



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

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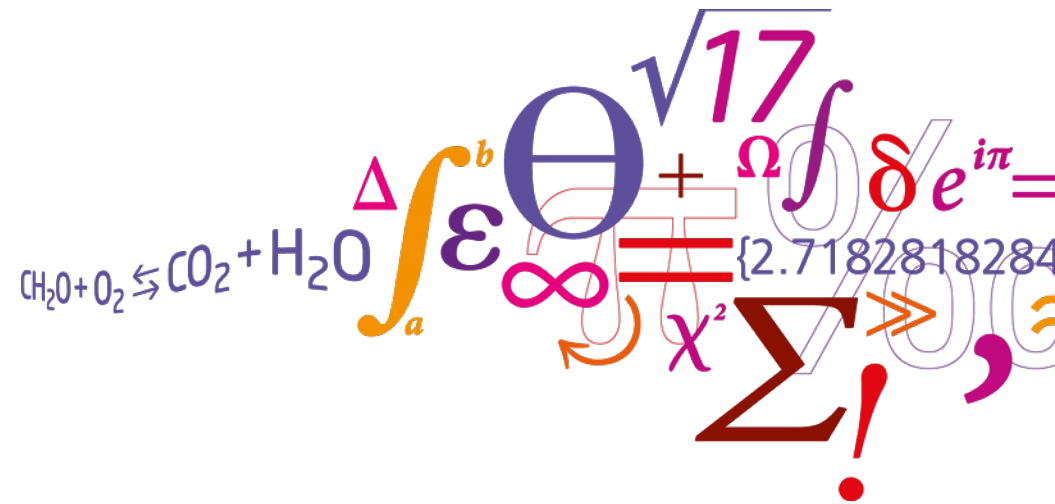
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# Kan vi få et bedre miljø med smartere kloakker?

Lektor Luca Vezzaro

Forskning Døgn

Slagelse, d. 26. april 2018



# 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)
- Jeg arbejder på DTU Miljø, hvor jeg forsker i styring og modellering af afløbssystemer
- Deltid ansat hos Krüger Veolia A/S (jeg tager forskning ud i "den virkelige verden")

DTU

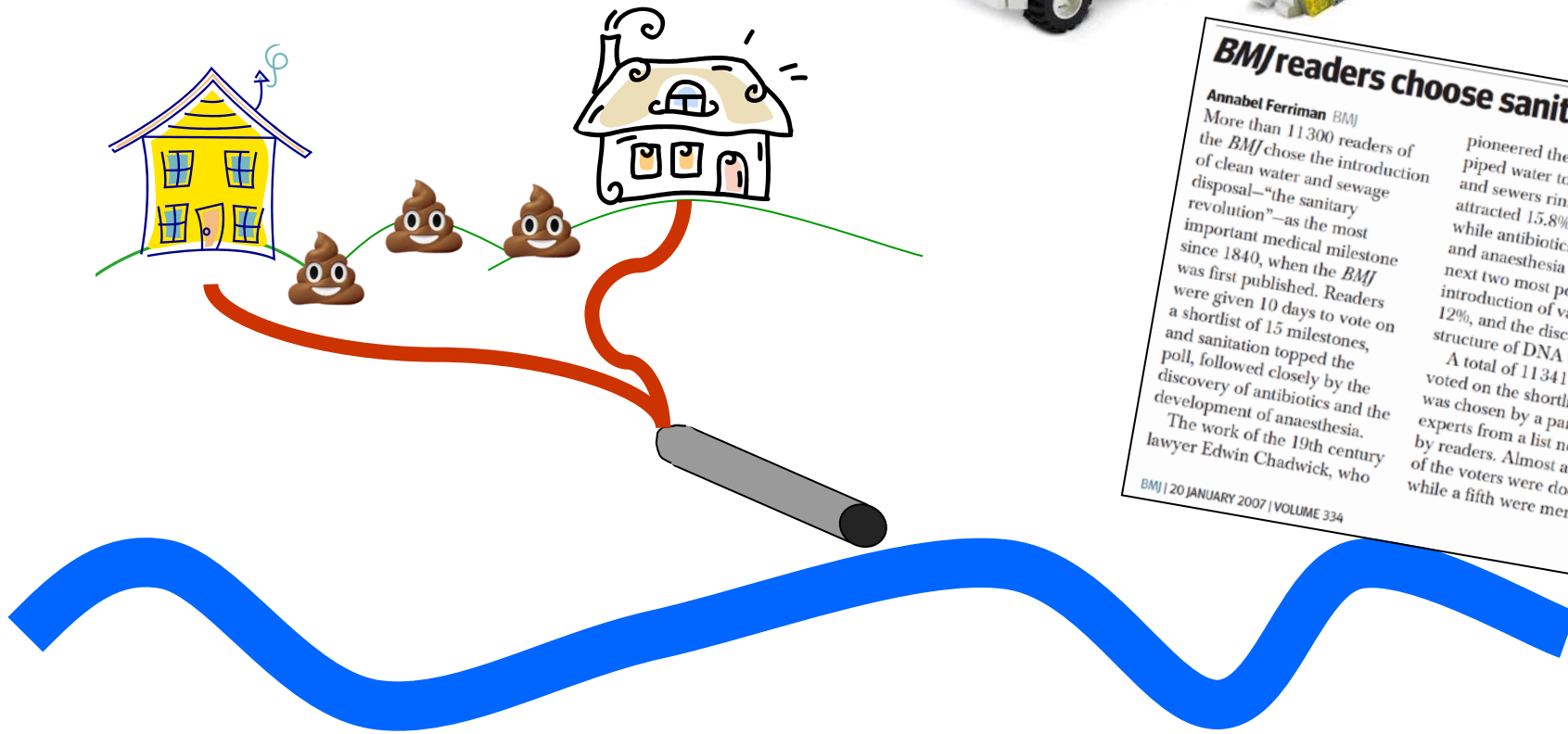
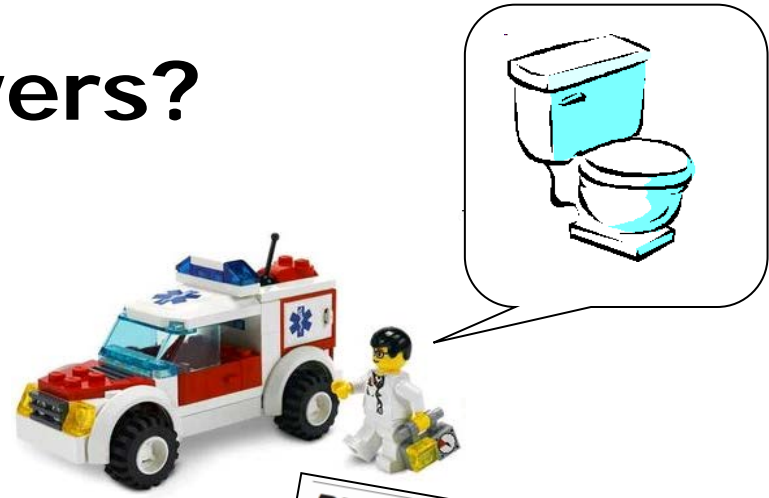




# Why do we have sewers?

# 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.

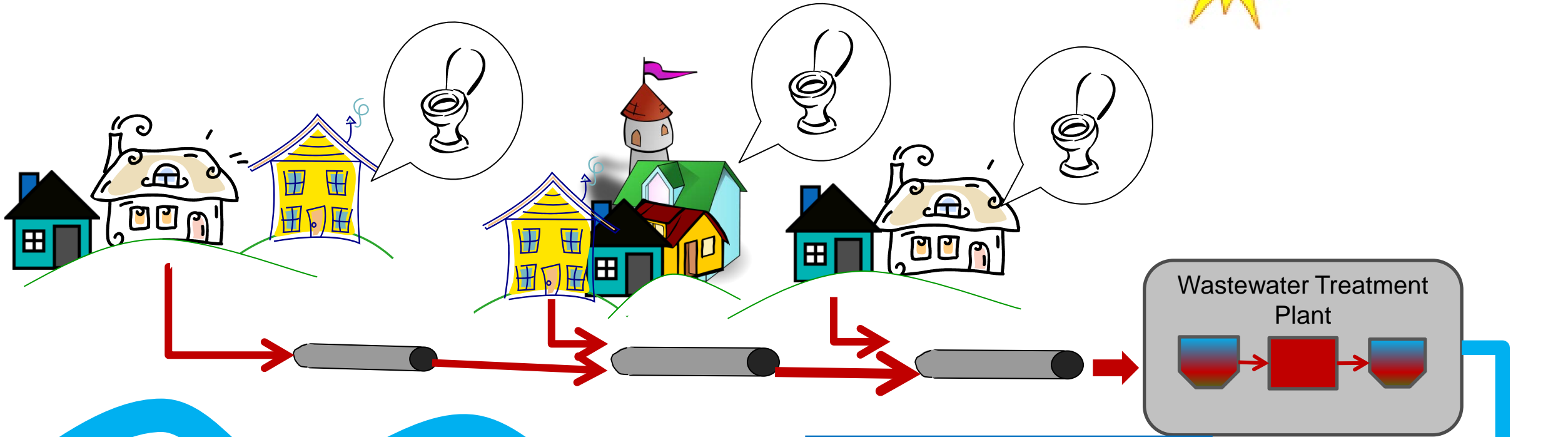
"Inadequate sanitation is still a major problem in the developing world."

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

BMJ | 20 JANUARY 2007 | VOLUME 334

111

# Our cities when sun is shining...



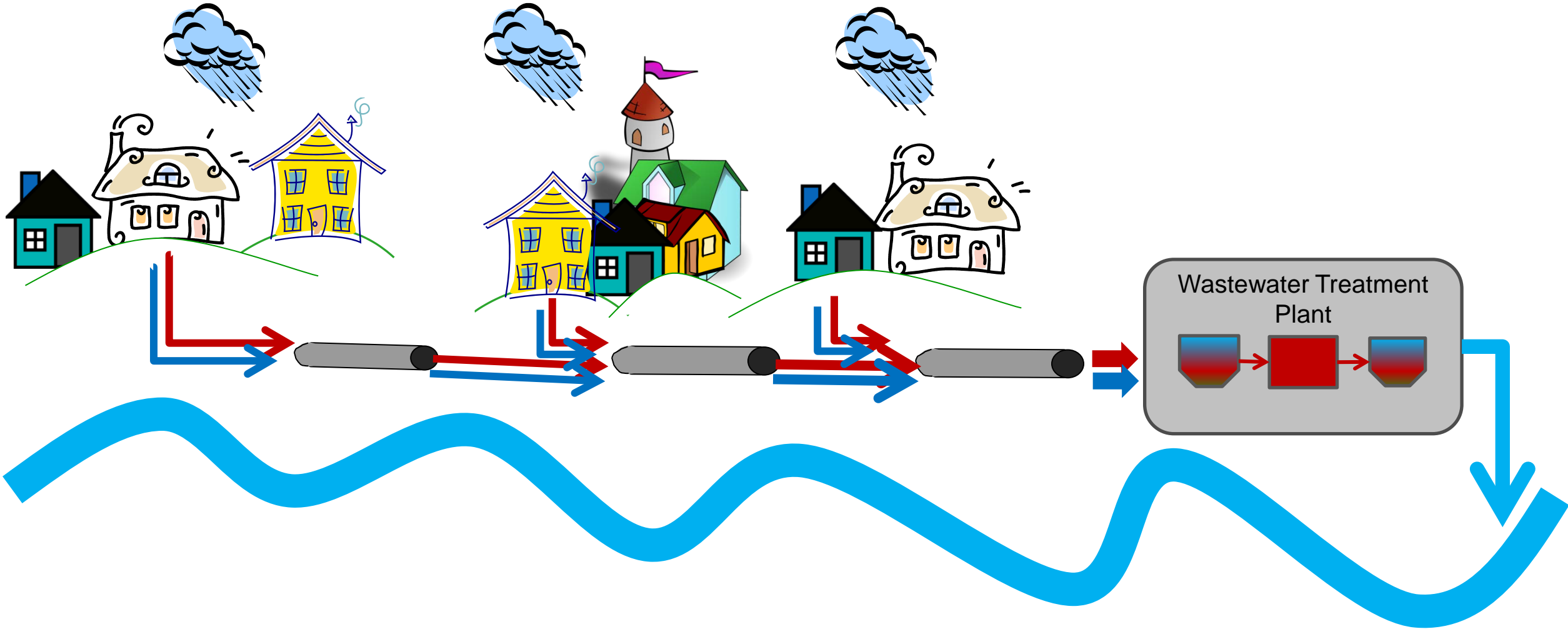
From [www.aldrigsur.dk/ved-stranden](http://www.aldrigsur.dk/ved-stranden)



