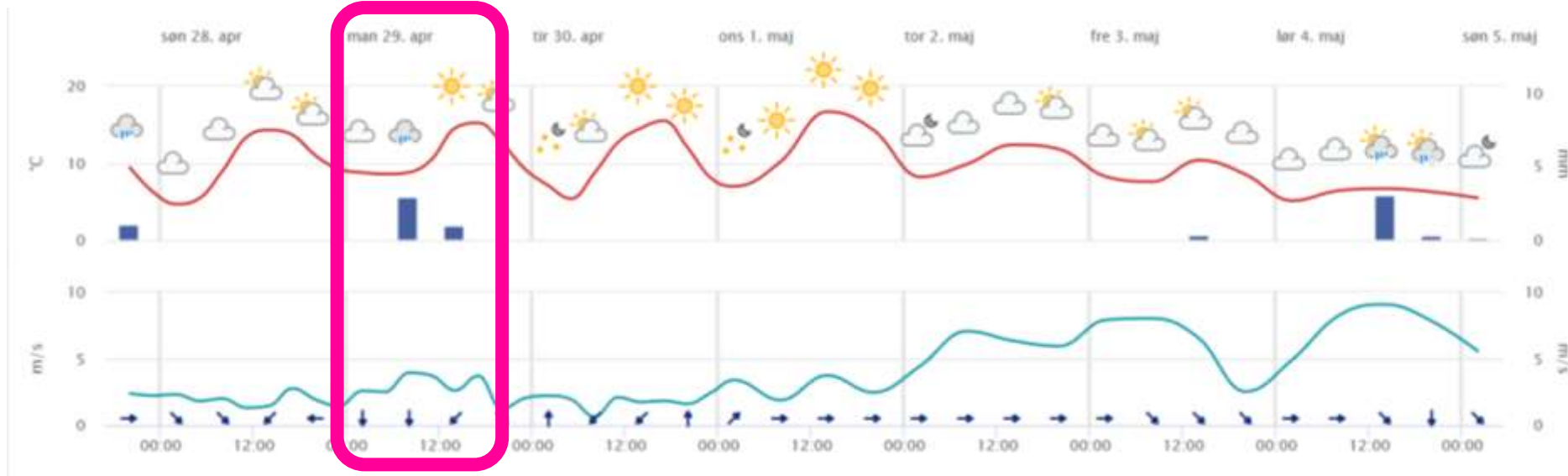


Tomorrow 24/04/2019	Thursday 25/04/2019	Friday 26/04/2019	Saturday 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	Tuesday 30/04/2019	Wednesday 01/05/2019	Thursday 02/05/2019
15°	18°	17°	13°	12°	12°	15°	13°	14°
Partly cloudy. Moderate breeze, 7 m/s from south-southeast. 0 mm precipitation.	Clear sky. Gentle breeze, 4 m/s from south-southeast. 0 mm precipitation.	Partly cloudy. Moderate breeze, 6 m/s from east. 0 mm precipitation.	Cloudy. Light breeze, 3 m/s from north-northwest. 0 mm precipitation.	Cloudy. Gentle breeze, 4 m/s from northwest. 0 mm precipitation.	Rain showers. Moderate breeze, 6 m/s from northwest. 1.8 mm precipitation.	Clear sky. Light breeze, 3 m/s from north-northwest. 0 mm precipitation.	Clear sky. Light breeze, 3 m/s from south. 0 mm precipitation.	Rain. Gentle breeze, 4 m/s from south-southwest. 1.3 mm precipitation.

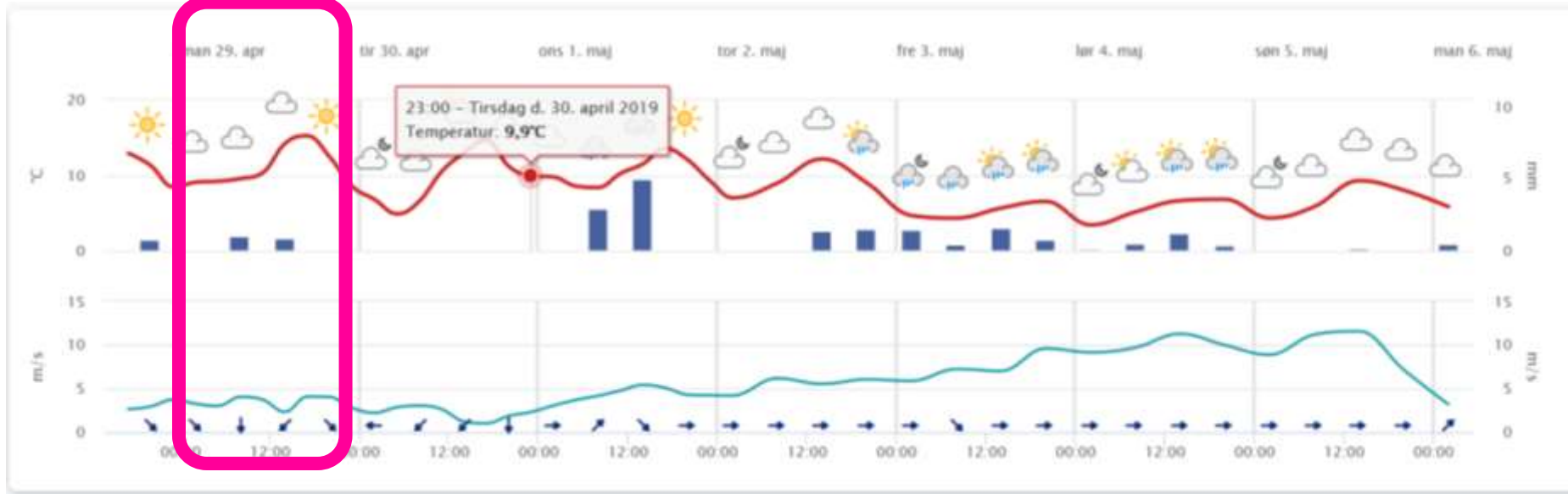




Tomorrow 25/04/2019	Friday 26/04/2019	Saturday 27/04/2019	Sunday 28/04/2019	<b>Monday 29/04/2019</b>	Tuesday 30/04/2019	Wednesday 01/05/2019	Thursday 02/05/2019	Friday 03/05/2019
<b>18°</b>	<b>20°</b>	<b>14°</b>	<b>13°</b>	<b>14°</b>	<b>14°</b>	<b>14°</b>	<b>13°</b>	<b>14°</b>
Fair. Light breeze, 3 m/s from south-southeast. 0 mm precipitation.	Partly cloudy. Gentle breeze, 4 m/s from east. 0 mm precipitation.	Rain. Gentle breeze, 5 m/s from north. 1.1 mm precipitation.	Fair. Light breeze, 3 m/s from south-southeast. 0 mm precipitation.	<b>Cloudy. Light breeze, 2 m/s from northwest. 0 mm precipitation.</b>	Fair. Light air, 1 m/s from north. 0 mm precipitation.	Partly cloudy. Light breeze, 3 m/s from east. 0 mm precipitation.	Fair. Light breeze, 2 m/s from southeast. 0 mm precipitation.	Clear sky. Light breeze, 2 m/s from south-southeast. 0 mm precipitation.

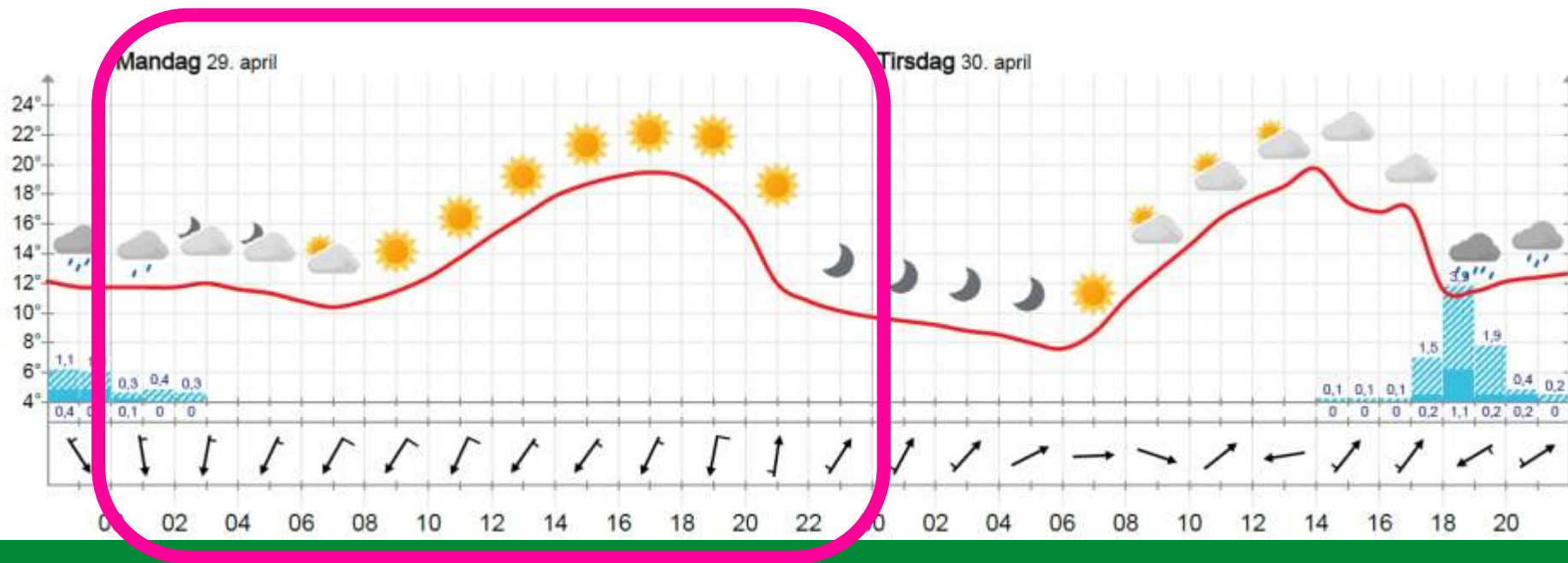
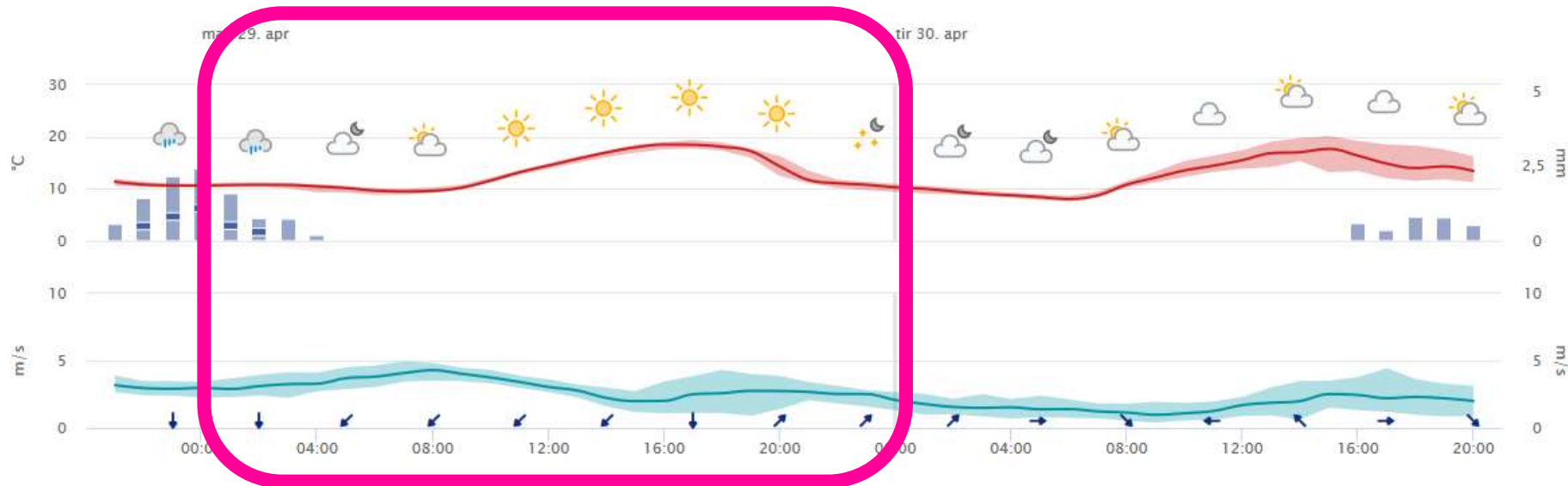


Tomorrow 26/04/2019	Saturday 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	Tuesday 30/04/2019	Wednesday 01/05/2019	Thursday 02/05/2019	Friday 03/05/2019	Saturday 04/05/2019
19°	8°	13°	14°	13°	16°	12°	10°	7°
Partly cloudy. Light breeze, 3 m/s from east. 0 mm precipitation.	Heavy rain. Gentle breeze, 5 m/s from west- northwest. 5 mm precipitation.	Partly cloudy. Light breeze, 3 m/s from east- northeast. 0 mm precipitation.	Fair. Light breeze, 2 m/s from north- northwest. 0 mm precipitation.	Clear sky. Light air, 1 m/s from northwest. 0 mm precipitation.	Clear sky. Light breeze, 3 m/s from southwest. 0 mm precipitation.	Partly cloudy. Moderate breeze, 7 m/s from west. 0 mm precipitation.	Cloudy. Moderate breeze, 7 m/s from northwest. 0 mm precipitation.	Partly cloudy. Fresh breeze, 10 m/s from west- northwest. 0 mm precipitation.



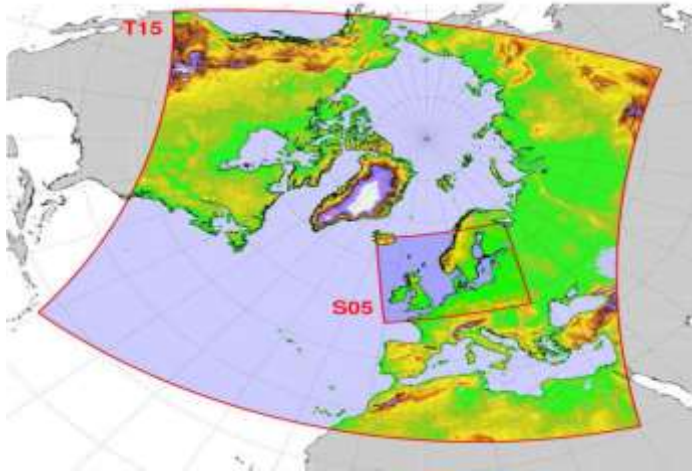
Tomorrow 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	Tuesday 30/04/2019	Wednesday 01/05/2019	Thursday 02/05/2019	Friday 03/05/2019	Saturday 04/05/2019	Sunday 05/05/2019
10°	14°	13°	12°	11°	12°	6°	7°	9°
Cloudy. Gentle breeze, 5 m/s from northwest. 0 mm precipitation.	Partly cloudy. Light breeze, 3 m/s from northeast. 0 mm precipitation.	Fair. Light air, 1 m/s from northwest. 0 mm precipitation.	Cloudy. Light breeze, 2 m/s from northwest. 0 mm precipitation.	Fair. Moderate breeze, 6 m/s from west-northwest. 0 mm precipitation.	Rain showers. Moderate breeze, 6 m/s from west-southwest. 1.3 mm precipitation.	Rain showers. Fresh breeze, 8 m/s from west-northwest. 1.4 mm precipitation.	Fair. Strong breeze, 13 m/s from west. 0 mm precipitation.	Partly cloudy. Strong breeze, 13 m/s from west-northwest. 0 mm precipitation.





# How weather forecasts are made?

The DMI-HIRLAM-S05 model



- Horizontal resolution =  $0.05^\circ$  (5.5 km)
- Time Step = 1h
- Forecast length = 54h
- Forecast frequency = 4 times per day
- Members = 25

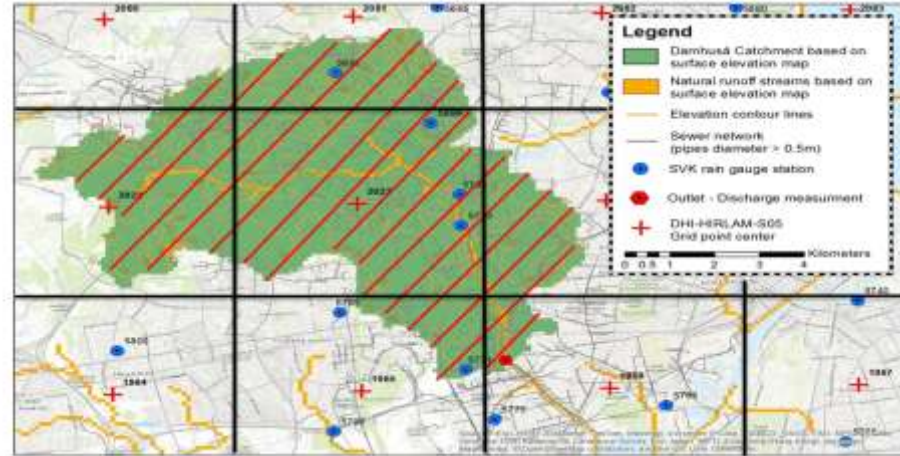
5 # model structures

5 # initial conditions

Ensemble members	STRACO		KF/RK		STRACO
		Stoc. Phys.		Stoc. Phys.	Pert. Roughn.
Ini. cond. 1	1	6	11	16	21
Ini. cond. 2	2	7	12	17	22
Ini. cond. 3	3	8	13	18	23
Ini. cond. 4	4	9	14	19	24
Ini. cond. 5	5	10	15	20	25

# Context vs. Model Uncertainty

what do we ask to the model?



Meteorological perspective



Weather behavior, pattern, feature



The big picture

Urban hydrology perspective



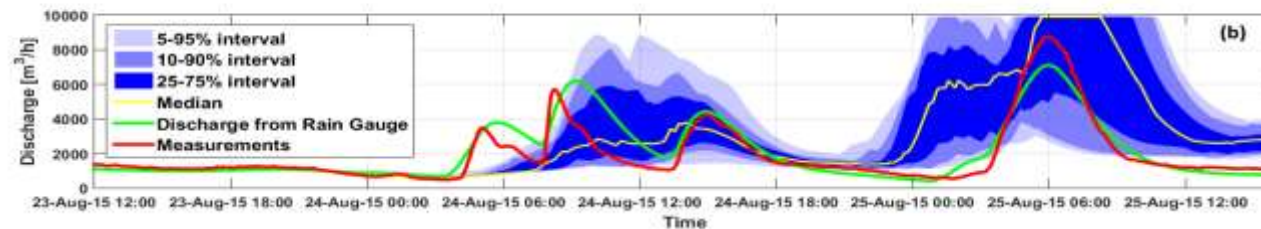
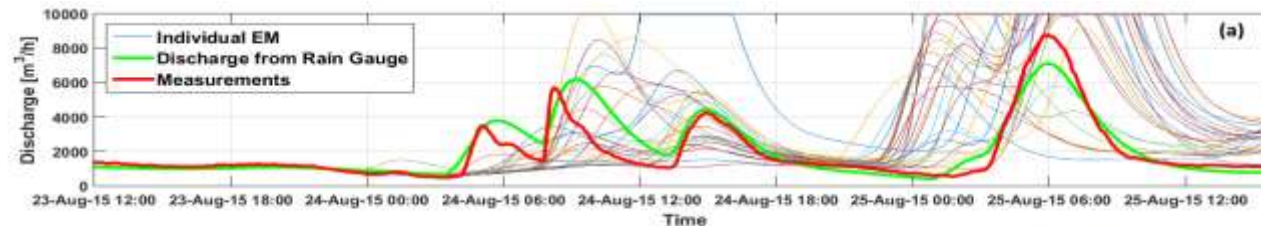
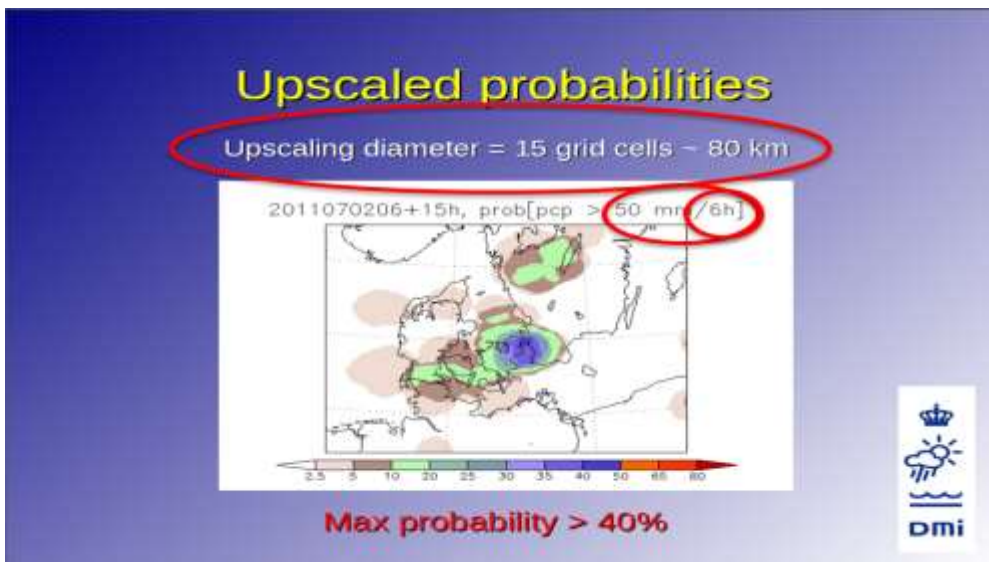
Local value with high resolution



The pixel

# Context vs. Model Uncertainty

what do we ask to the model?



Meteorological perspective

These weather forecast are great!

Urban hydrology perspective

These weather forecast are crap



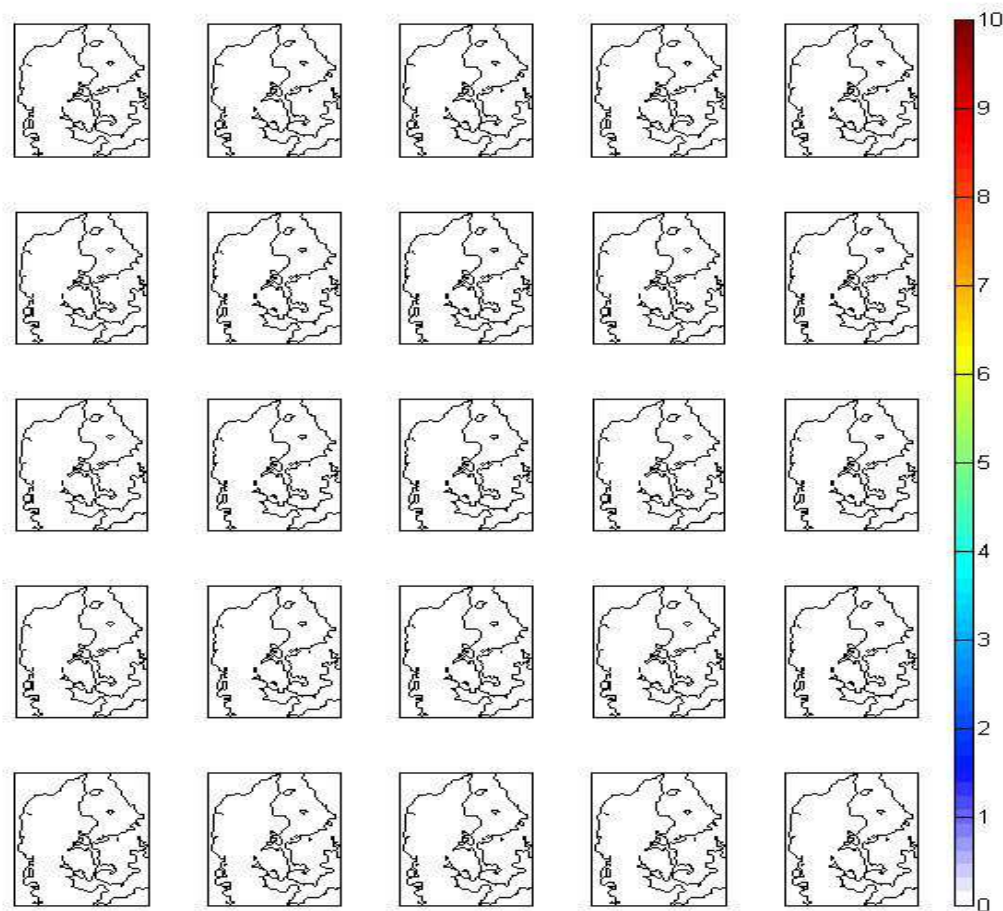
# DMI model prediction (winter)

15-Jan-2015 - lead time 0 hours (in [mm/h])



# DMI model prediction (summer)

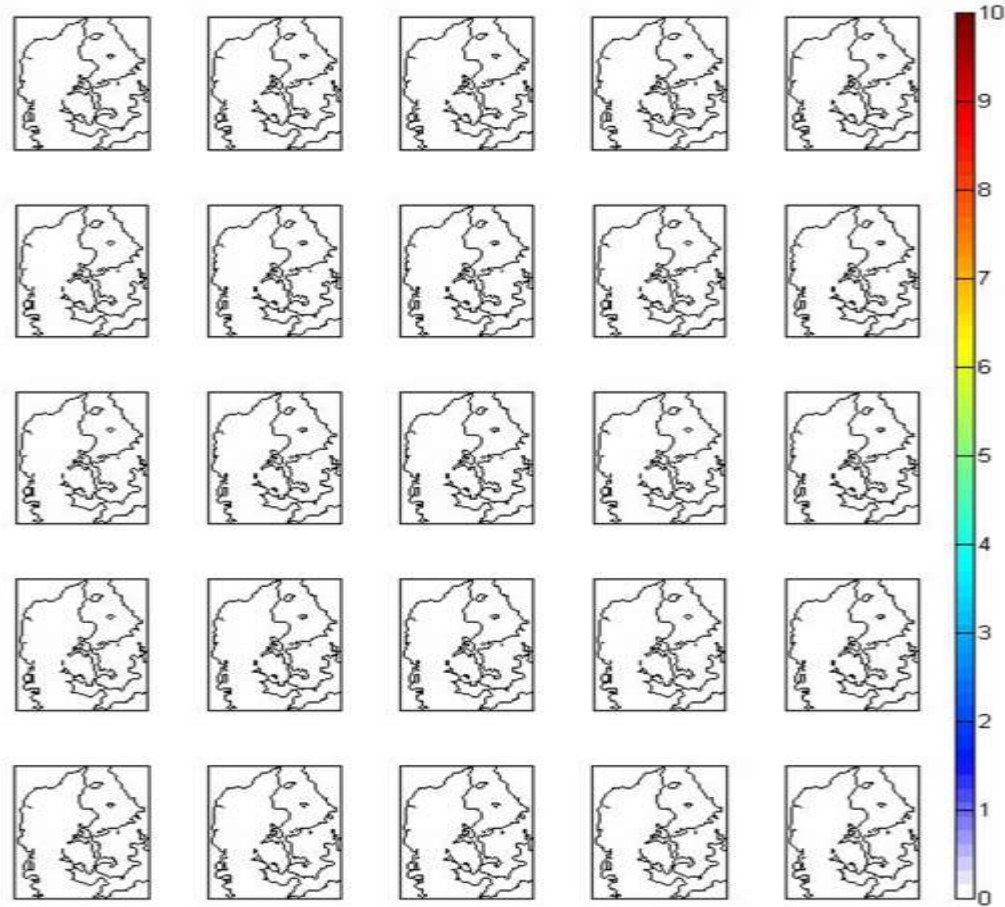
31-Aug-2015 06:00:00 - lead time 0 hours (in [mm/h])





# DMI model prediction (summer)

31-Aug-2015 06:00:00 - lead time 0 hours (in [mm/h])