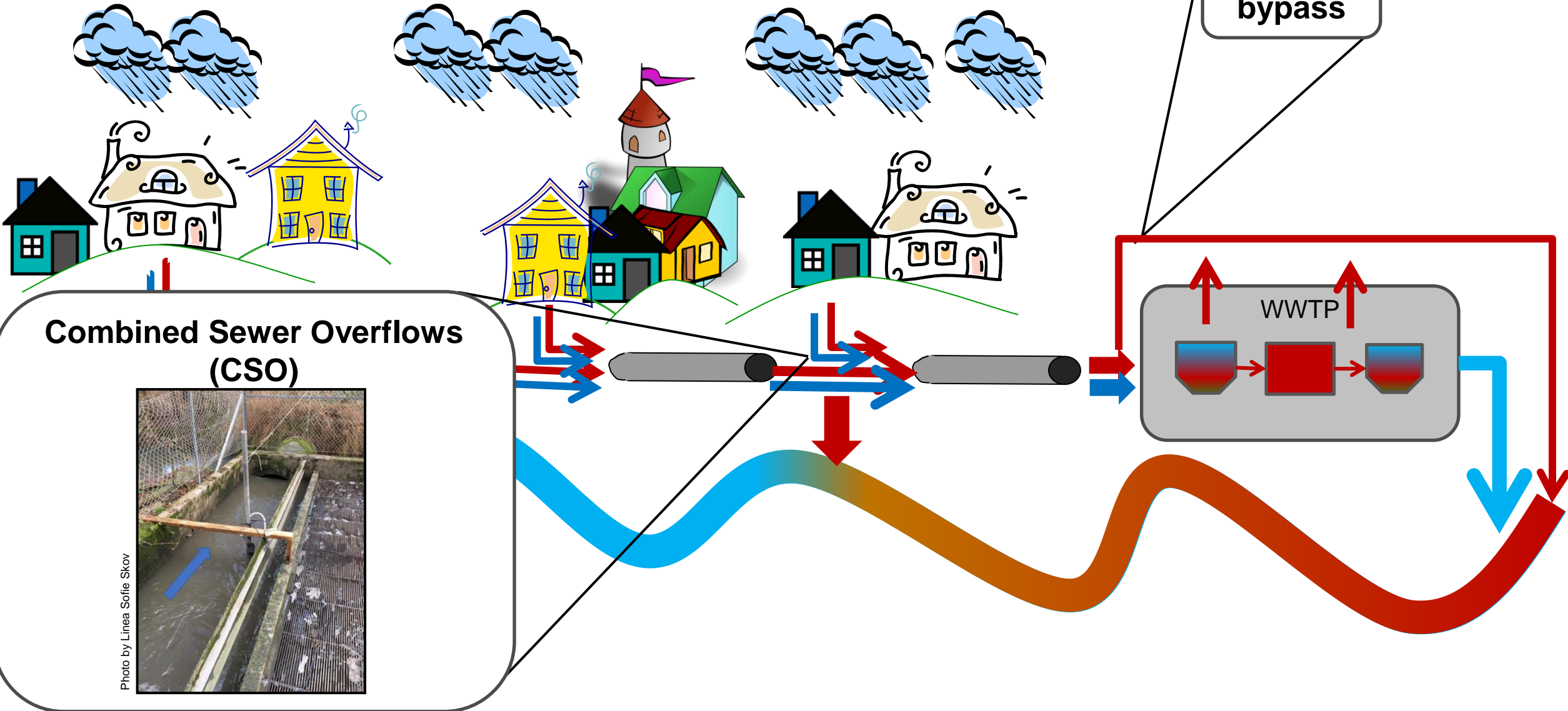
From <http://natmus.dk/museerne/brede-vaerk/>



...but sometimes it rains...



# ...and it rains more...

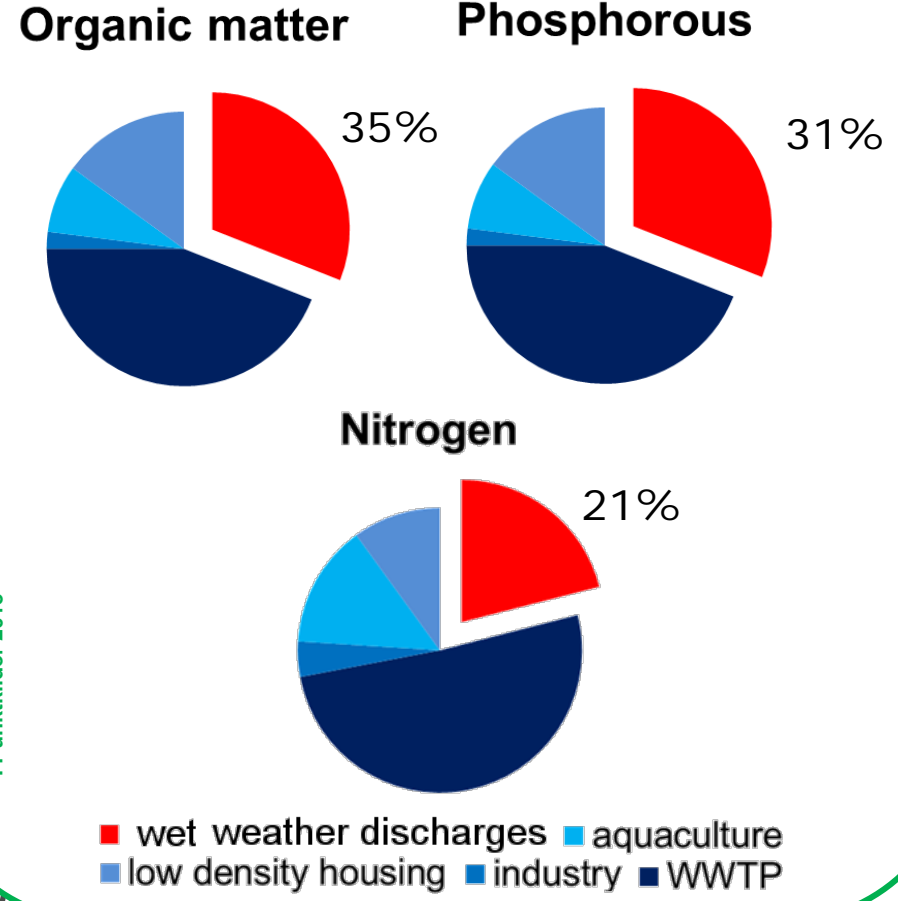




# ...and it rains more...



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

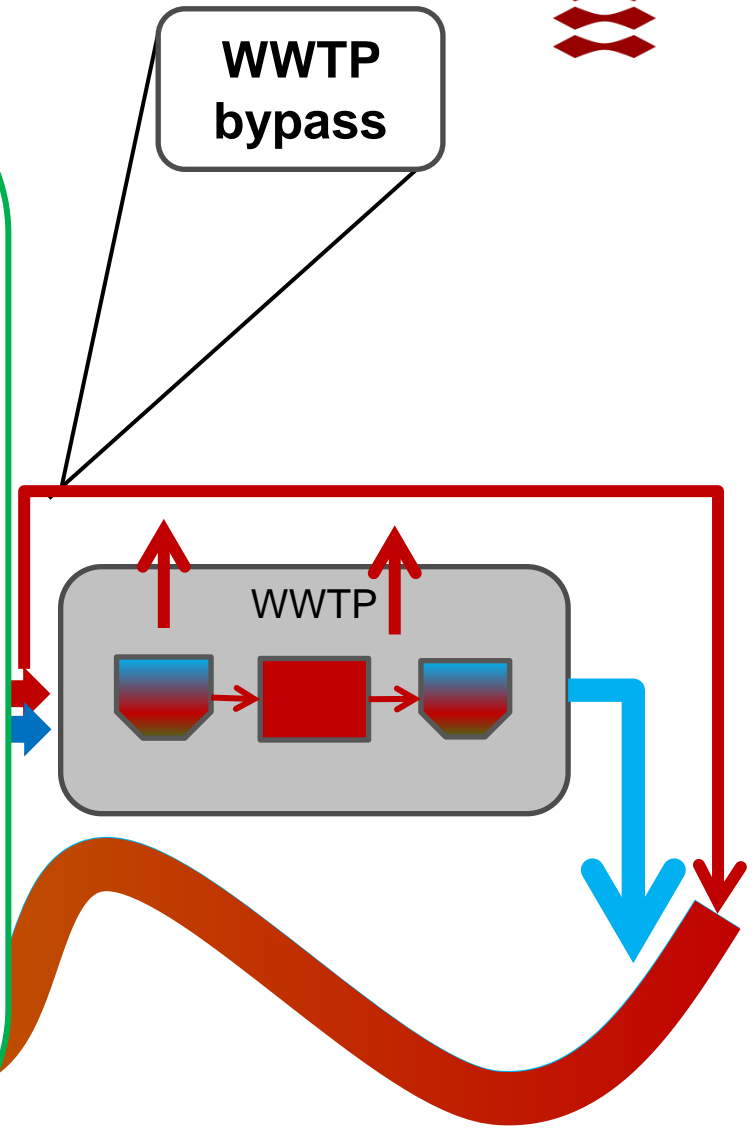


Source: Miljø- og Fødevarerministeriet Styrelsen for Vand- og Naturforvaltning (2017). Punktkilder 2015

## Combined Sewer Overflows (CSO)



Photo by Linea Sofie Skov



# ...and it rains more...



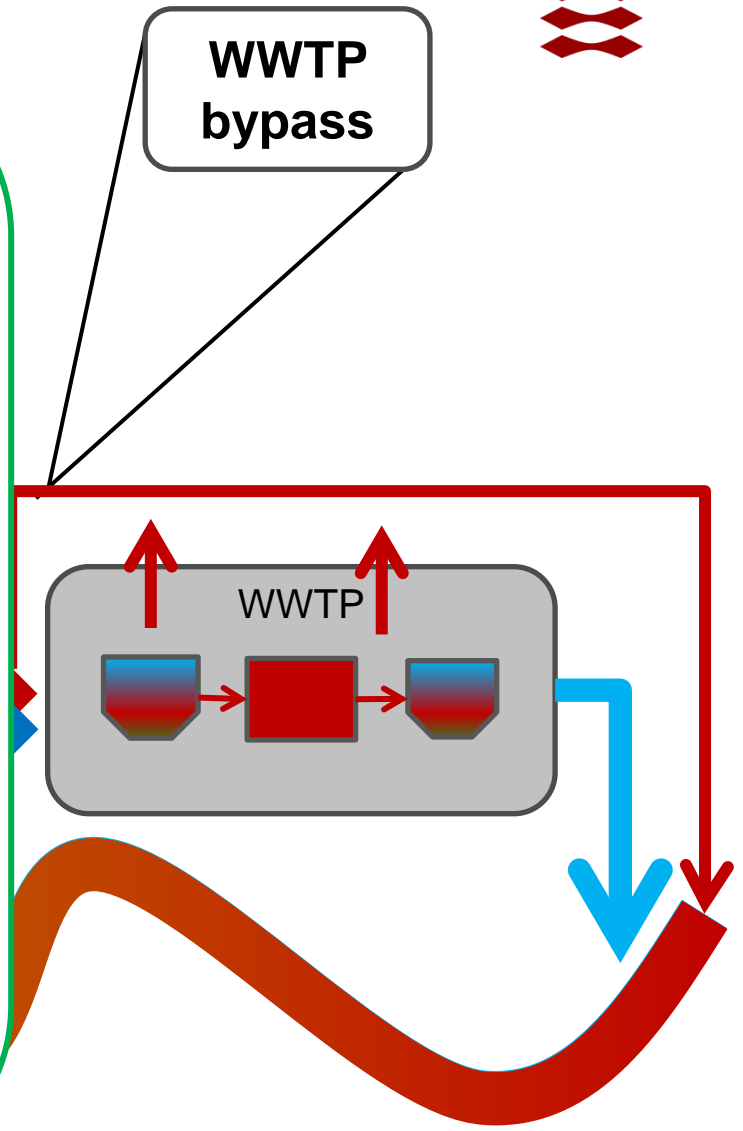
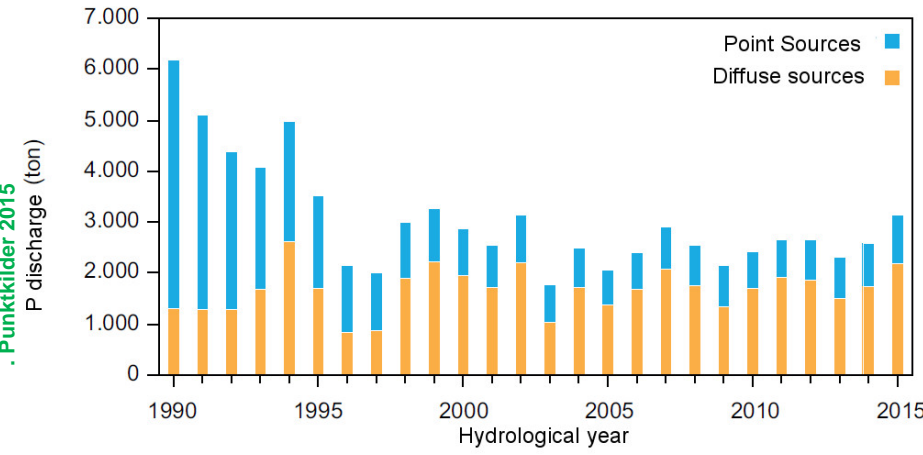
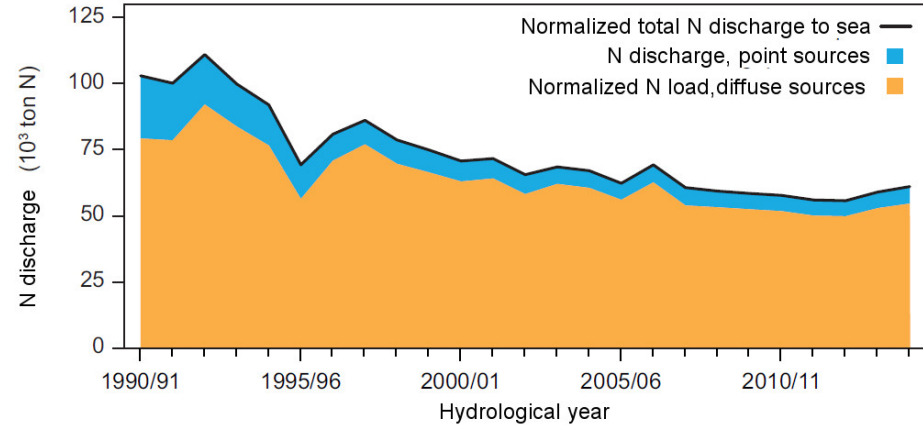
## Combined Sewer Overflows (CSO)