25 (physically based) models = 25 different results

Measurements

+

Models

+

Forecasts

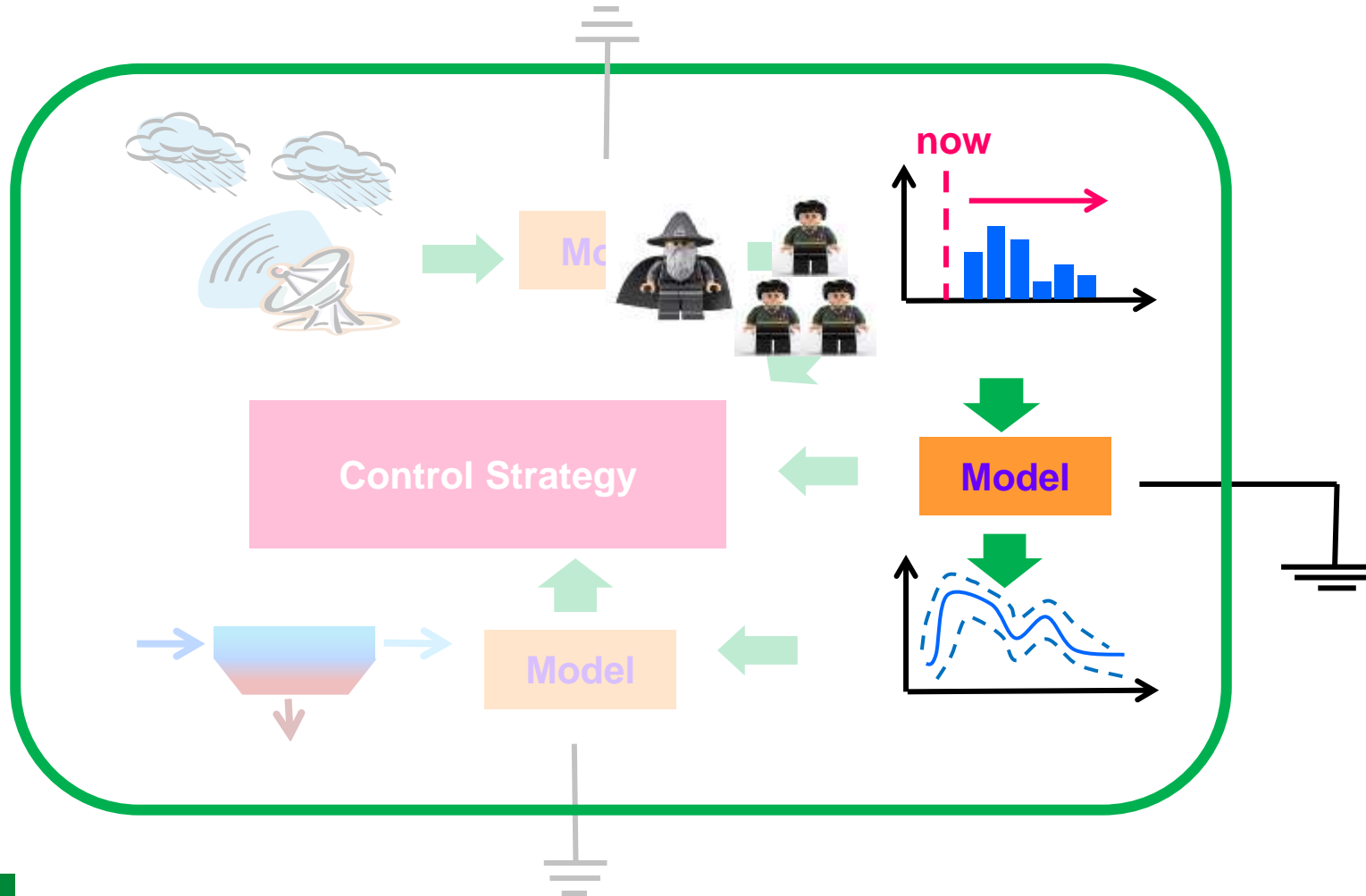
+

Uncertainty

=

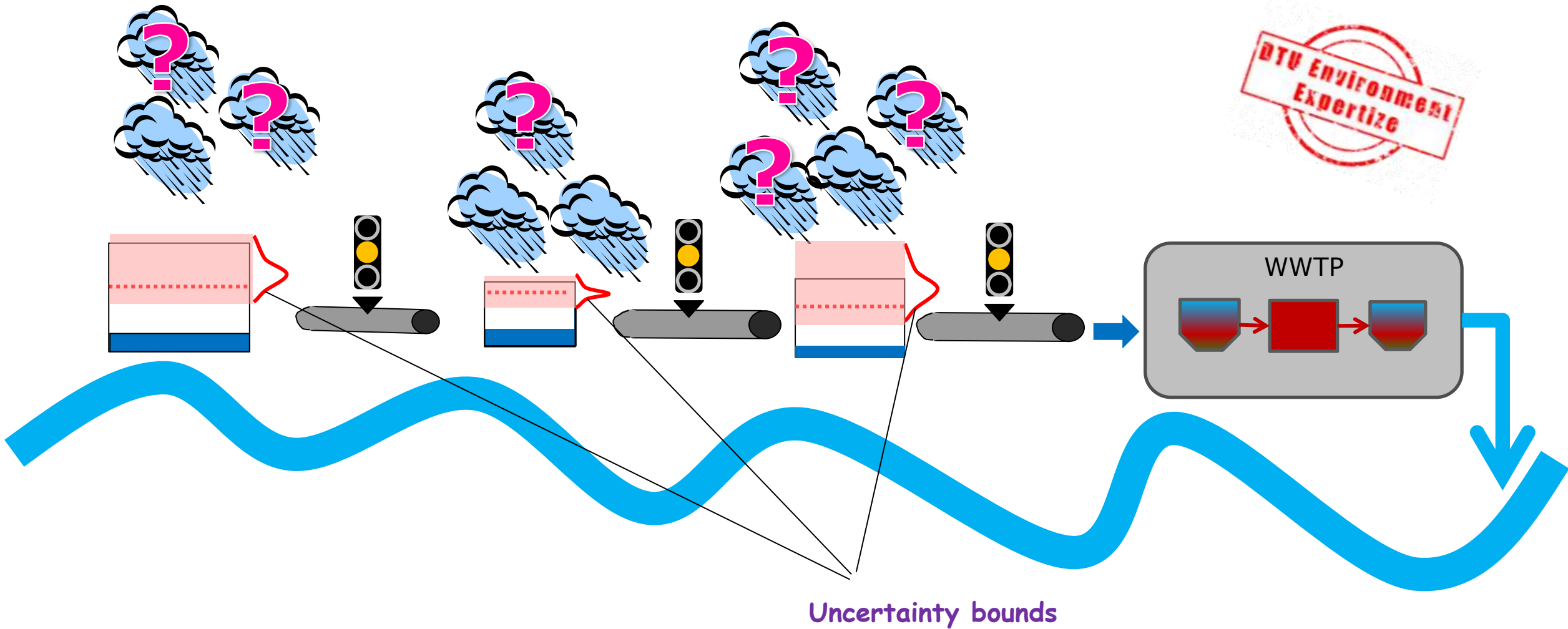


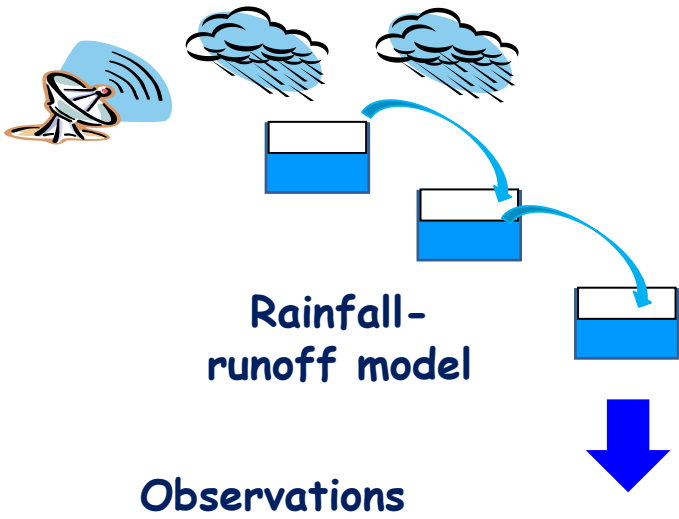
*The happy operator*



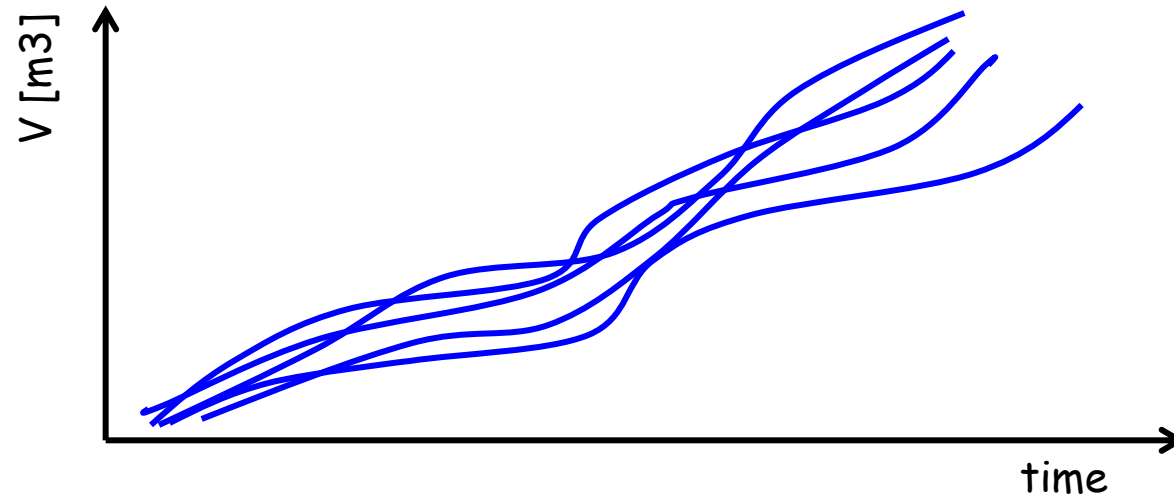
- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

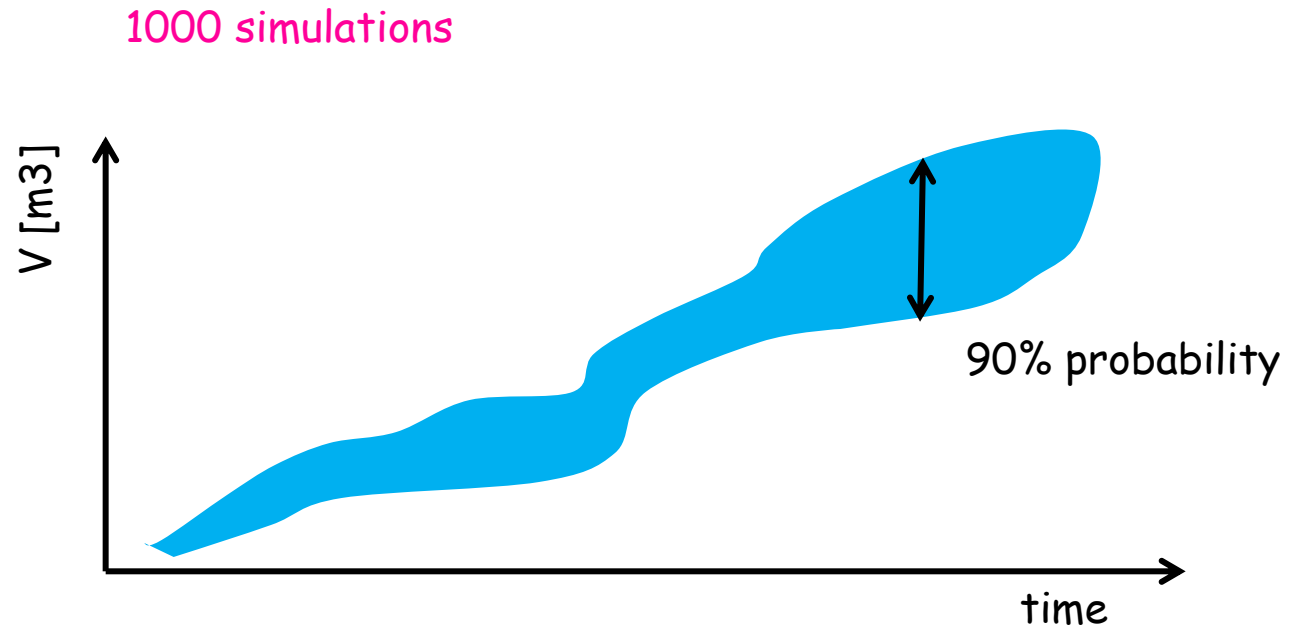
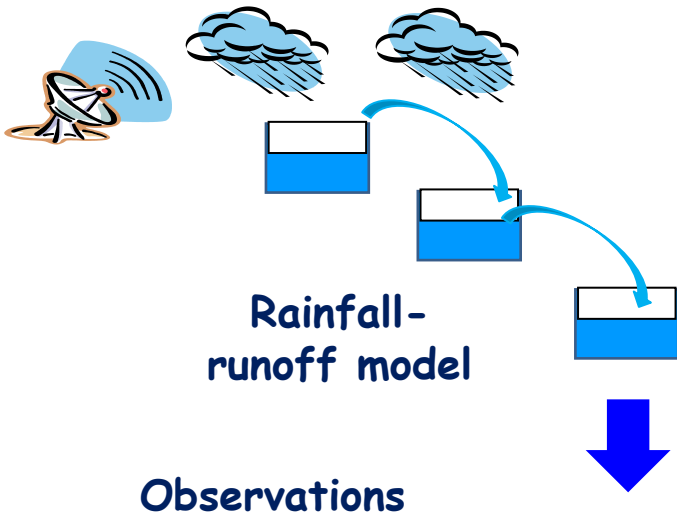
# Model Predictive Control with uncertainty