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Source: Miljø- og Fødevareministeriet Styrelsen for Vand- og Naturforvaltning (2017)  
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## Pollutant contribution from point discharges in DK

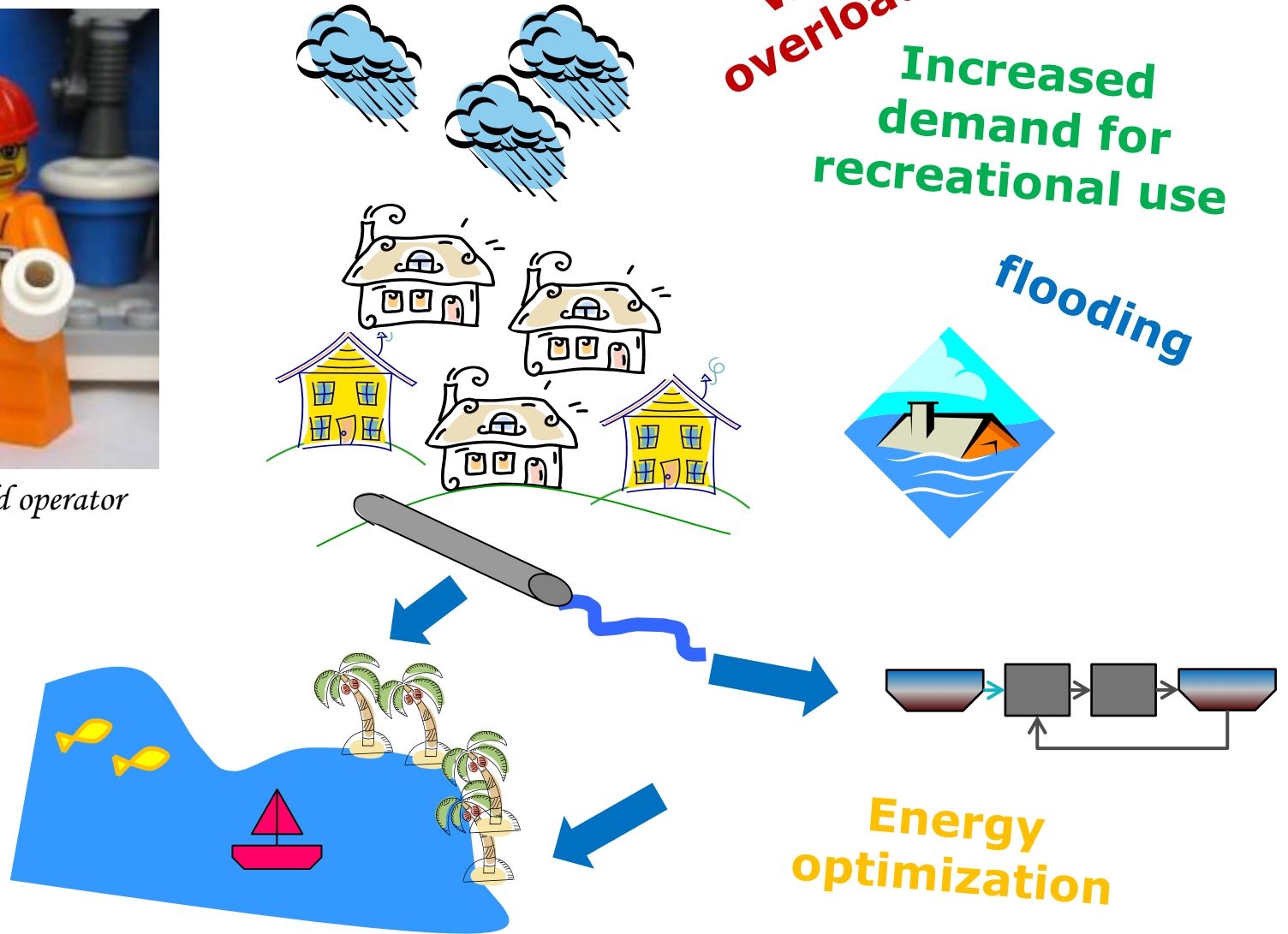
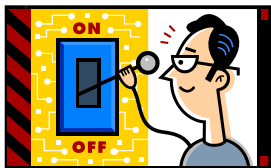


WWTP bypass

# Once upon a time in Denmark



*The good old operator*





# 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

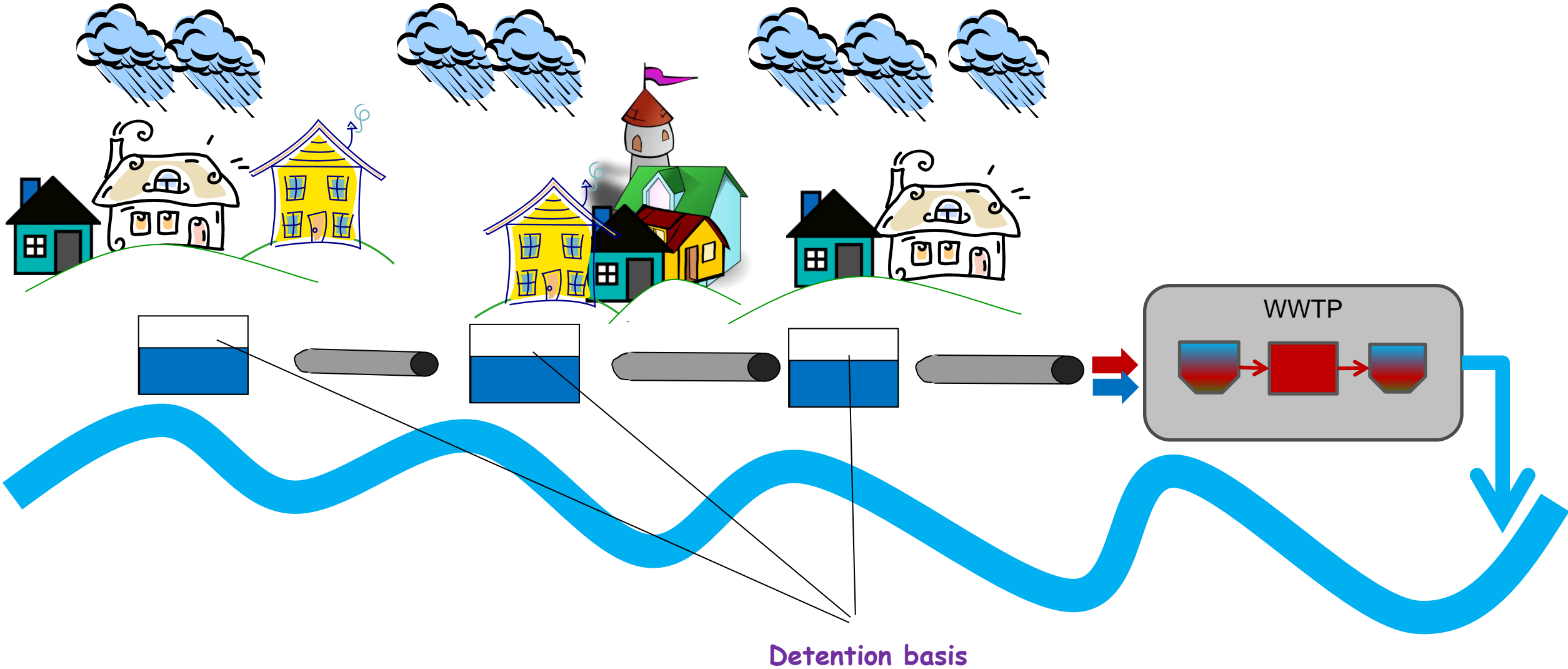
- Storm- and Wastewater Informatics (SWI)
- Klimaspring
- Prepared
- AMOK
- Water Smart Cities



- Industrial PhDs
- Industrial postdocs
- Many MSc theses



# One option to avoid overflow...

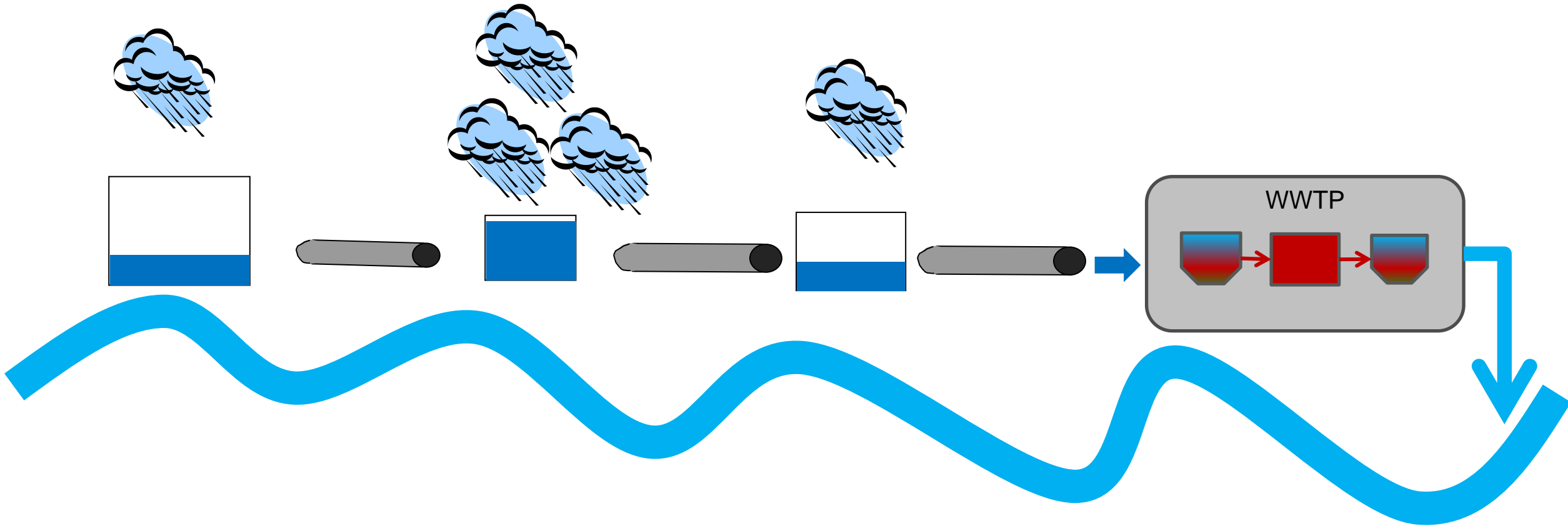


DTU



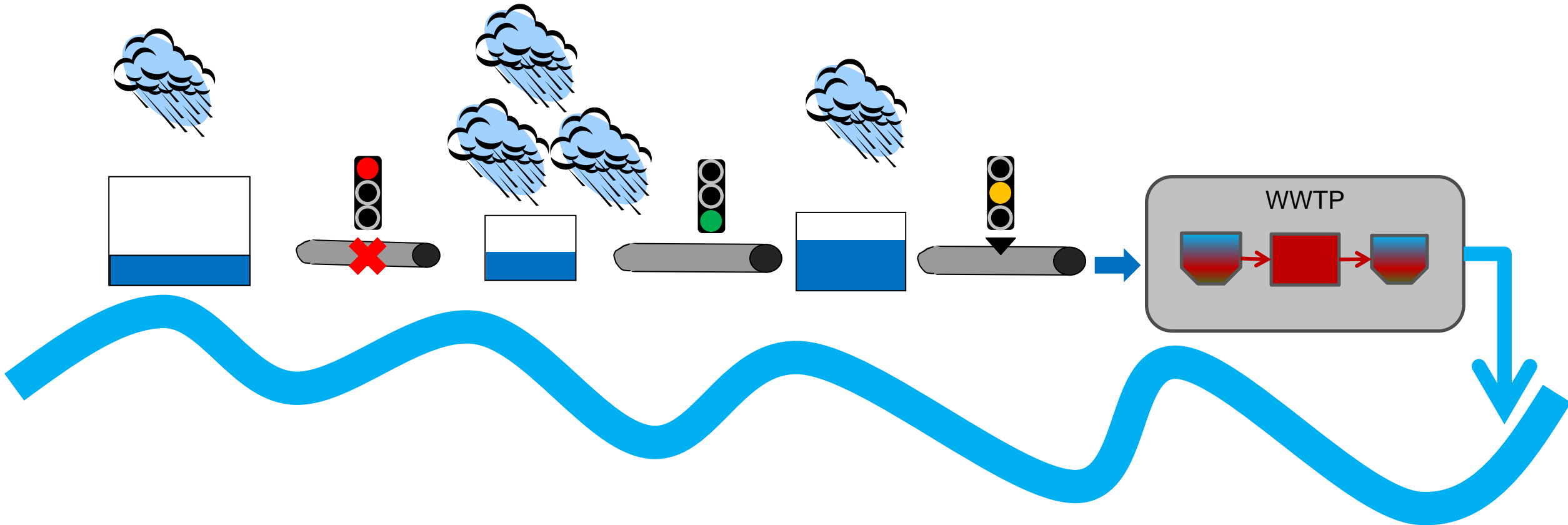
# Real Time Control of drainage network

- 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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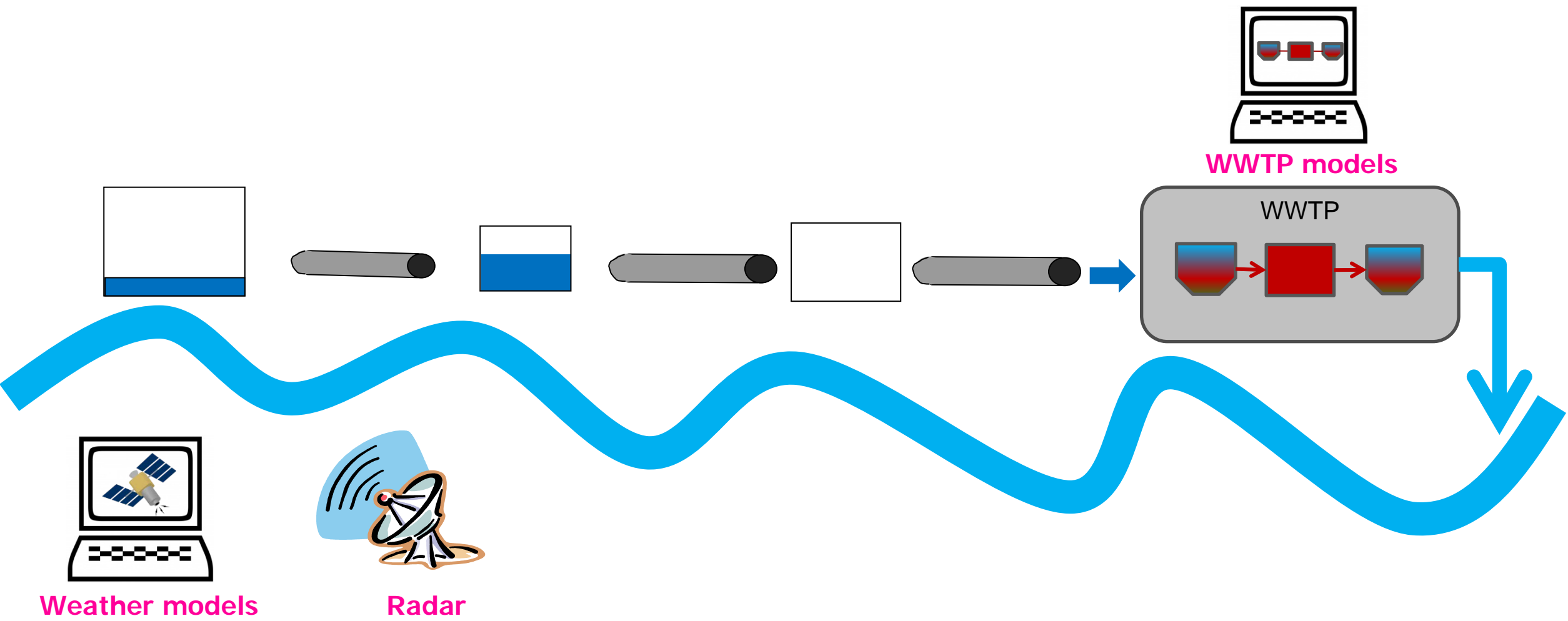


DTU



# Model Predictive Control

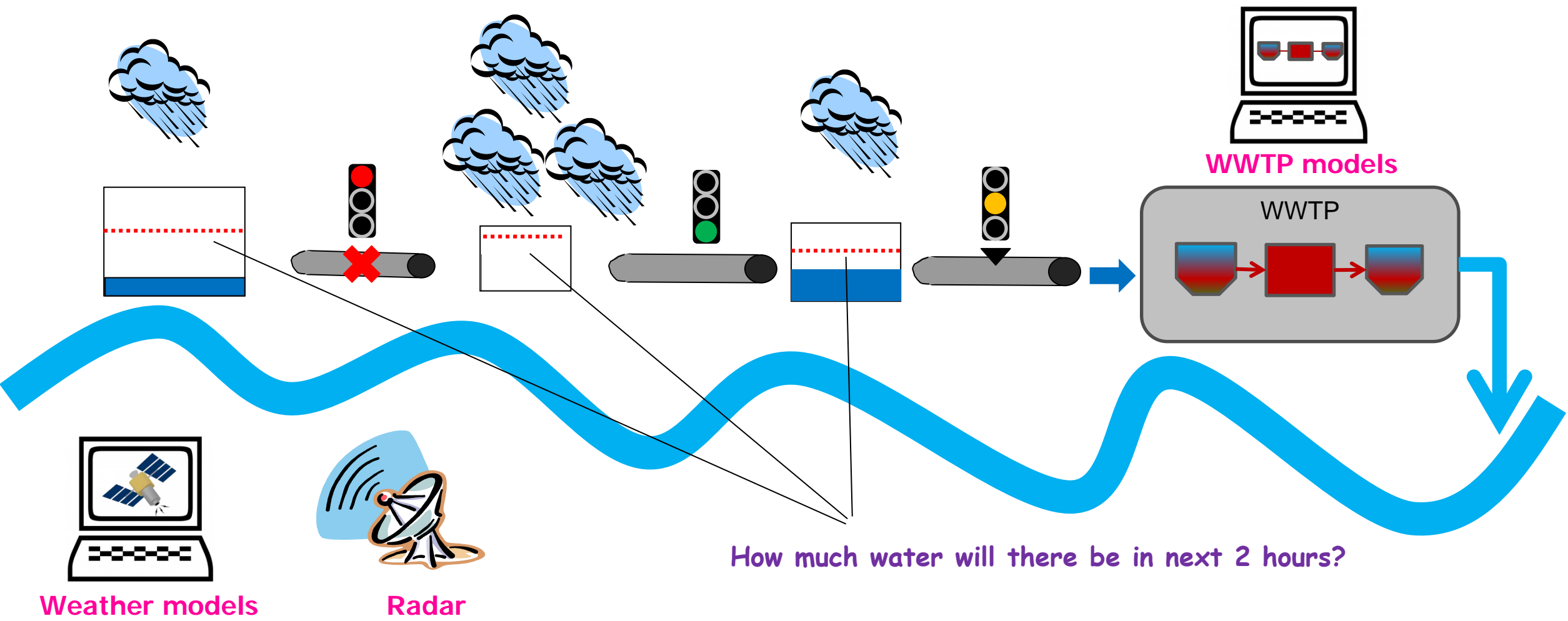
- We can forecast rainfall → where and how much is going to rain → even less CSO
- We can forecast WWTP status → how much water the WWTP can treat → even less bypass