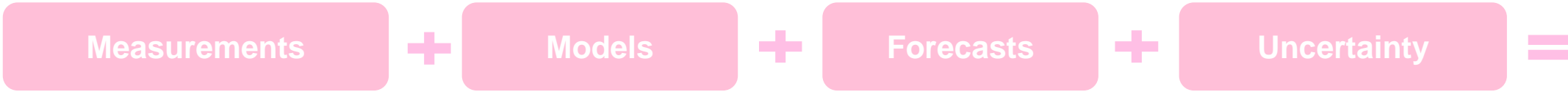
1000 simulations



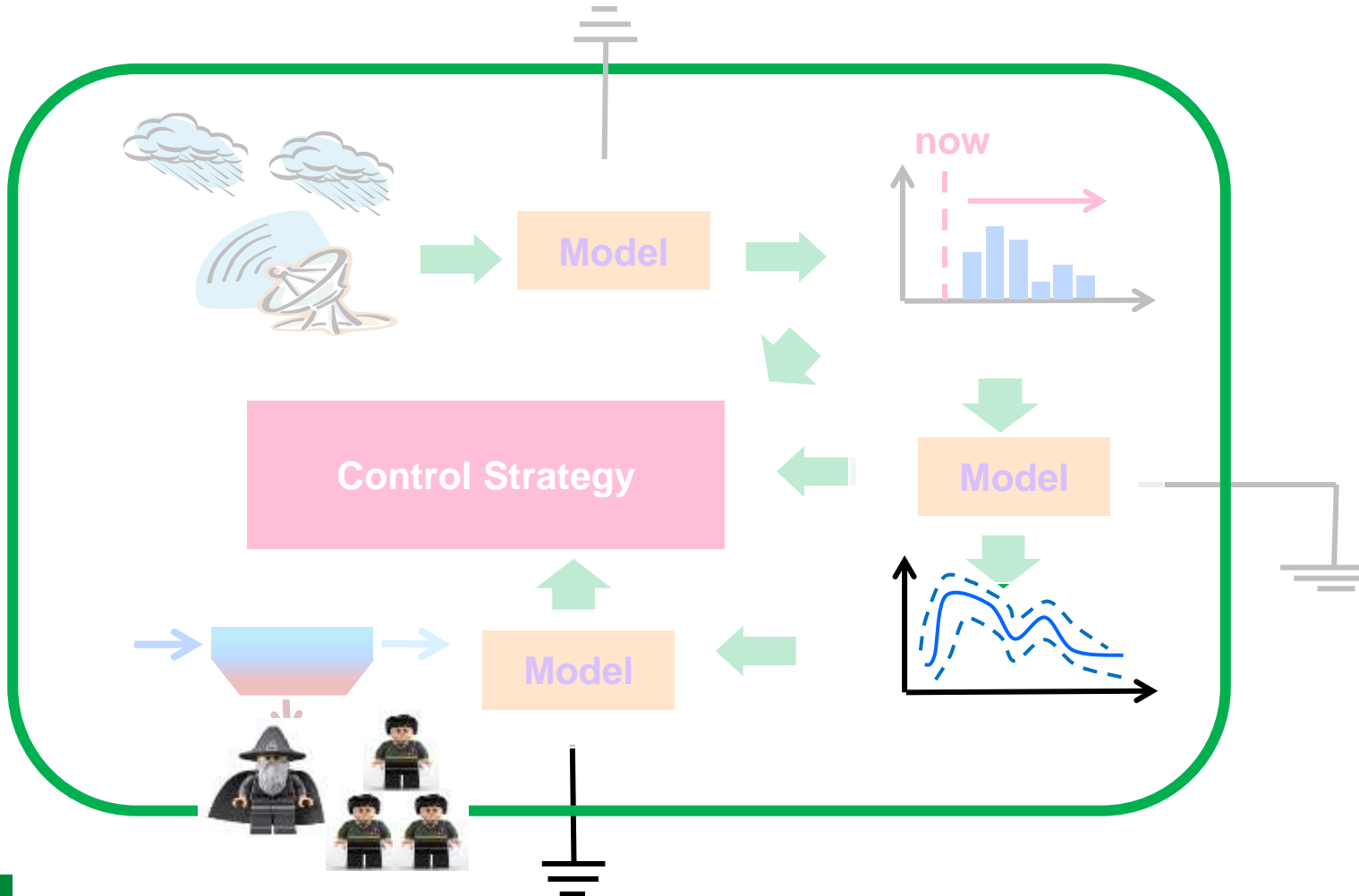




# The fellowship of SWI – the long journey



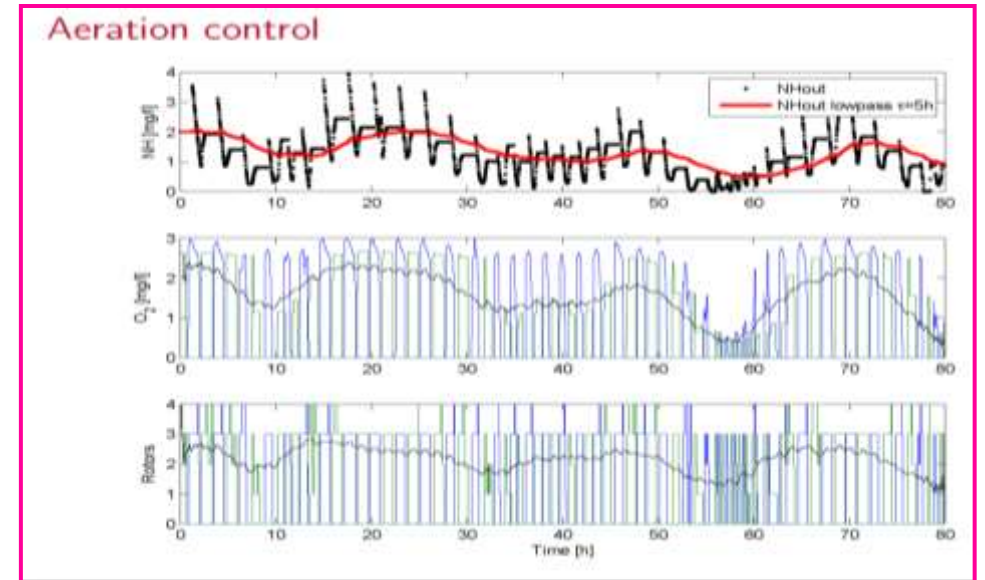
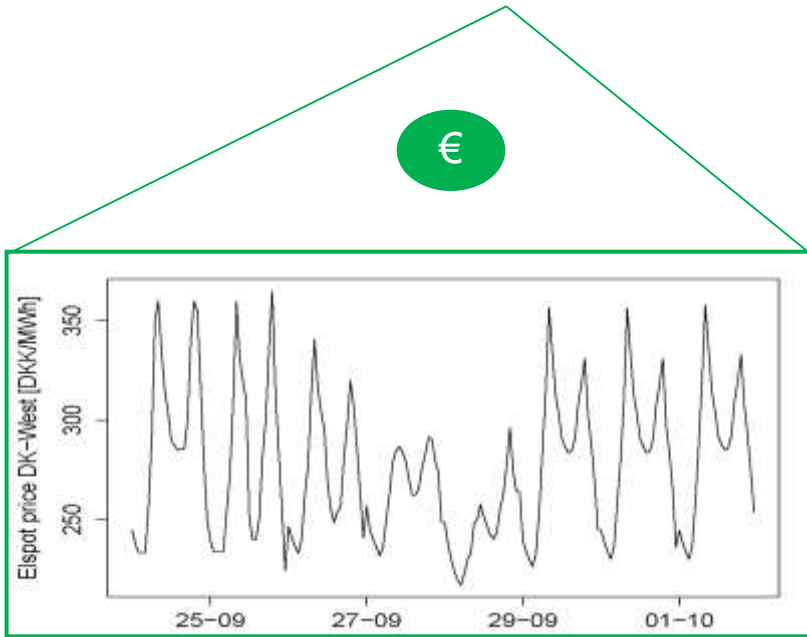
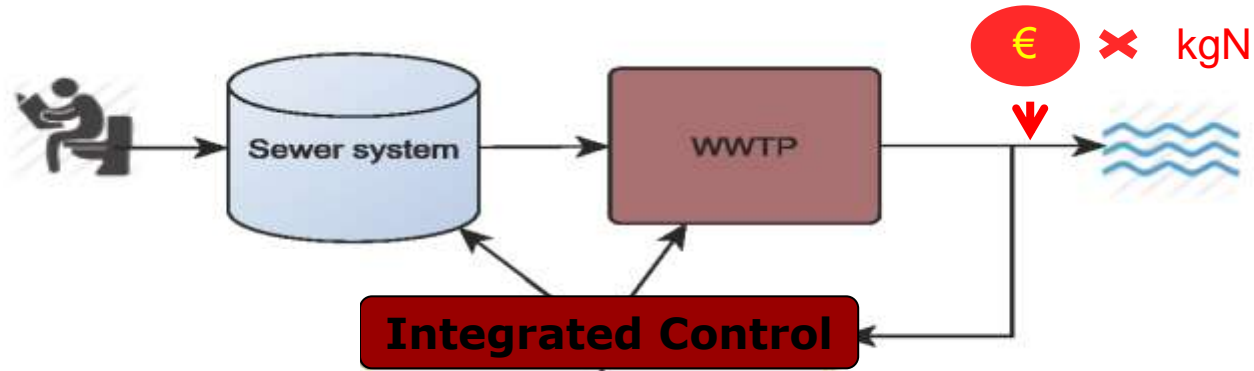
*The happy operator*



- Rainfall measurements
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- Continuously updated hydrodynamic models
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- MPC strategy addressing uncertainty

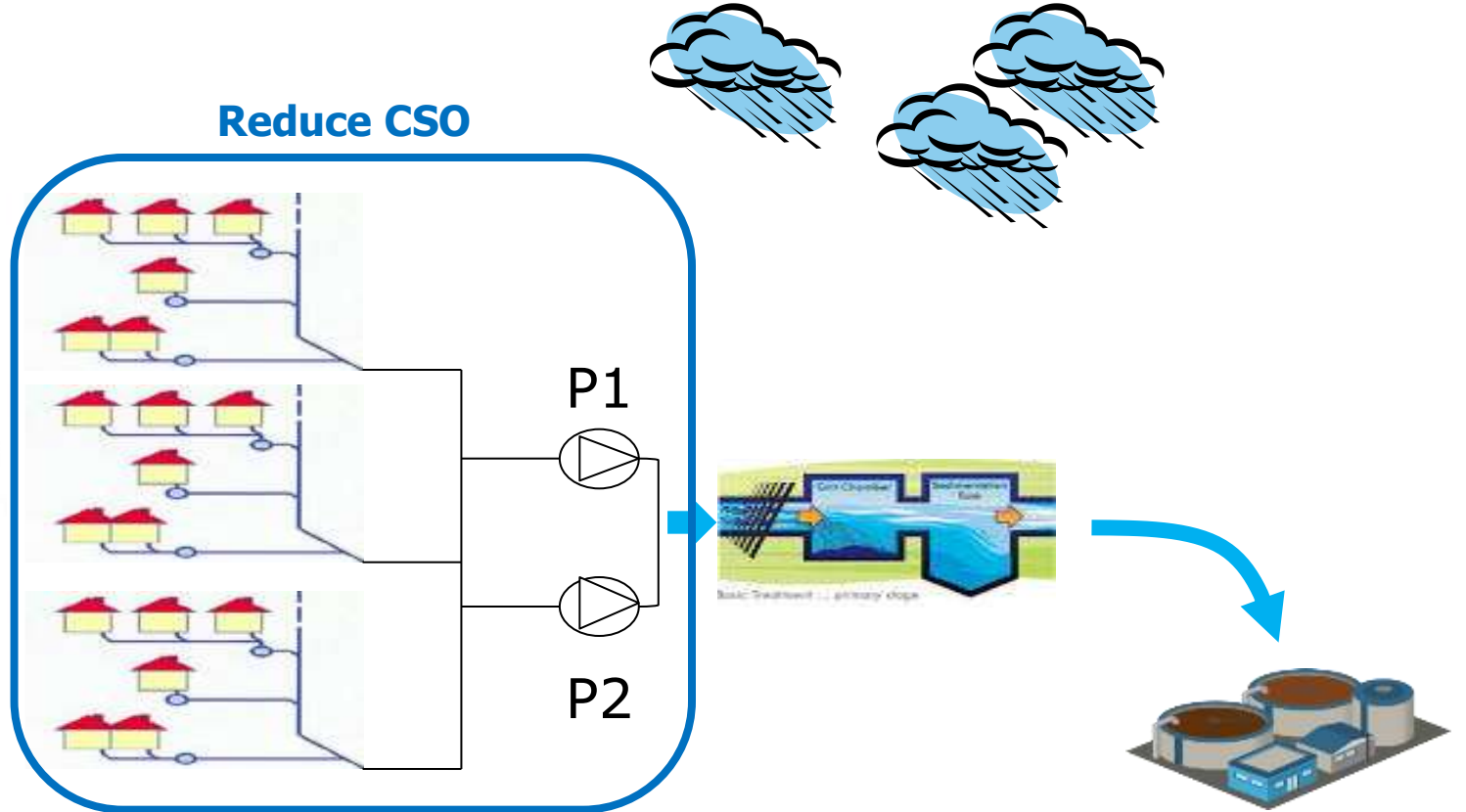
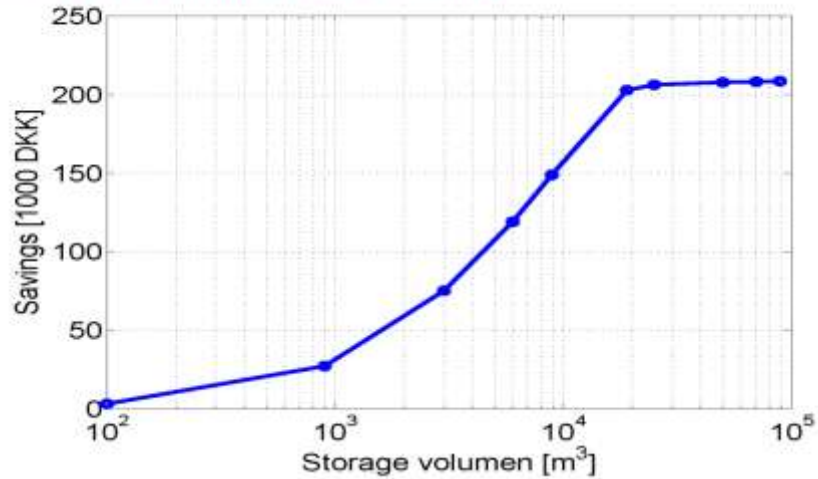
# Controlling the WWTP based on energy prices

the Blue Kolding example



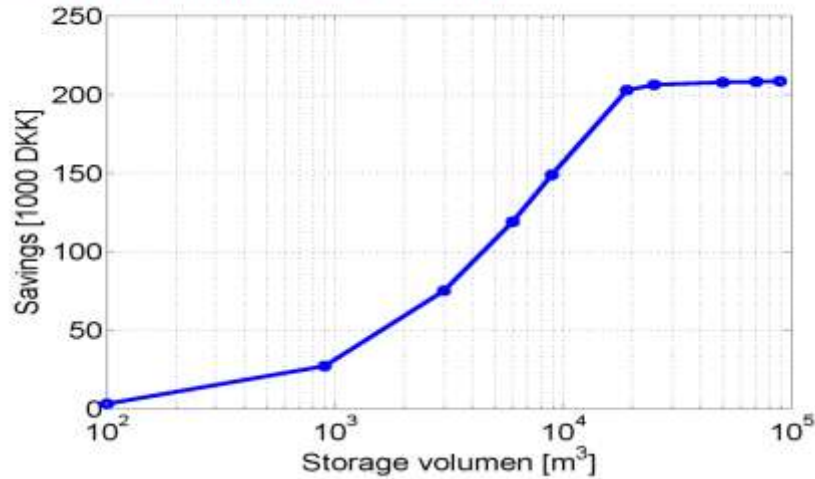
# Controlling the WWTP based on energy prices – moving upstream