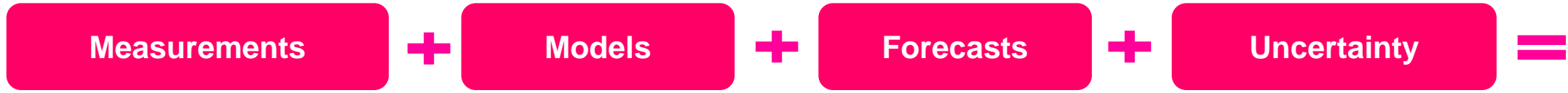


# Model Predictive Control

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# The SWI concept

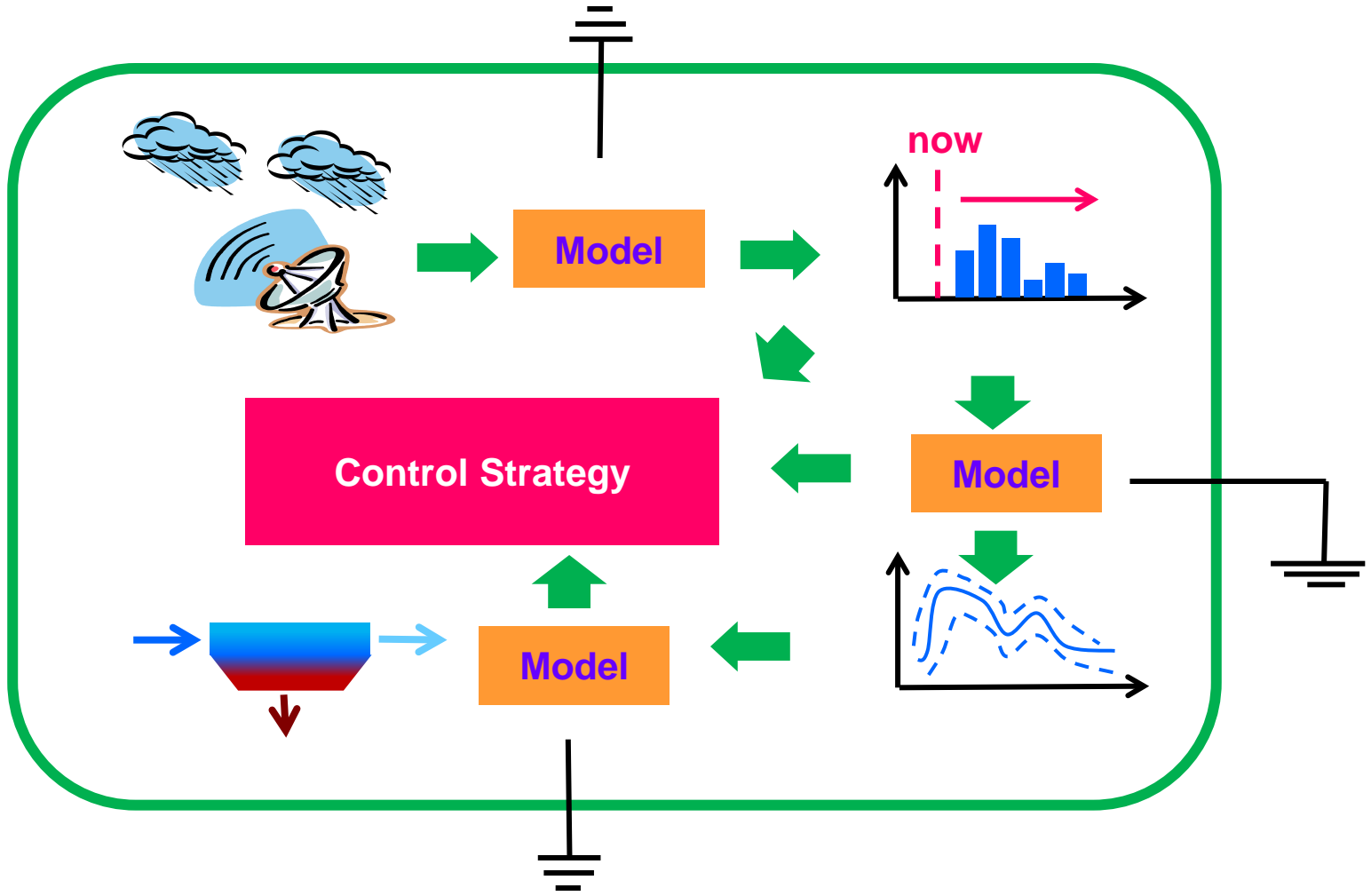


*The happy operator*

# The fellowship of SWI – the long journey



*The happy operator*

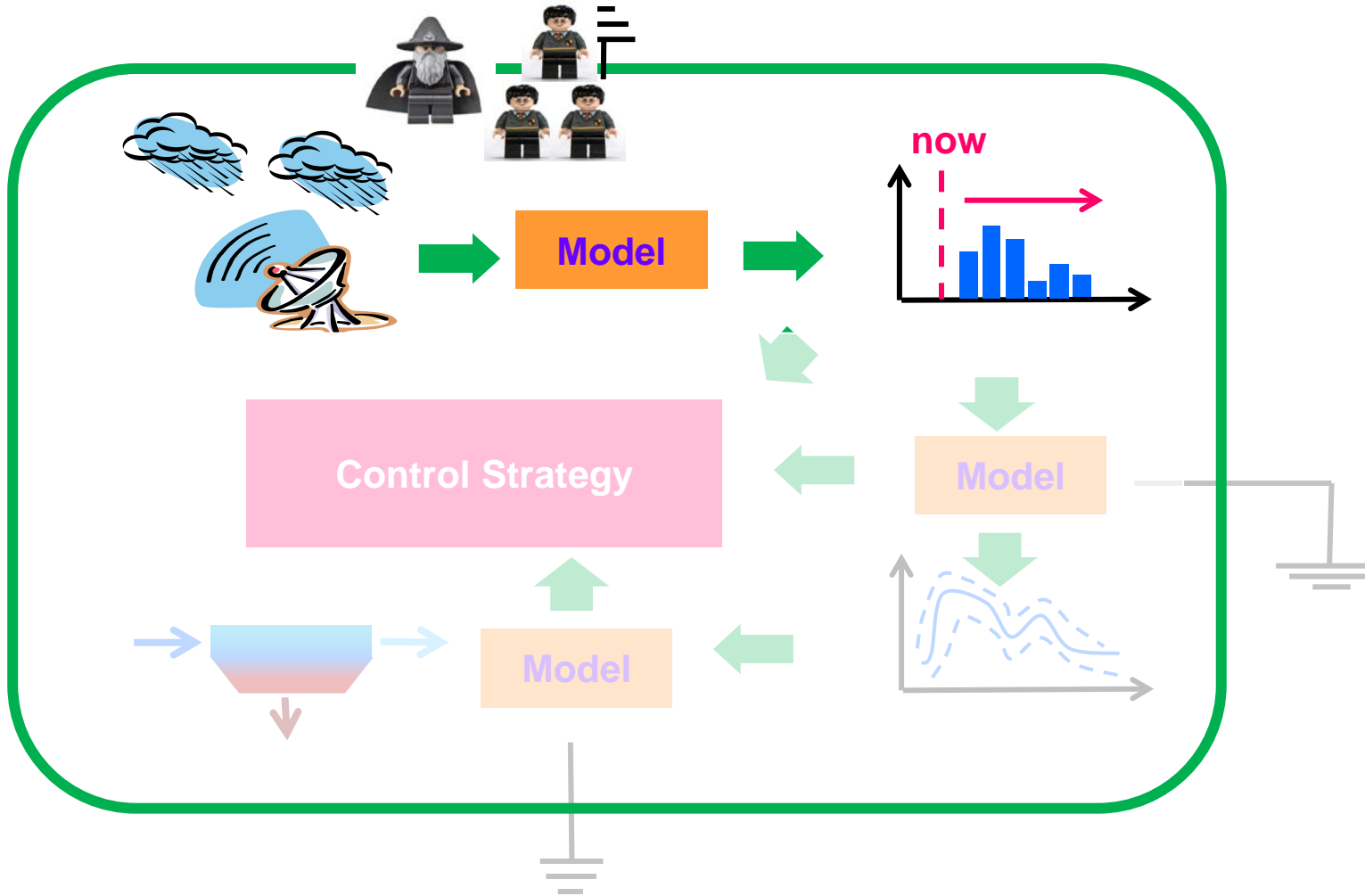
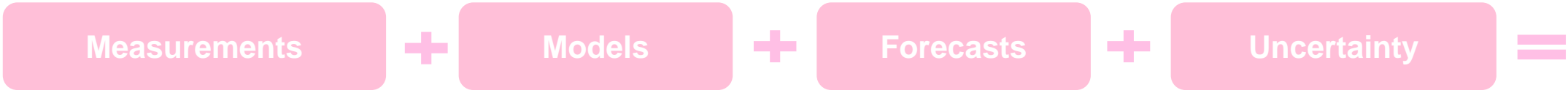


- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

# The fellowship of SWI – the long journey



*The happy operator*

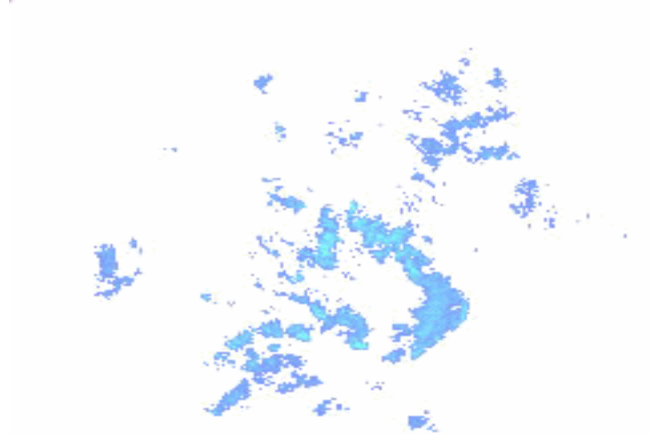


- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

# Rainfall input

Where is it raining?

And how much?



- Rainfall is not easy to measure

Rain gauge

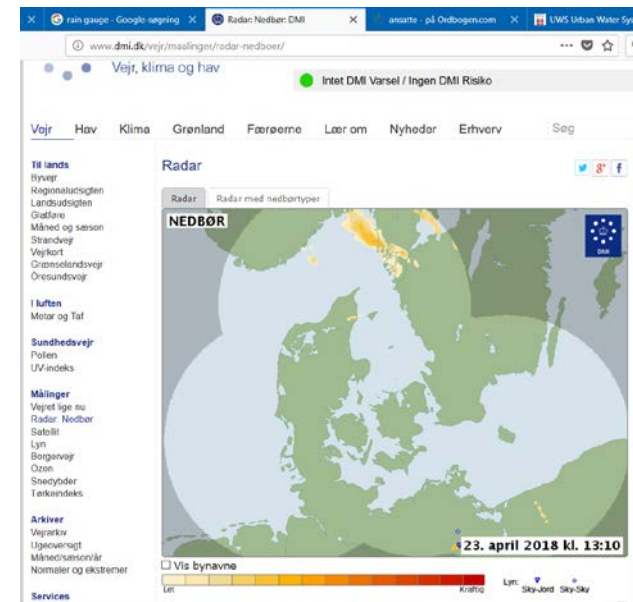


Slagelse Pumpestation (5485)



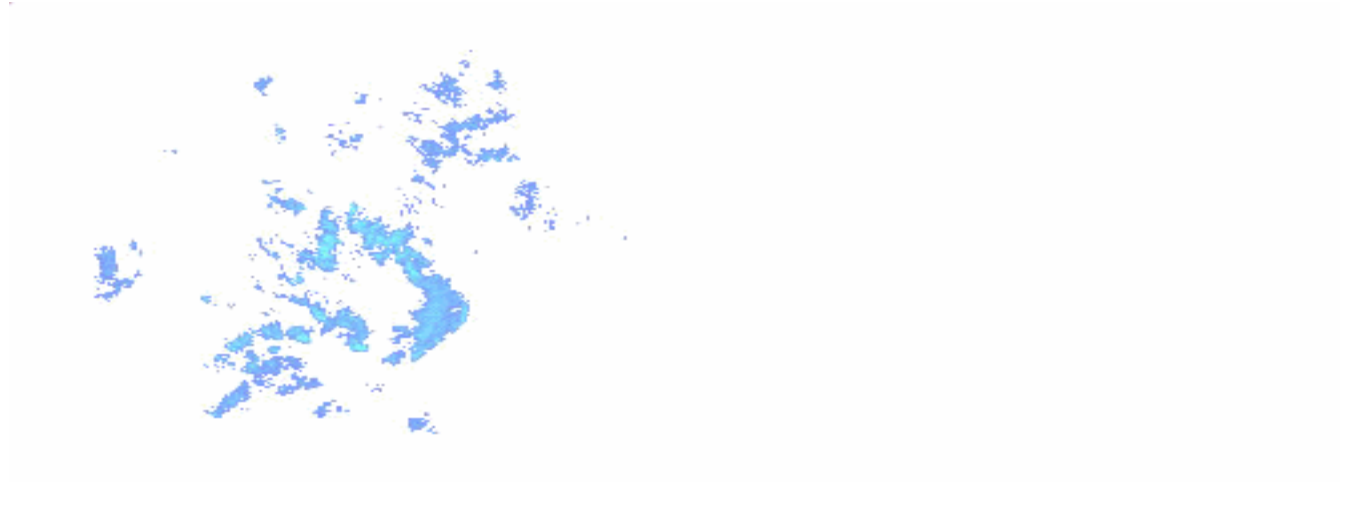
Slagelse centralrenseanlæg (5490)

Radar



# Rainfall input

Where is it raining?  
And how much?



- Rainfall is not easy to measure

	Volume	Spatial distribution
• Rain gauges	✓	✗
• Radar	✗	✓
• Flow measurements	?	?

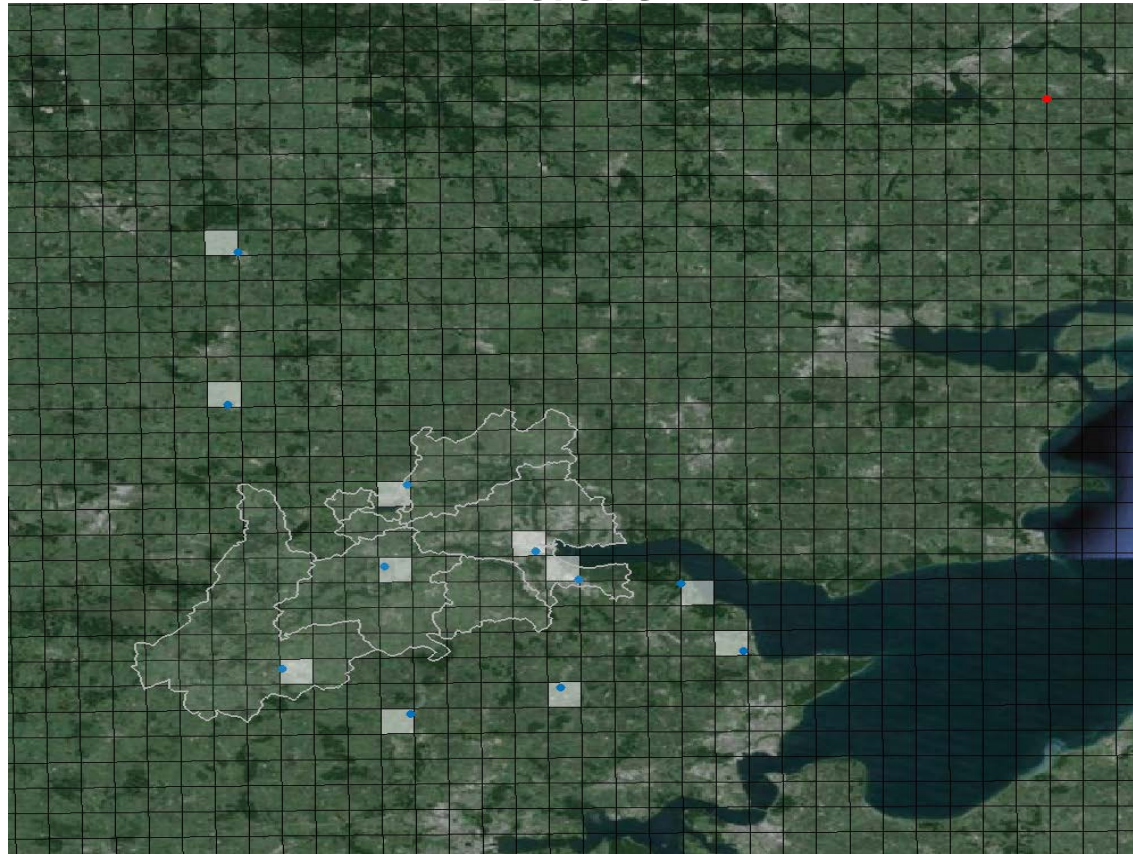
- But you can combine them



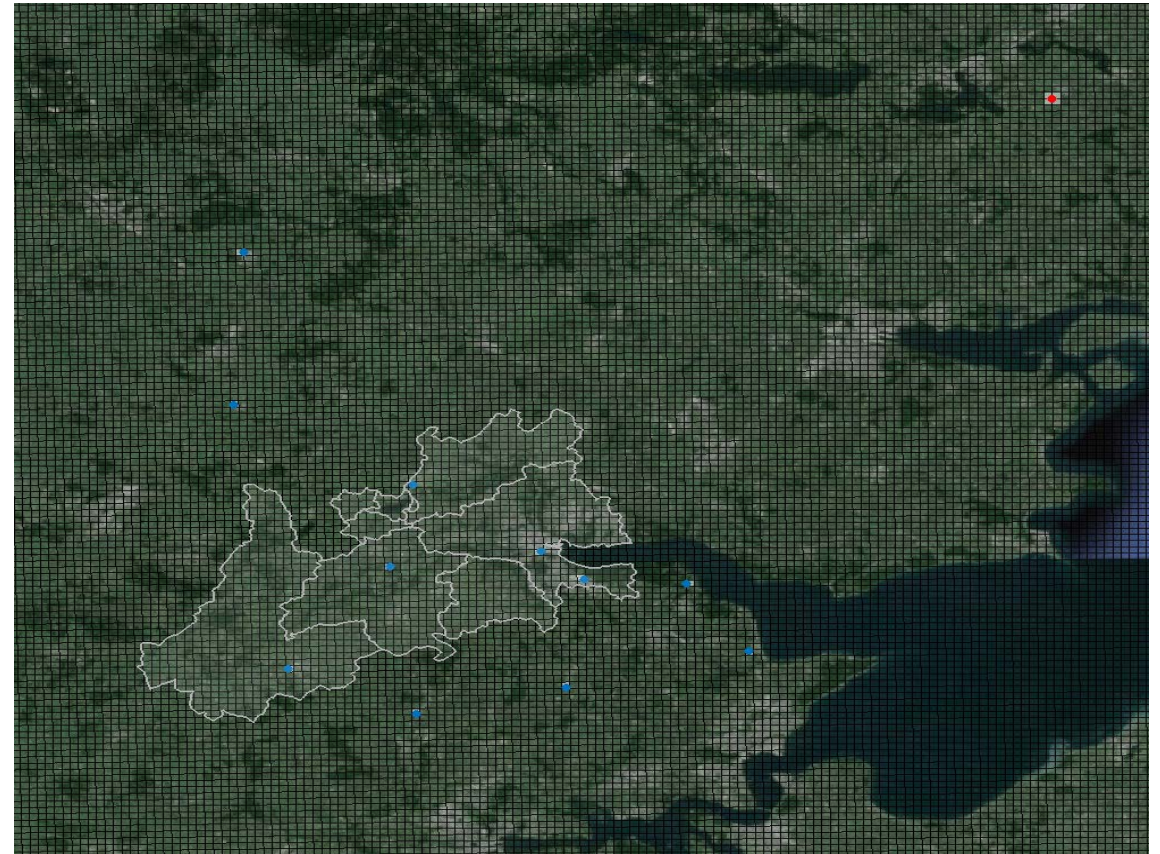
# The new AAU Nowcaster

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

Before



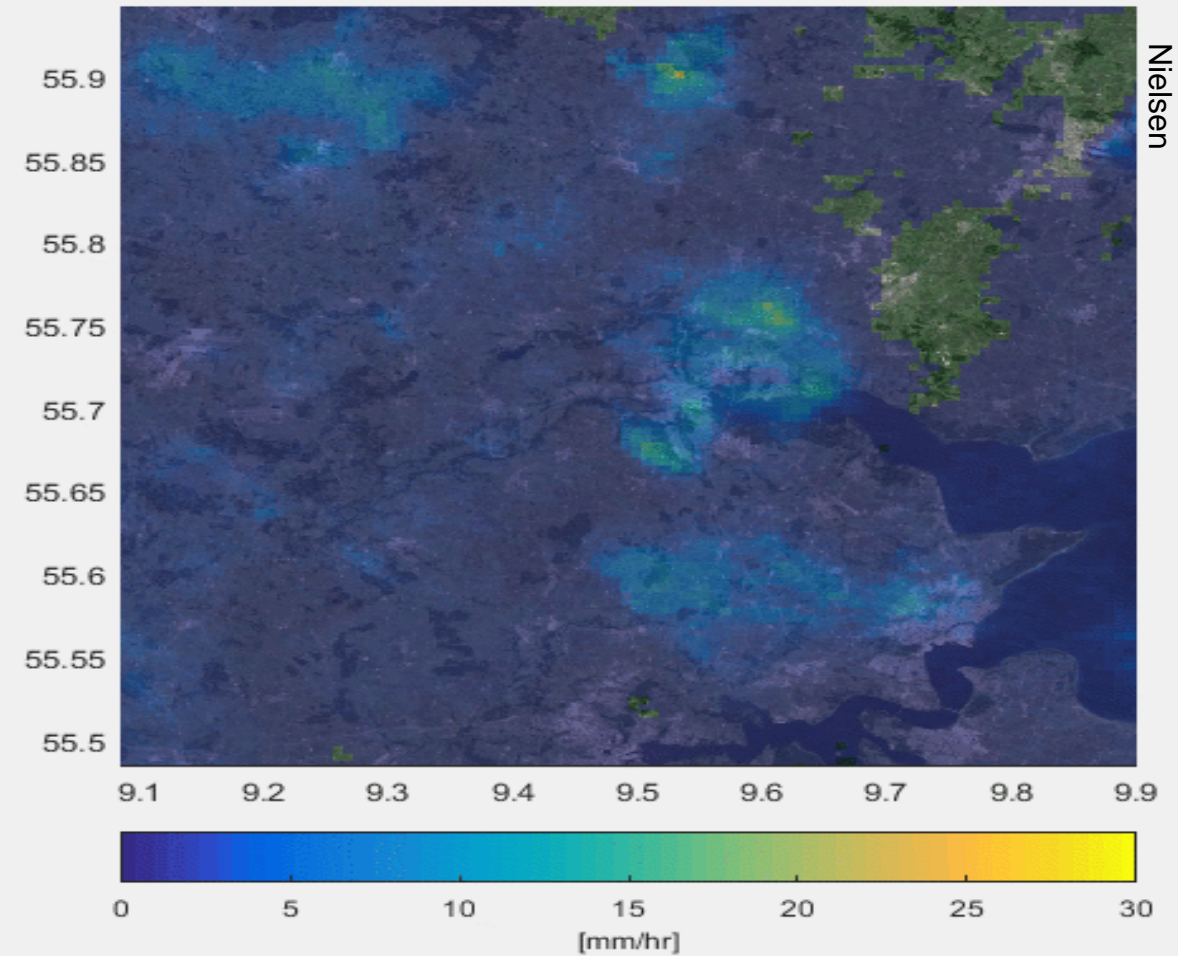
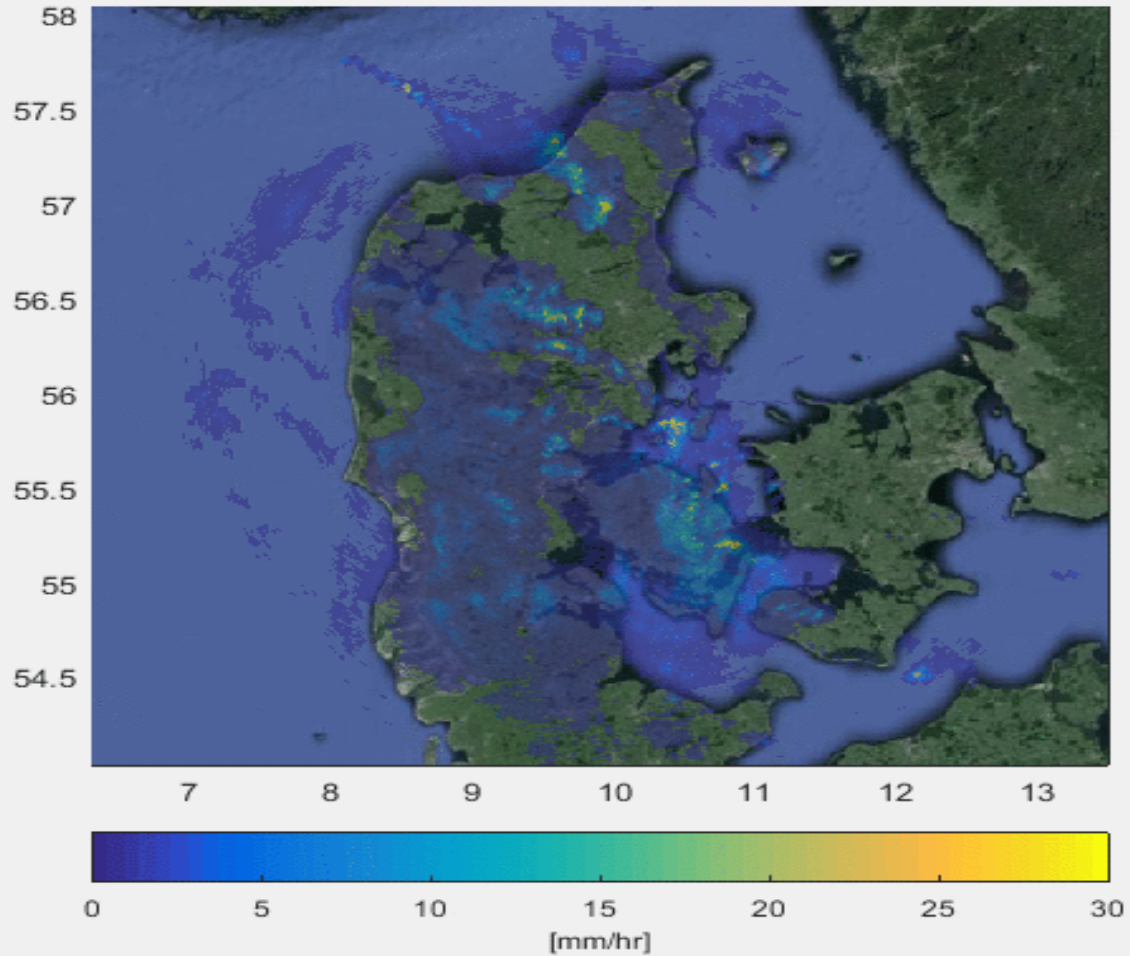
After