Sewer system annual Elspot savings

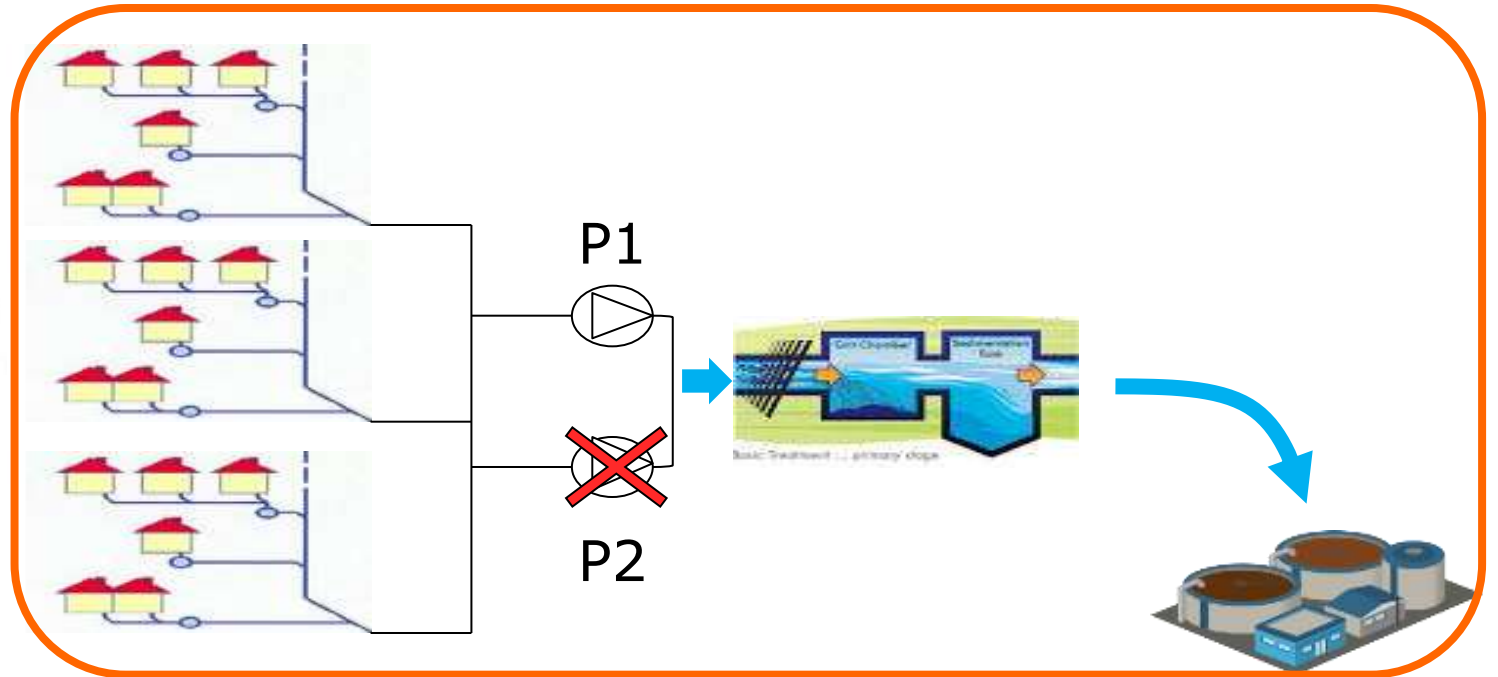


# Controlling the WWTP based on energy prices – moving upstream

Sewer system annual Elspot savings



## Optimize WWTP Operations

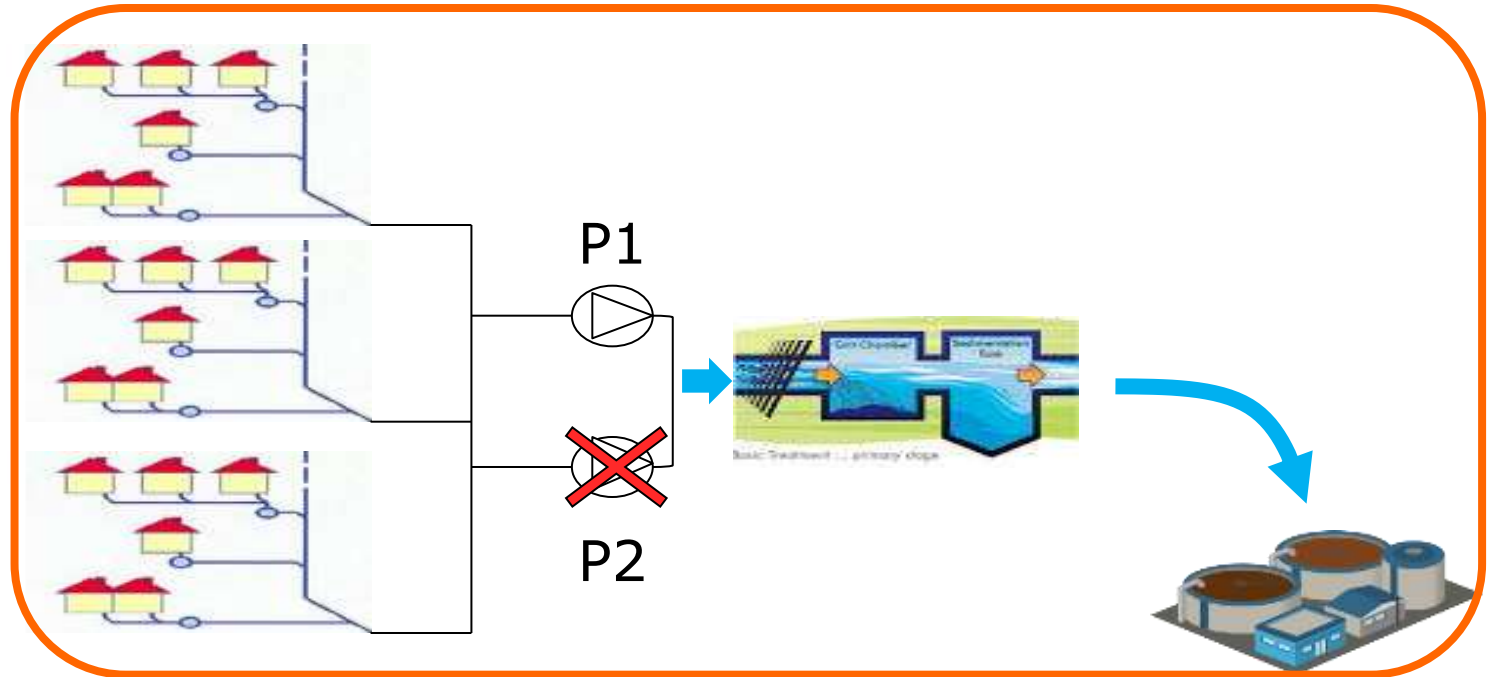


# Controlling the WWTP based on energy prices – moving upstream



Numerical Weather Prediction models are used to switch between the two controls

## Optimize WWTP Operations

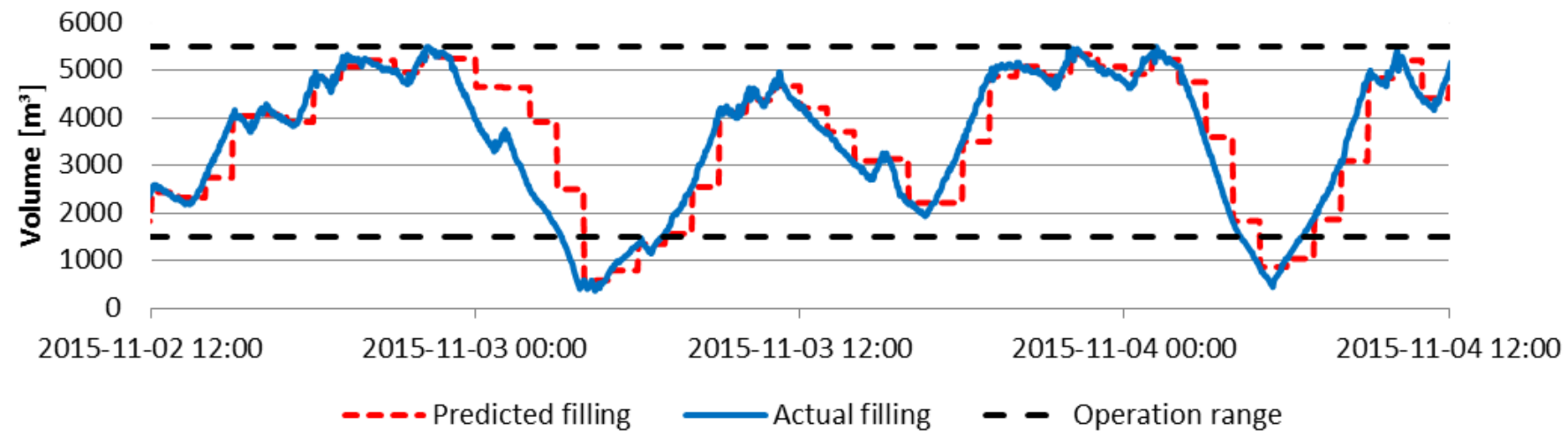
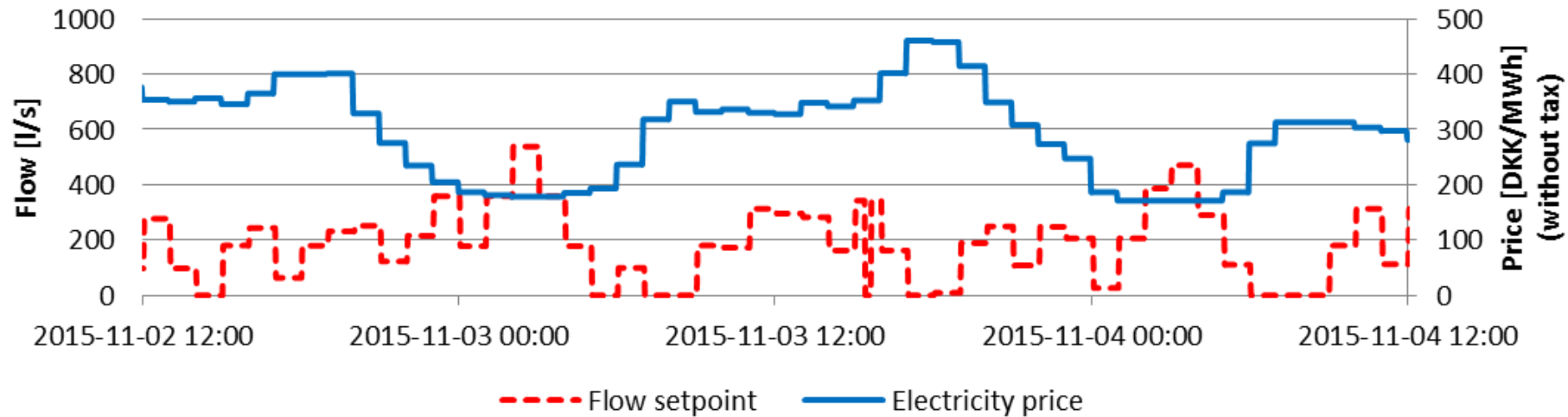






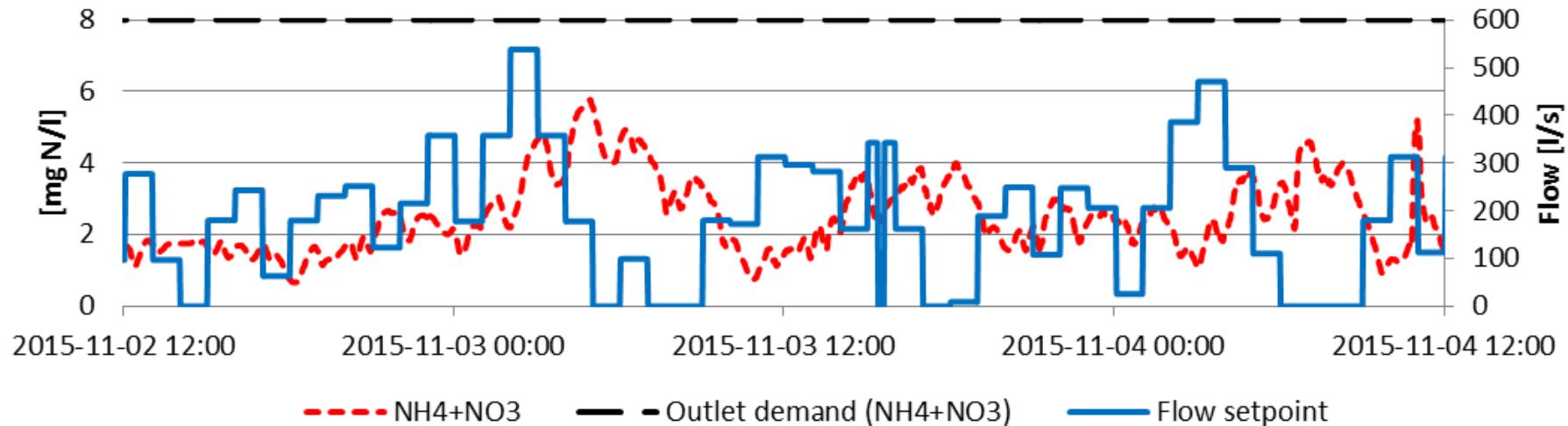
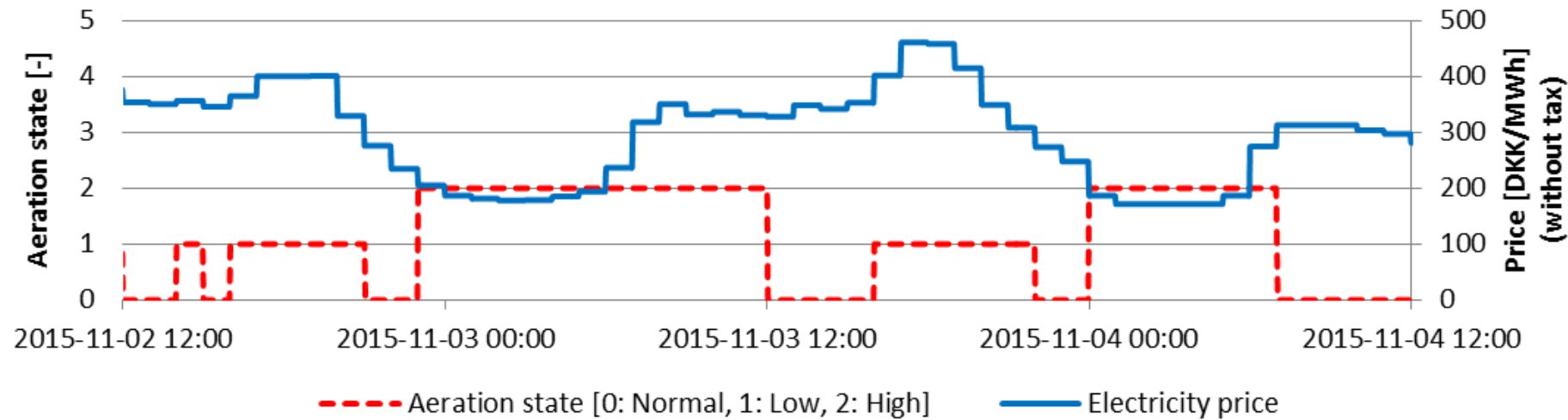
# SMARTGRID in Kolding - Sewer

(3 days of full scale)



# SMARTGRID in Kolding – WWTP

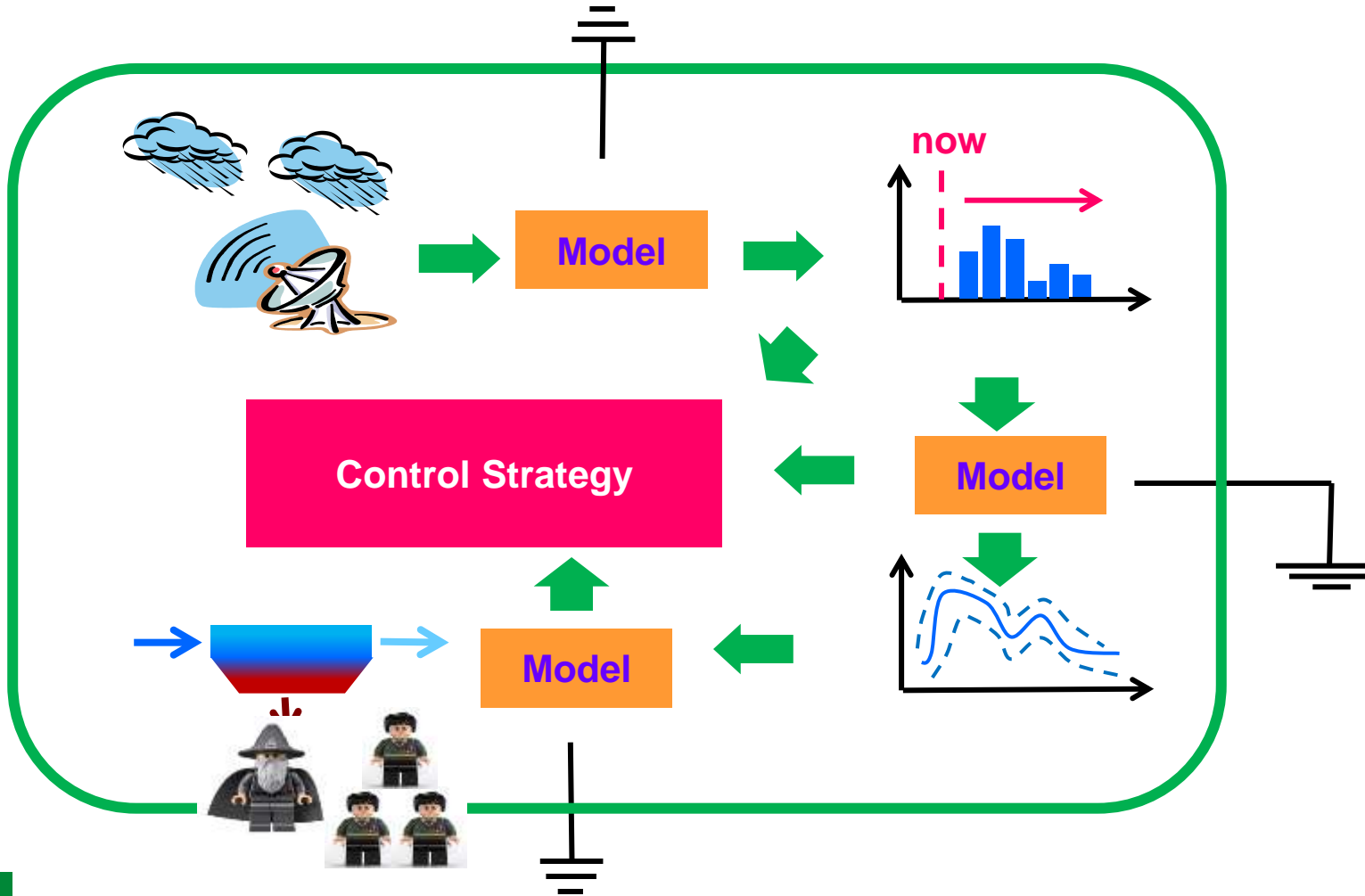
(3 days of full scale)



Measurements
+
Models
+
Forecasts
+
Uncertainty
=



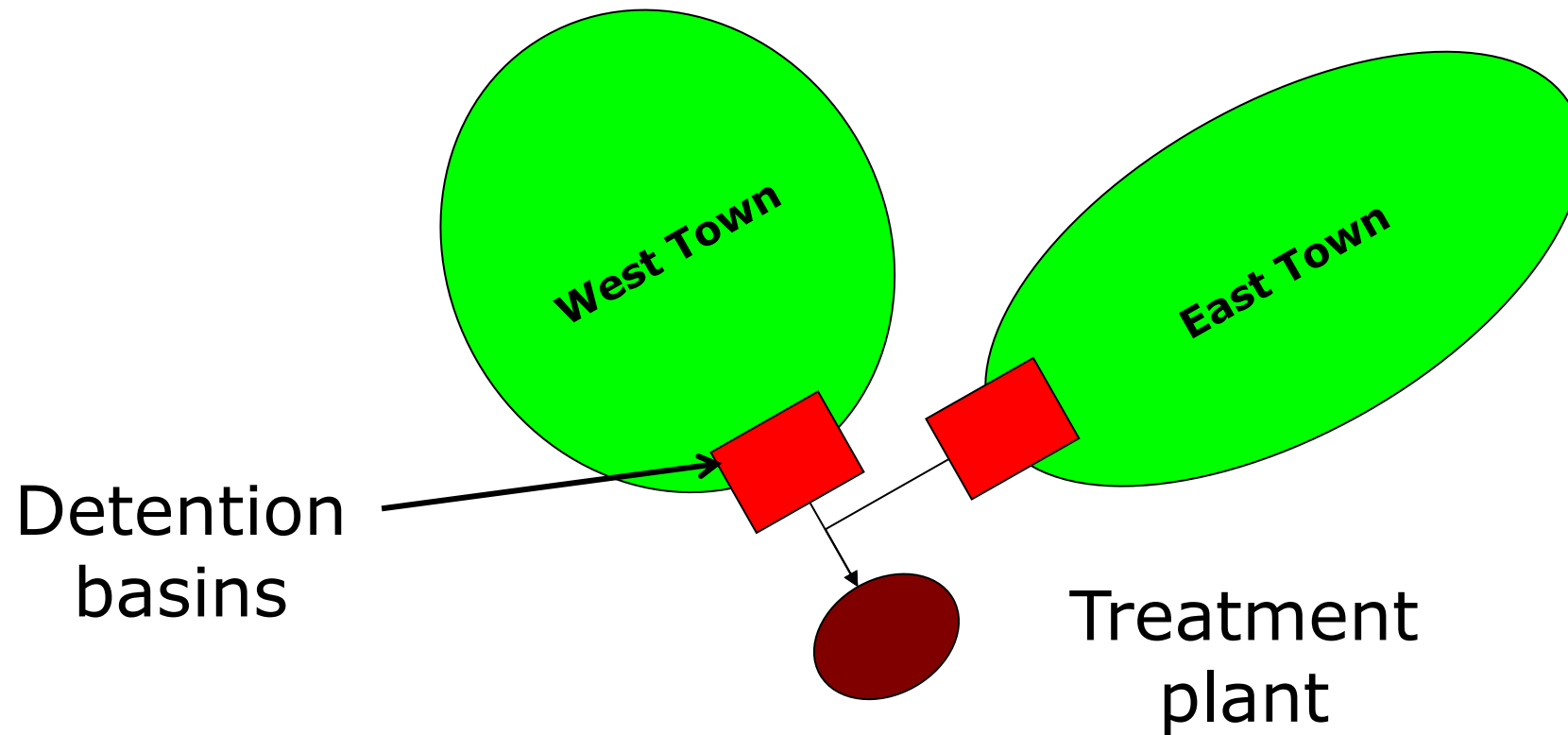
*The happy operator*



- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

# Why uncertainty matters

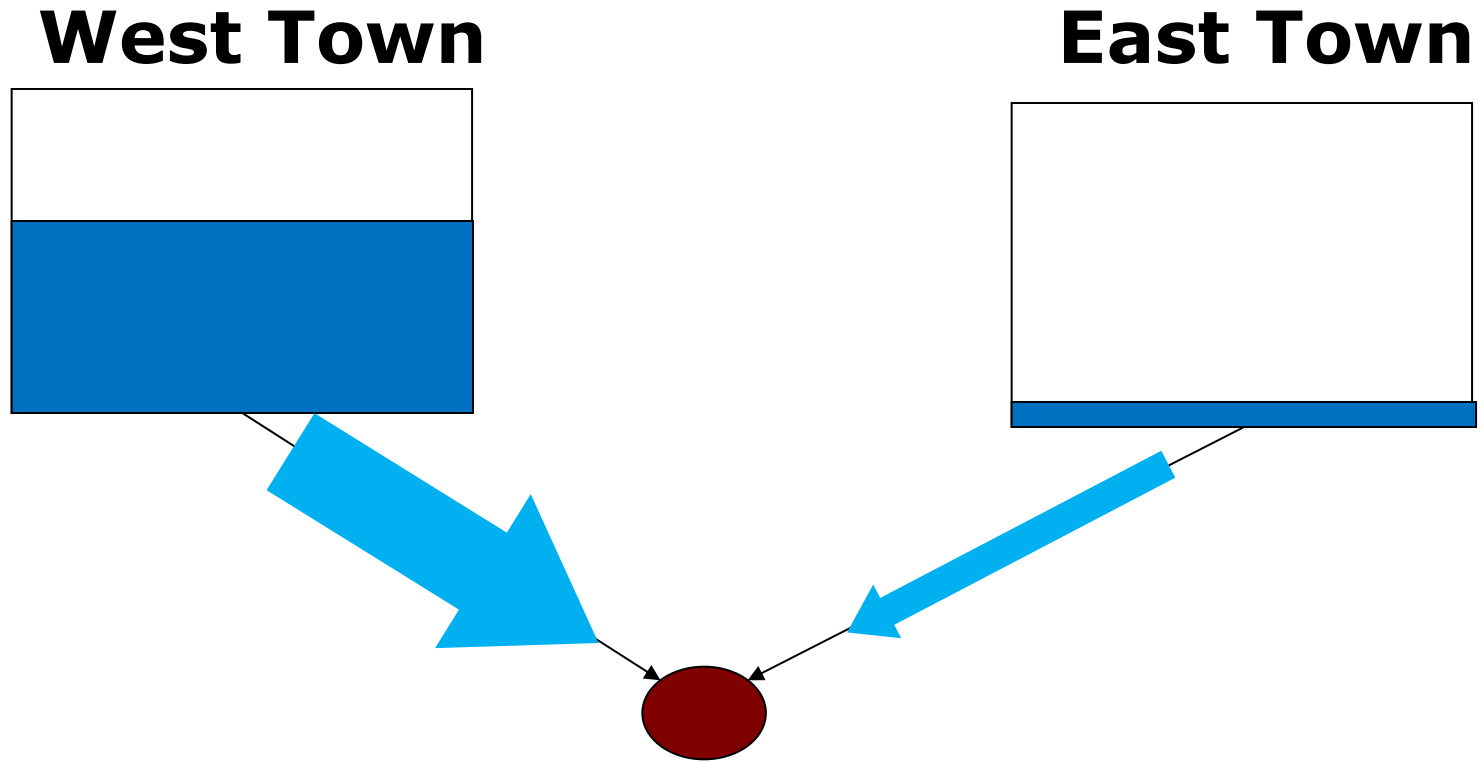
Didactical example





# Real Time Control

**Objective:**  
Maximize storage

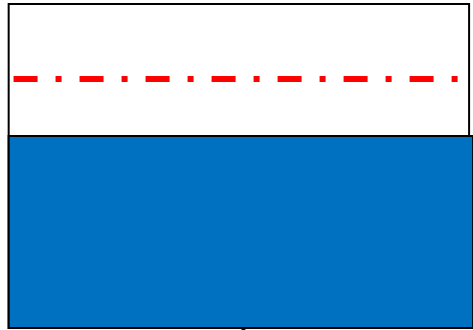


# “Traditional” MPC

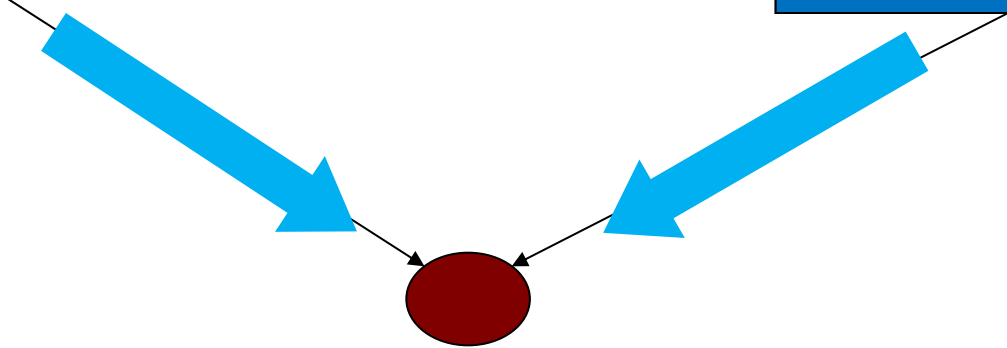
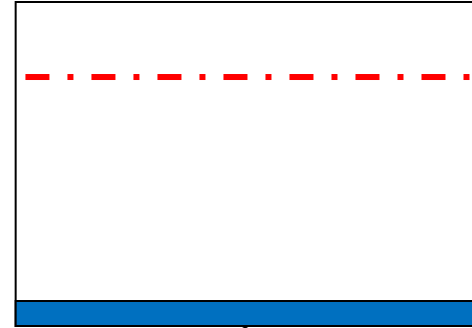
**Objective:**  
Maximize future storage