# Demonstration of online nowcaster (WP-3)

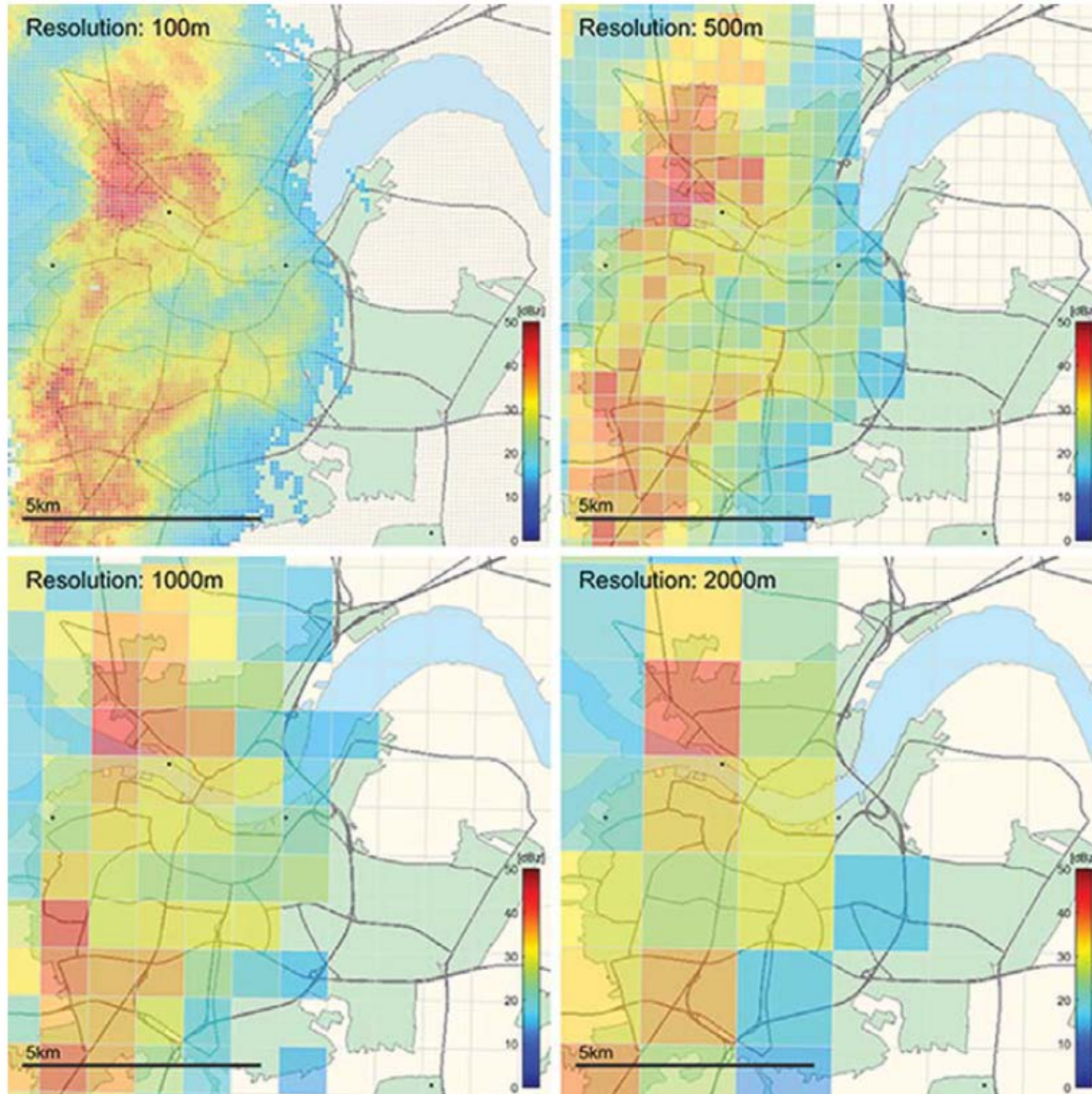
Observation: 04-Aug-2015 16:51:00



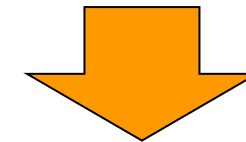
Slide courtesy of Jesper Ellerbaek Nielsen



# Radar resolution

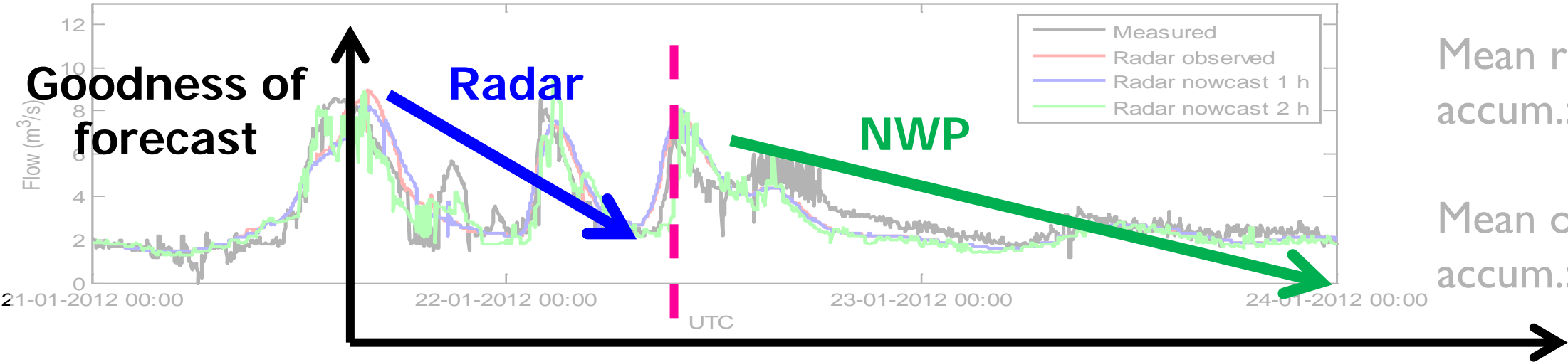


- Which one is the good one for the urban scale?
- Radar can are only useful to predict up to 2 hrs in the future
- What about longer horizons?



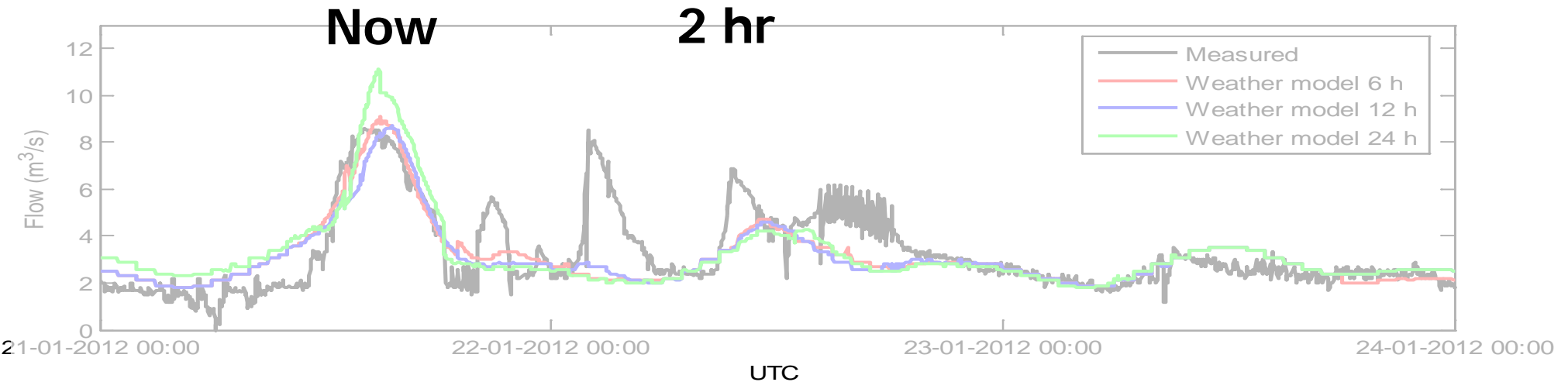
- Numerical Weather Prediction (NWP) models

# Flow forecast results - Event 6: 21 - 24 January 2012



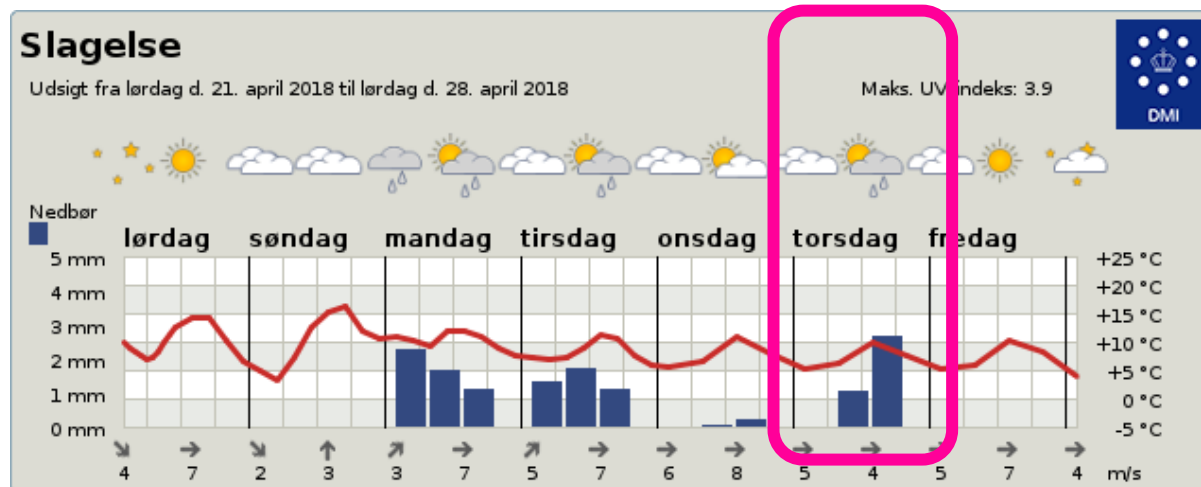
Mean rain gauge accum.: 8.6 mm

Mean obs. radar accum.: 7.3 mm



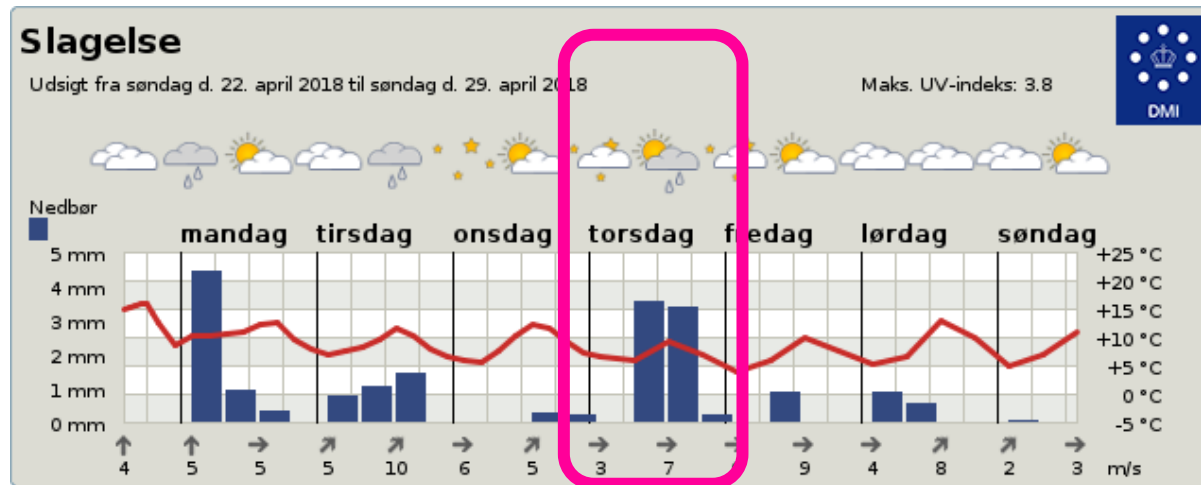
**Hvordan er vejret i dag?**

# Slagelse - 19/04



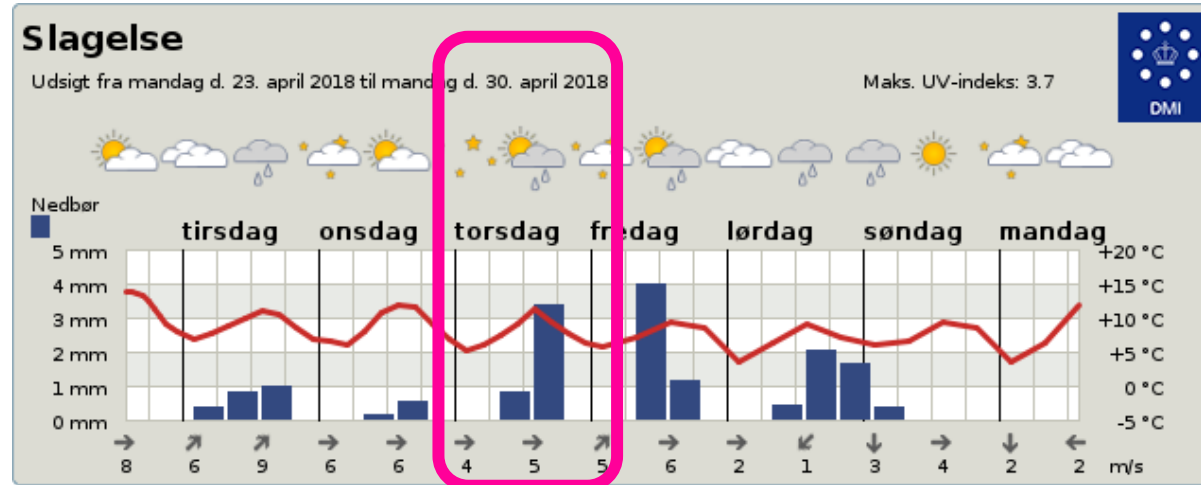
I morgen 20.04.2018	Lørdag 21.04.2018	Søndag 22.04.2018	Mandag 23.04.2018	Tirsdag 24.04.2018	Onsdag 25.04.2018	Torsdag 26.04.2018	Fredag 27.04.2018	Lørdag 28.04.2018
20°	14°	15°	12°	11°	11°	10°	10°	8°
Klarvær. Lett bris, 5 m/s fra sør. 0 mm nedbør.	Klarvær. Lett bris, 5 m/s fra vest-nordvest. 0 mm nedbør.	Delvis skyet. Lett bris, 4 m/s fra sør-sørøst. 0 mm nedbør.	Regnbyger. Laber bris, 7 m/s fra vest-sørvest. 1,1 mm nedbør.	Lett regn. Frisk bris, 8 m/s fra vest. 0,6 mm nedbør.	Lette regnbyger. Frisk bris, 8 m/s fra vest-nordvest. 0,6 mm nedbør.	Lette regnbyger. Lett bris, 4 m/s fra vest-sørvest. 0,9 mm nedbør.	Lettskyet. Laber bris, 7 m/s fra vest-nordvest. 0 mm nedbør.	Skyet. Lett bris, 5 m/s fra sør-sørvest. 0 mm nedbør.