**Model forecast  
(without uncertainty)**

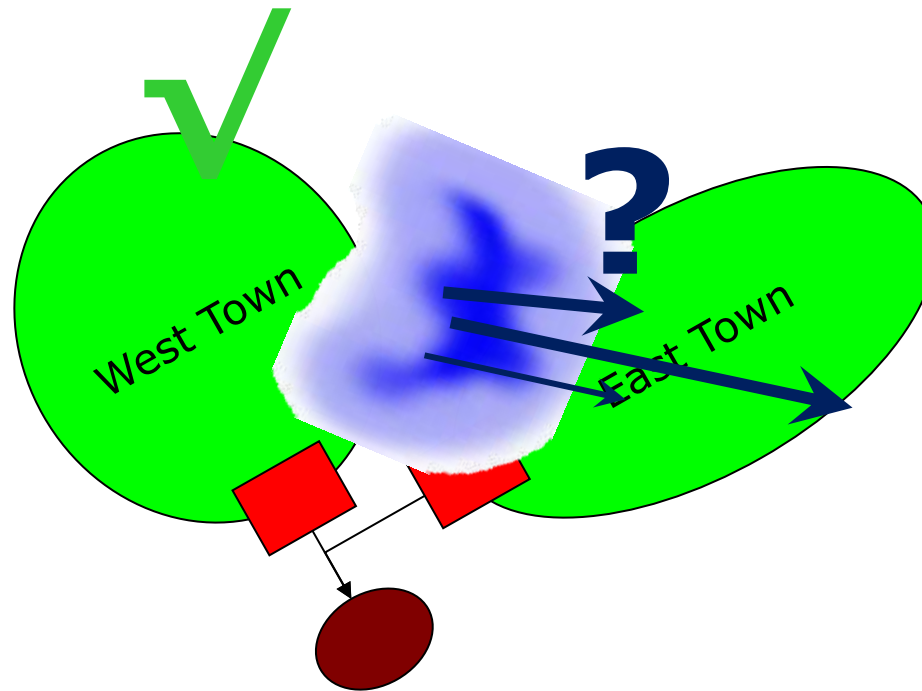
## West Town



## East Town

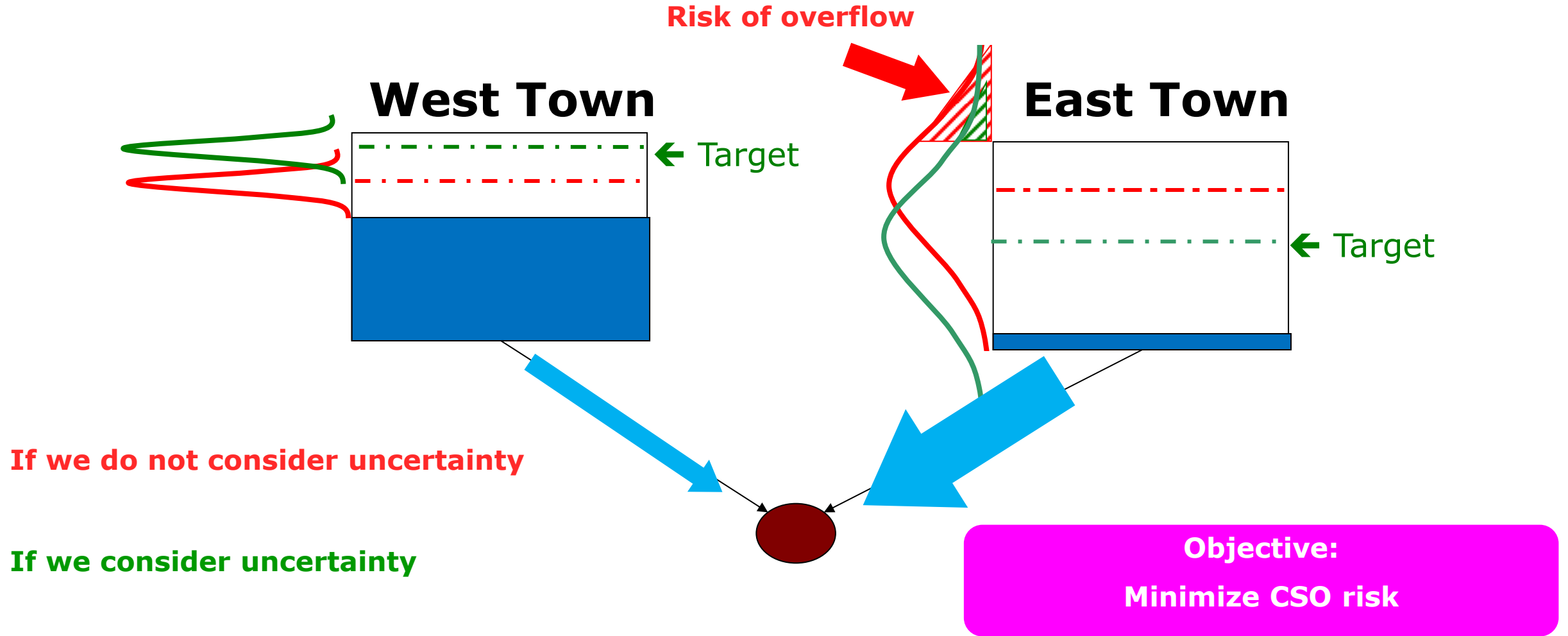


# Risk-based Model Predictive Control

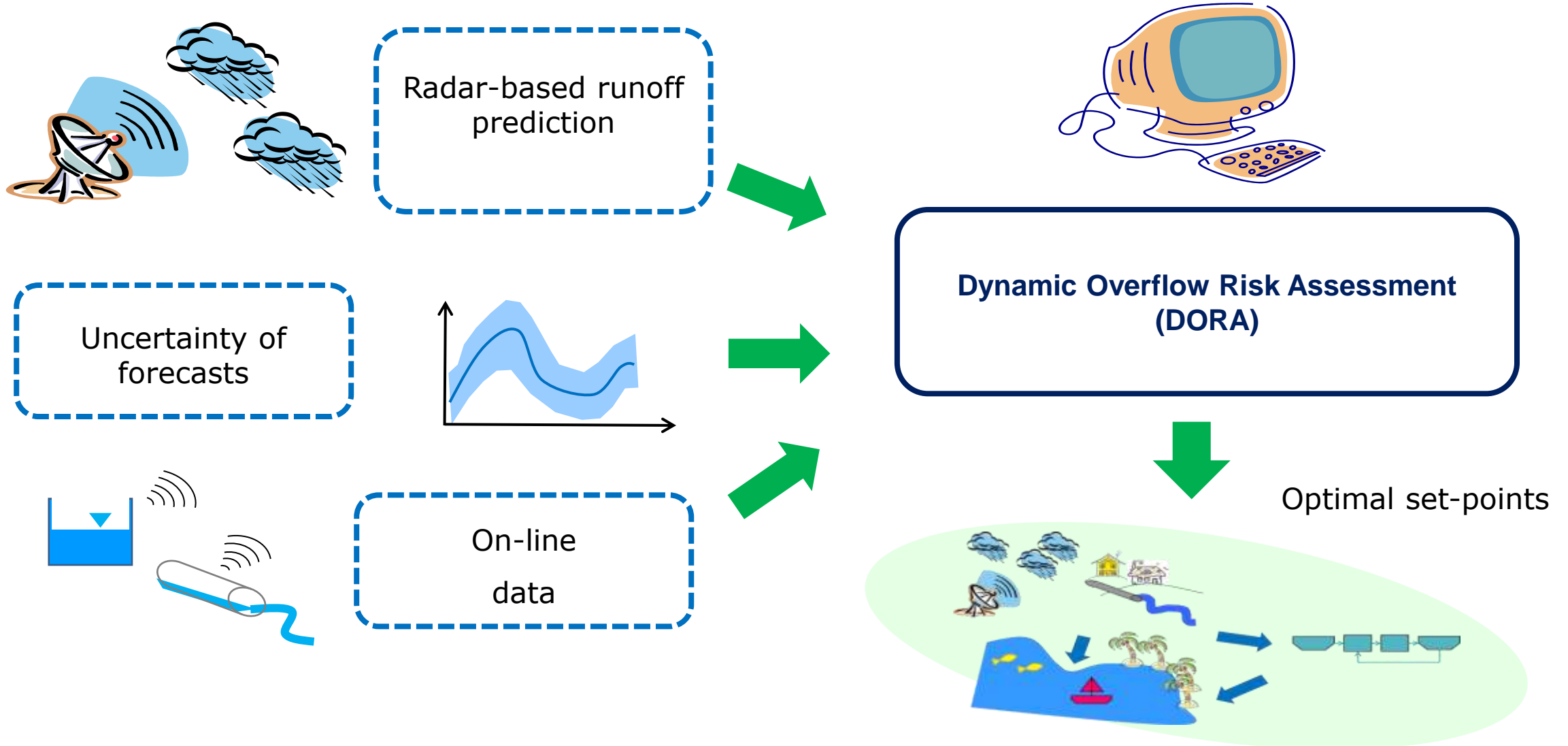


**Rainfall evolution is  
uncertain**

# Risk-based Model Predictive Control



# The Dynamic Overflow Risk Analysis (DORA)

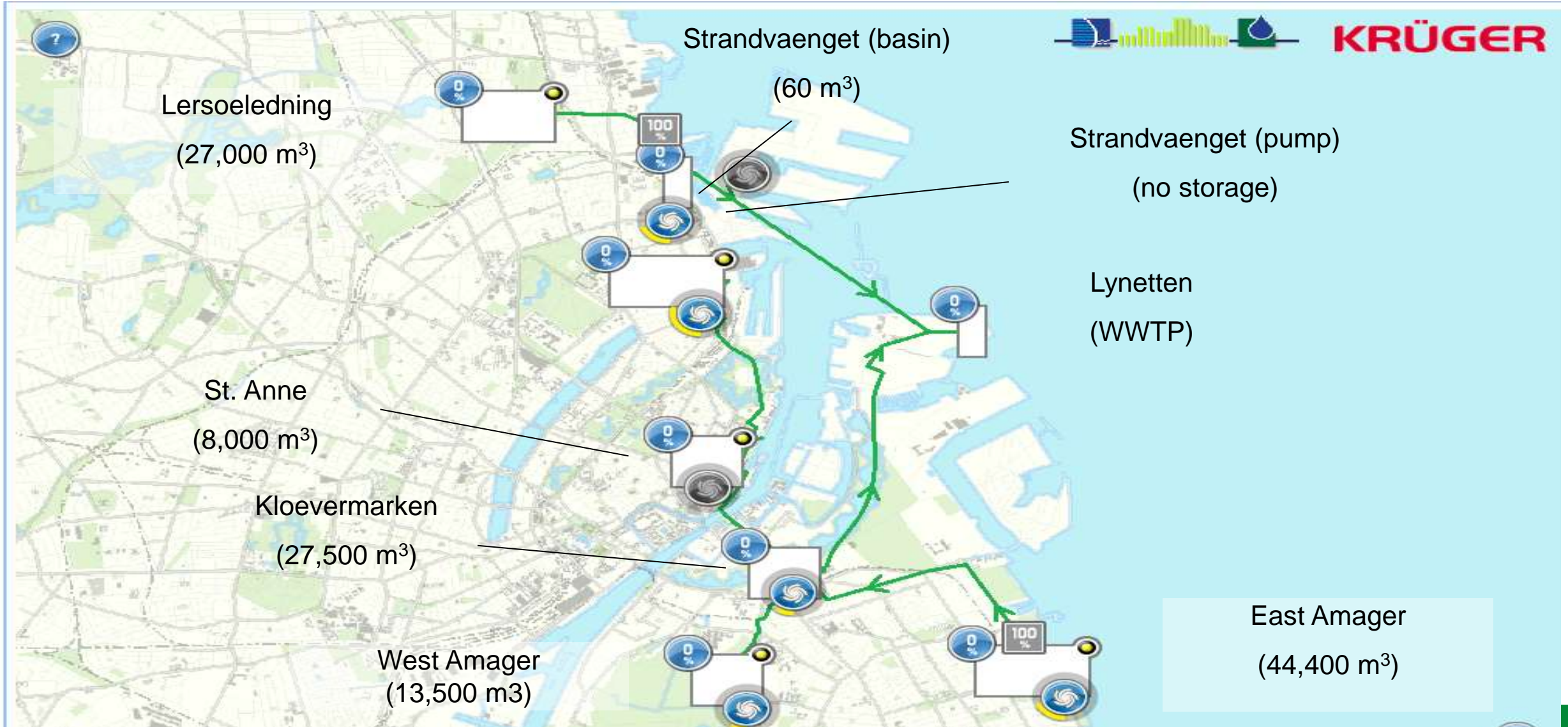






# The Lynetten catchment

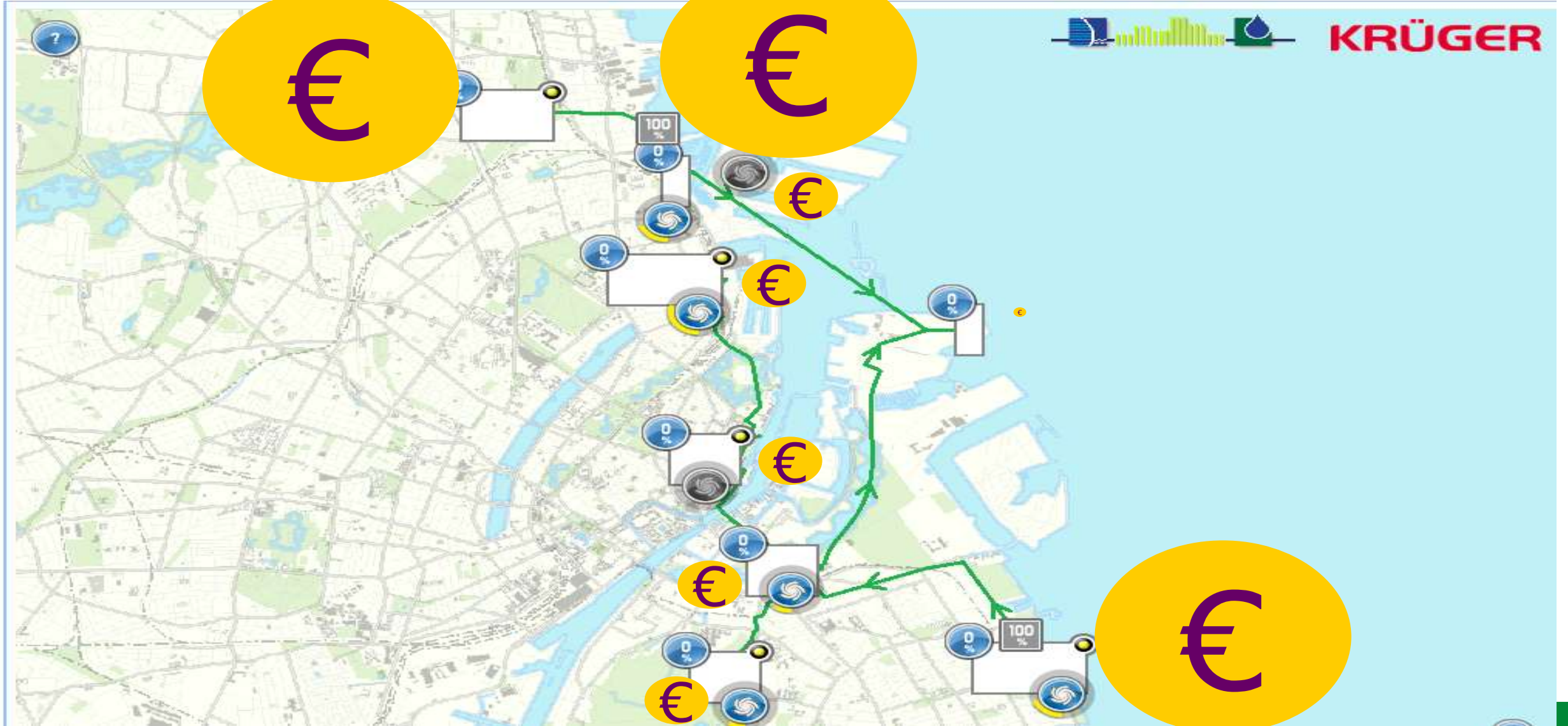
## Central Copenhagen, Denmark



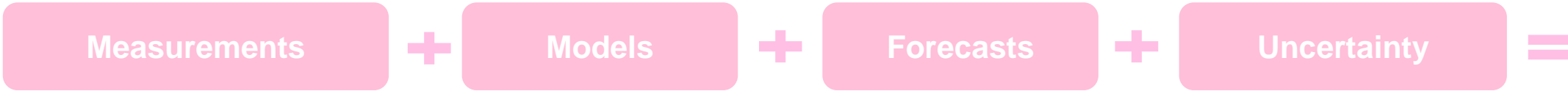


# Sensitivity of overflow recipient

CSO "price"

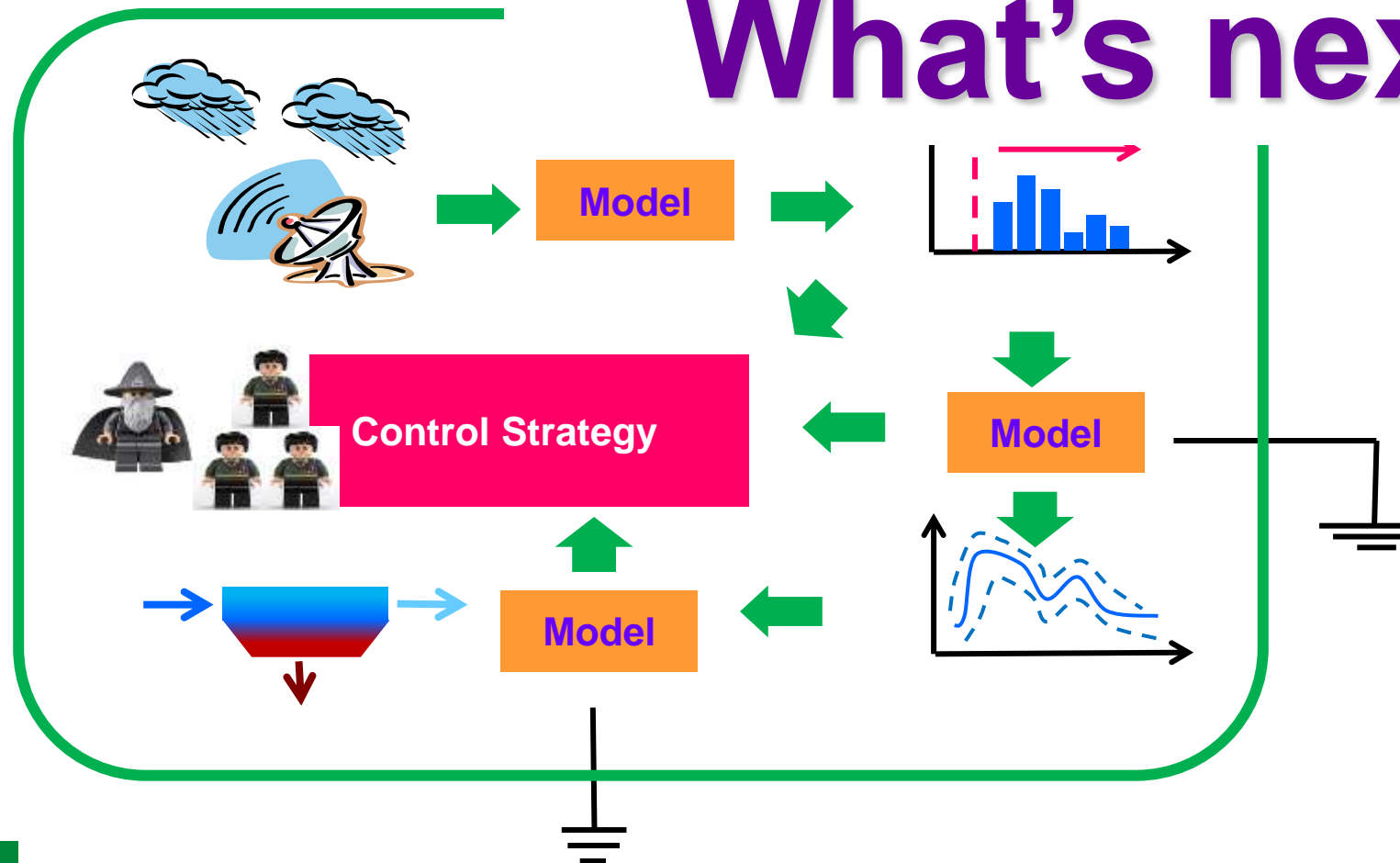






*The happy operator*

## What's next?



measurements  
in rainfall forecasts

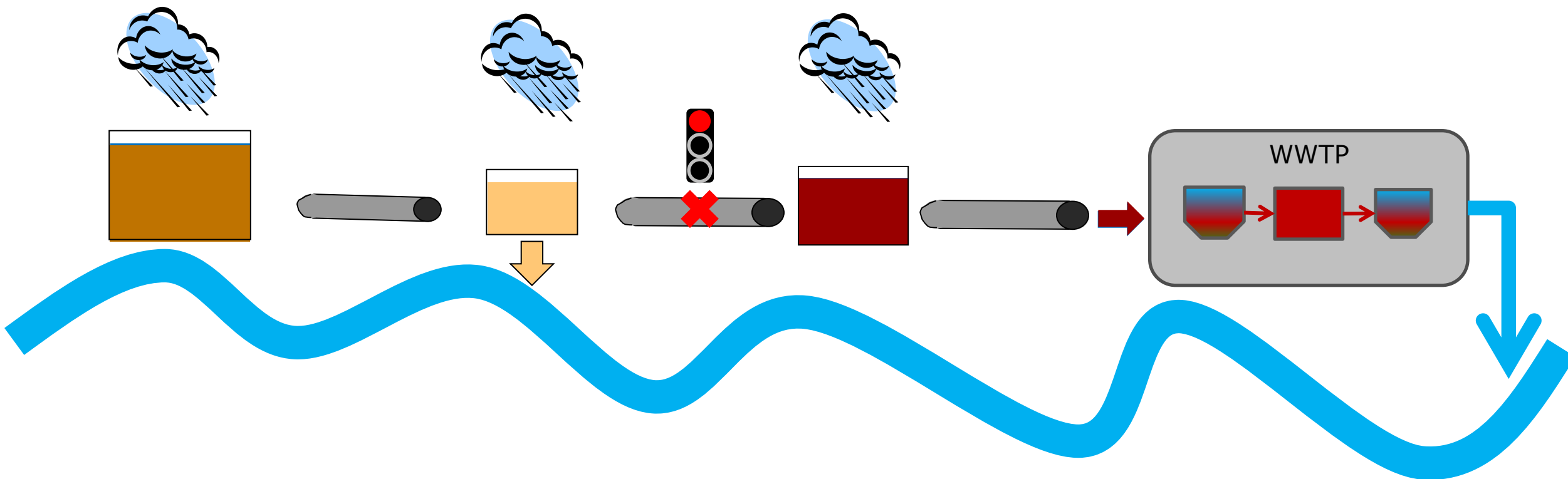
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty



# Water Quality-based control



- Pollutant concentrations are not uniform →

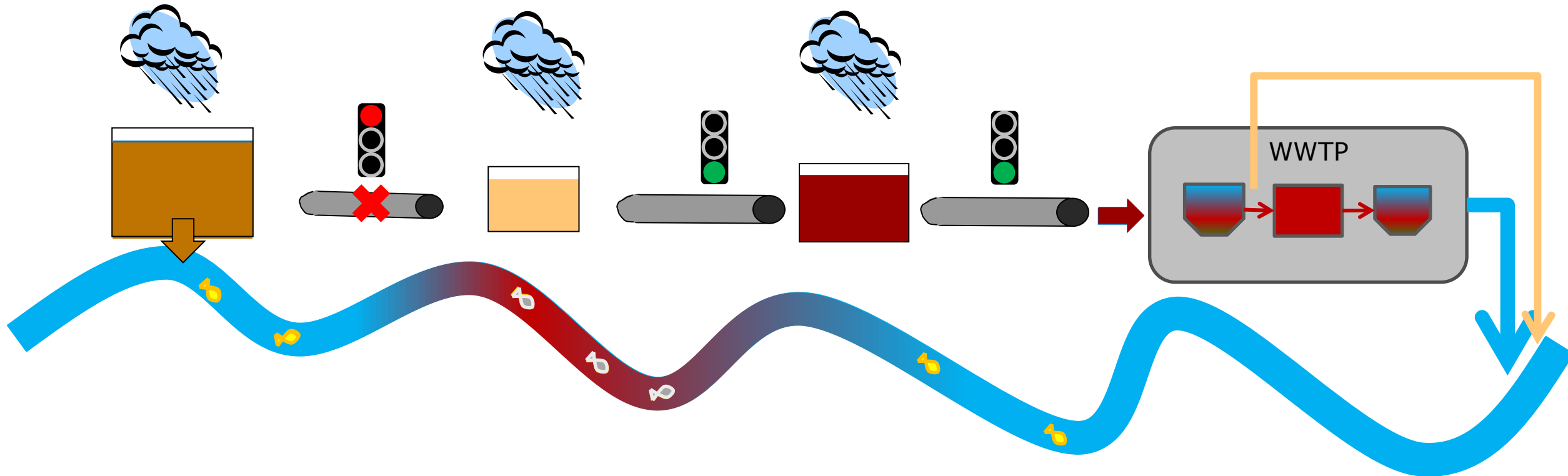




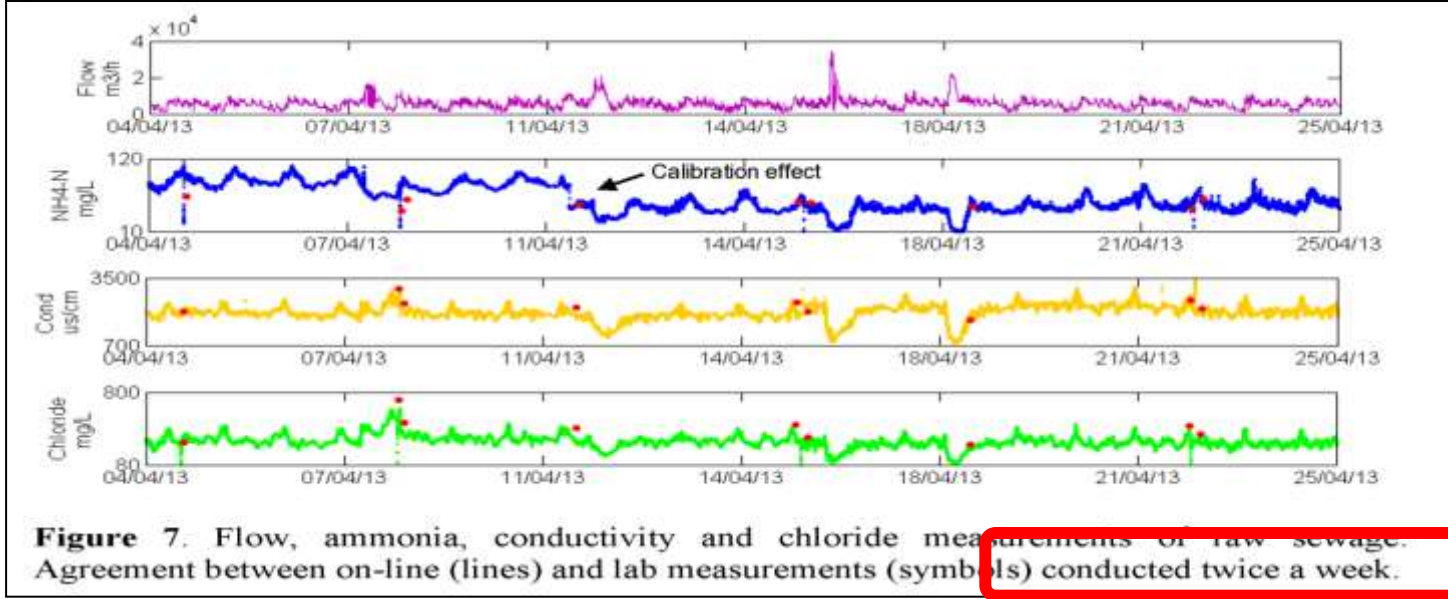
# Water Quality-based control



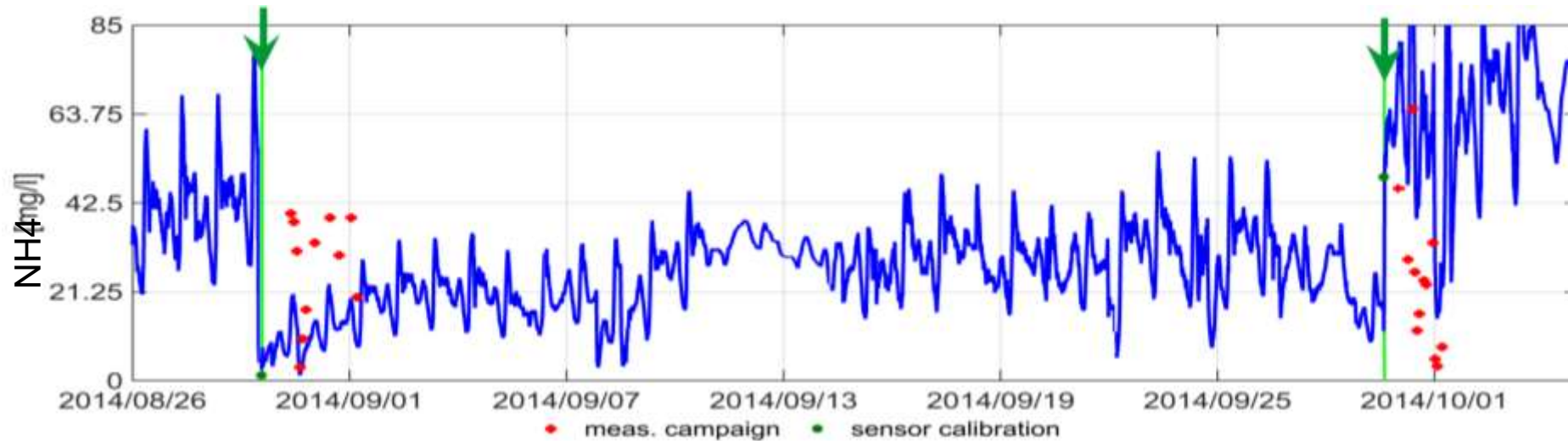
- Pollutant concentrations are not uniform → we can control the system based on Water Quality (instead of water quantity)
- The natural waters have not all the same status →



# On-line water quality data



*Alferes et al. (2014), Advanced monitoring of wastewater quality: data collection and data quality assurance, Proceedings of 13th ICUD2014*



I have thousand other things to do!



# The big challenge of online water quality measurements



Photo by Linea Sofie Skov

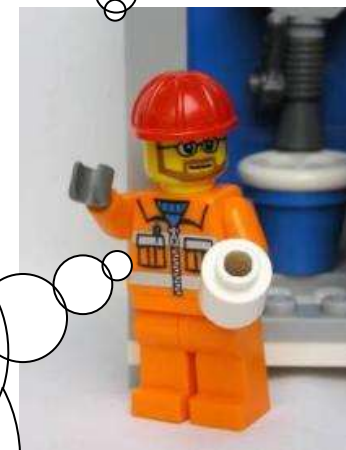


Photo by Ravi Kumar Chhetri



Sensor  
Maintenance  
Multivariate DQC  
Software Sensors  
...

WHAT????  
Which language  
is he/she  
talking?



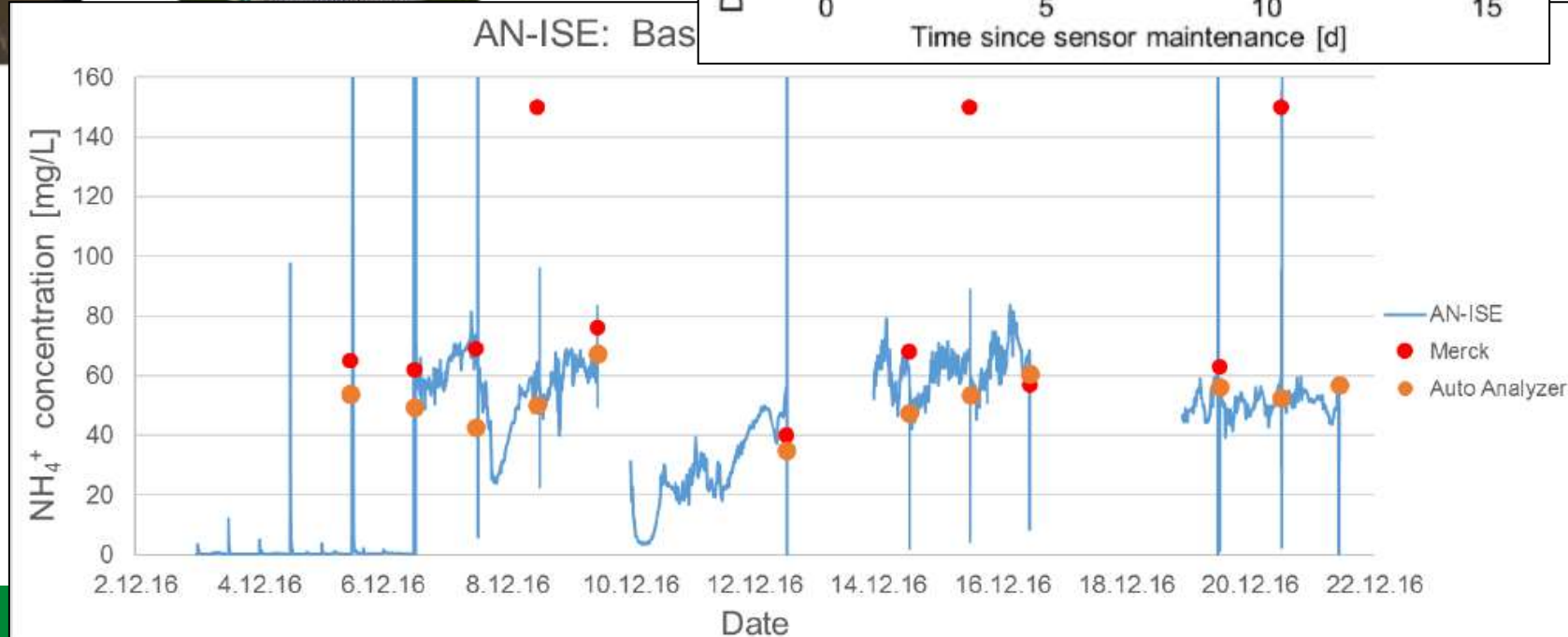
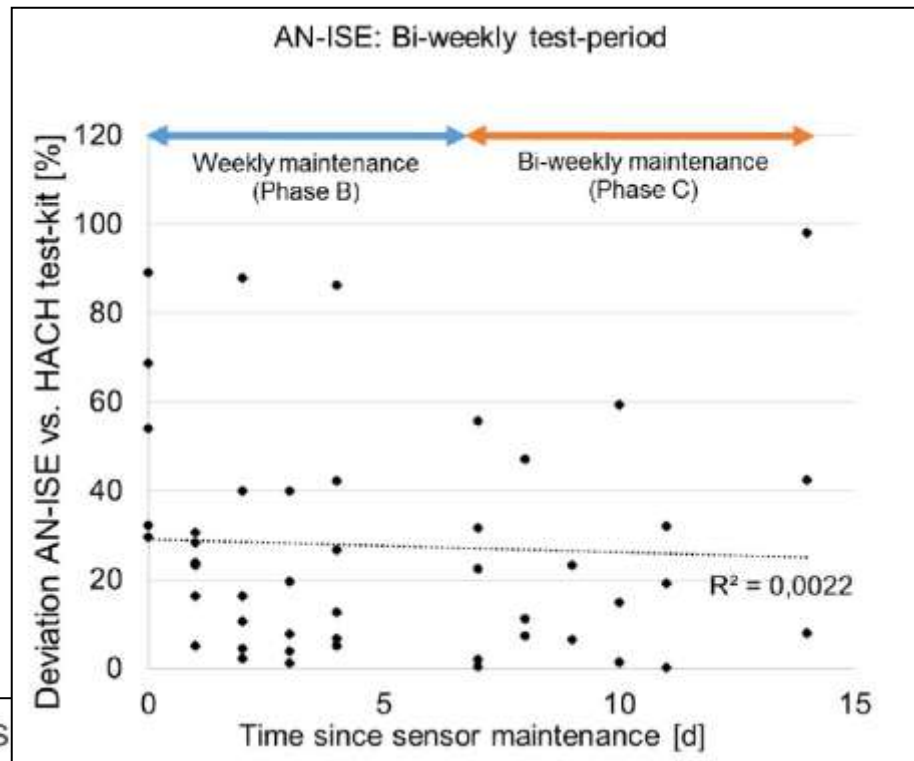
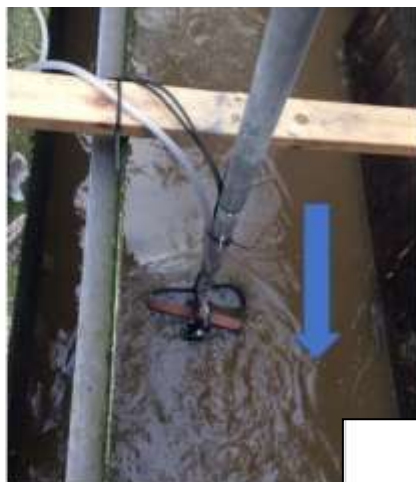


# The Ålebækken "playground"





# How much can we trust sensors?





# The importance of involving the final users



Dear smart people from university,  
what wonderful tool did you  
prepare for me?



If you use a stochastic  
differential equation...

With a genetic algorithm  
which minimizes risks you  
will....



We have an Extended Kalman  
Filter to assimilate data and...



??????

Can you please make a  
if-then scheme of you  
advanced control?

Thanks, but my system  
works fine as it is

# The importance of involving the final users



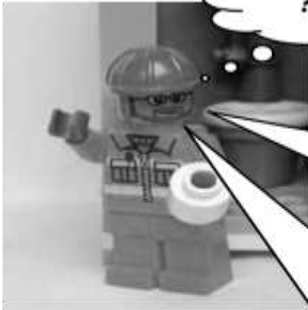
Dear smart people from university, what wonderful tool did you prepare for me?



If you use a stochastic differential equation...



- Making a smart tool is not enough – you need somebody ready to use it
- Collaboration between universities and final user is essential



???????

will....

Can you please make a if-then scheme of you DORA?



We have an Extended Kalman Filter to assimilate data and...

Thanks, but my system works fine as it is

# Conclusions

towards a better environment with smarter sewer systems



- We can have a better environment if we use our sewers in a smarter way
- We have now new tools for on-line model-based operation of integrated urban wastewater systems (more than 10 years of research/development)

Measurements



Models



Forecasts



Uncertainty



*The happy operator*



# Thank you for listening!



**A Combined Sewer  
Overflow**

**An overflow  
expert**

luve@env.dtu.dk