# Slagelse - 20/04



Tomorrow 21/04/2018	Sunday 22/04/2018	Monday 23/04/2018	Tuesday 24/04/2018	Wednesday 25/04/2018	Thursday 26/04/2018	Friday 27/04/2018	Saturday 28/04/2018	Sunday 29/04/2018
14°	15°	12°	11°	12°	9°	10°	13°	11°
Clear sky. Moderate breeze, 6 m/s from west-northwest. 0 mm precipitation.	Partly cloudy. Light breeze, 3 m/s from south. 0 mm precipitation.	Fair. Gentle breeze, 5 m/s from west. 0 mm precipitation.	Rain showers. Fresh breeze, 10 m/s from west-southwest. 1.4 mm precipitation.	Partly cloudy. Gentle breeze, 5 m/s from west-southwest. 0 mm precipitation.	Rain showers. Moderate breeze, 7 m/s from west. 3.3 mm precipitation.	Partly cloudy. Fresh breeze, 9 m/s from west-northwest. 0 mm precipitation.	Cloudy. Fresh breeze, 8 m/s from southwest. 0 mm precipitation.	Partly cloudy. Light breeze, 3 m/s from west. 0 mm precipitation.

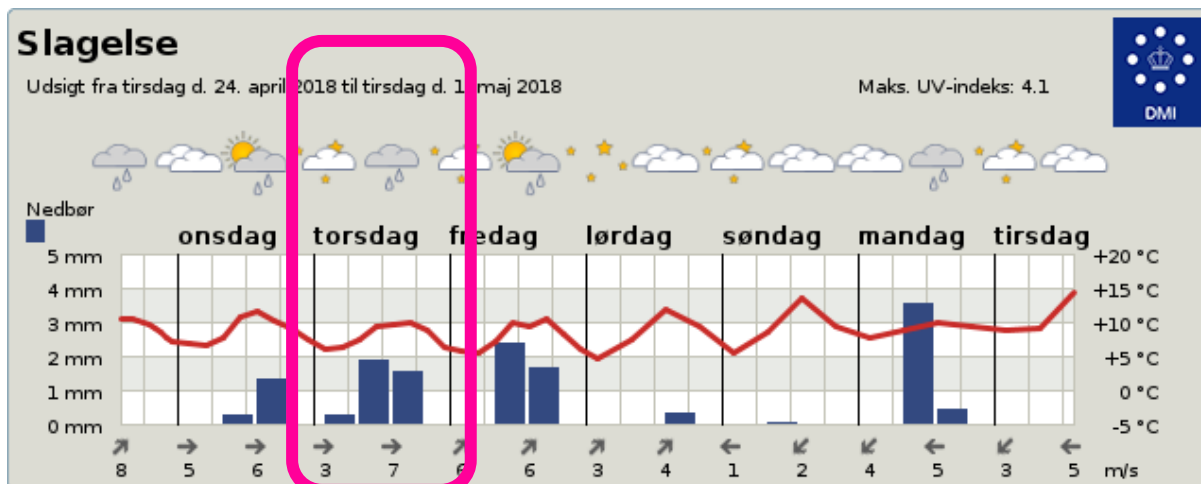
# Slagelse - 21/04



I morgen 22.04.2018	Mandag 23.04.2018	Tirsdag 24.04.2018	Onsdag 25.04.2018	Torsdag 26.04.2018	Fredag 27.04.2018	Lørdag 28.04.2018	Søndag 29.04.2018	Mandag 30.04.2018
14°	15°	11°	12°	11°	10°	9°	9°	12°
Delvis skyet. Svak vind, 2 m/s fra sørvest. 0 mm nedbør.	Delvis skyet. Frisk bris, 8 m/s fra vest. 0 mm nedbør.	Lette regnbyger. Frisk bris, 9 m/s fra vest-sørvest. 0,6 mm nedbør.	Lettskyet. Laber bris, 6 m/s fra vest. 0 mm nedbør.	Regnbyger. Laber bris, 6 m/s fra vest-sørvest. 1,9 mm nedbør.	Regnbyger. Laber bris, 7 m/s fra vest-sørvest. 2,1 mm nedbør.	Regn. Svak vind, 2 m/s fra nordøst. 1,8 mm nedbør.	Skyet. Lett bris, 5 m/s fra vest-nordvest. 0 mm nedbør.	Skyet. Flau vind, 1 m/s fra øst. 0 mm nedbør.

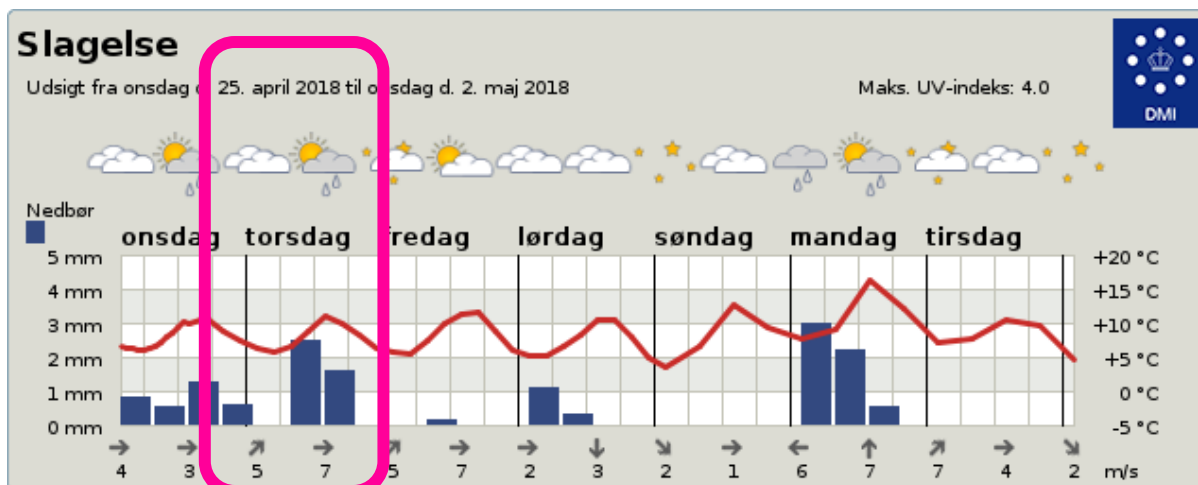


# Slagelse - 22/04



I morgen 23.04.2018	Tirsdag 24.04.2018	Onsdag 25.04.2018	Torsdag 26.04.2018	Fredag 27.04.2018	Lørdag 28.04.2018	Søndag 29.04.2018	Mandag 30.04.2018	Tirsdag 01.05.2018
16°	9°	12°	10°	10°	12°	14°	10°	14°
Delvis skyet. Frisk bris, 9 m/s fra vest. 0 mm nedbør.	Delvis skyet. Frisk bris, 9 m/s fra sørvest. 0 mm nedbør.	Lette regnbyger. Laber bris, 6 m/s fra vest- sørvest. 0,8 mm nedbør.	Lette regnbyger. Laber bris, 7 m/s fra vest- sørvest. 0,9 mm nedbør.	Regnbyger. Laber bris, 7 m/s fra vest- sørvest. 1,0 mm nedbør.	Letttskyet. Lett bris, 4 m/s fra sørvest. 0 mm nedbør.	Skyet. Svak vind, 2 m/s fra nordøst. 0 mm nedbør.	Skyet. Lett bris, 5 m/s fra øst. 0 mm nedbør.	Skyet. Lett bris, 5 m/s fra øst. 0 mm nedbør.

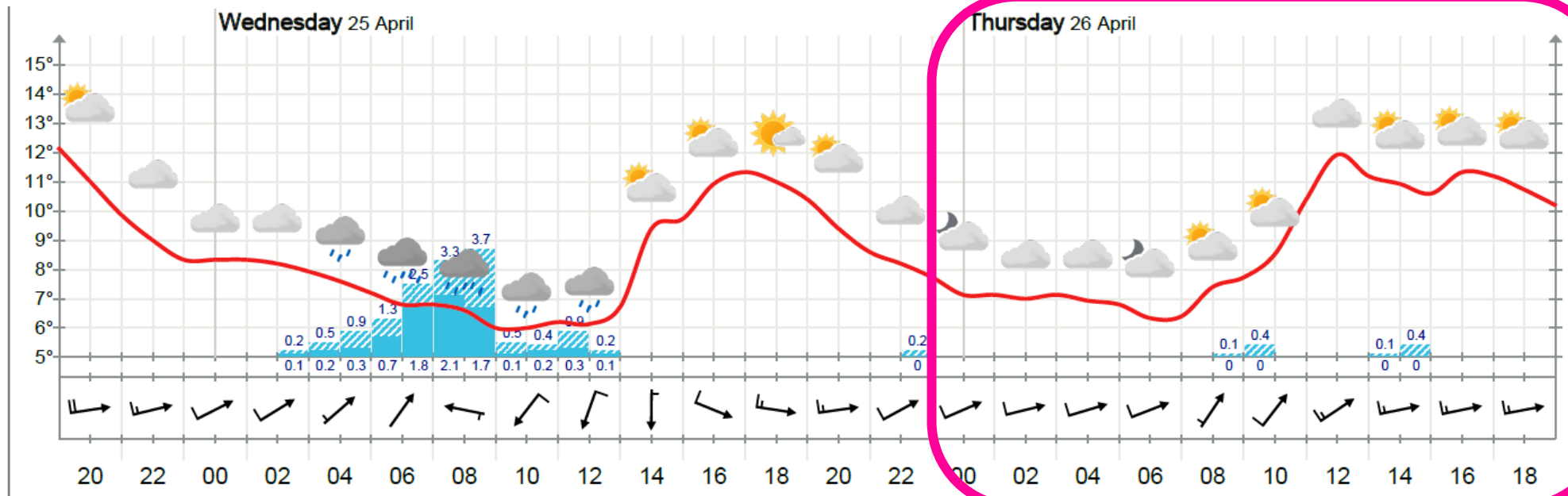
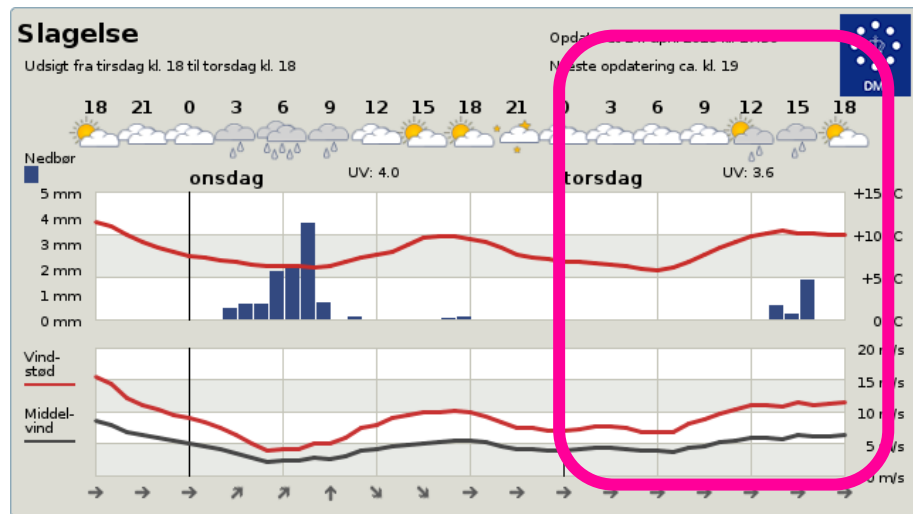
# Slagelse - 23/04



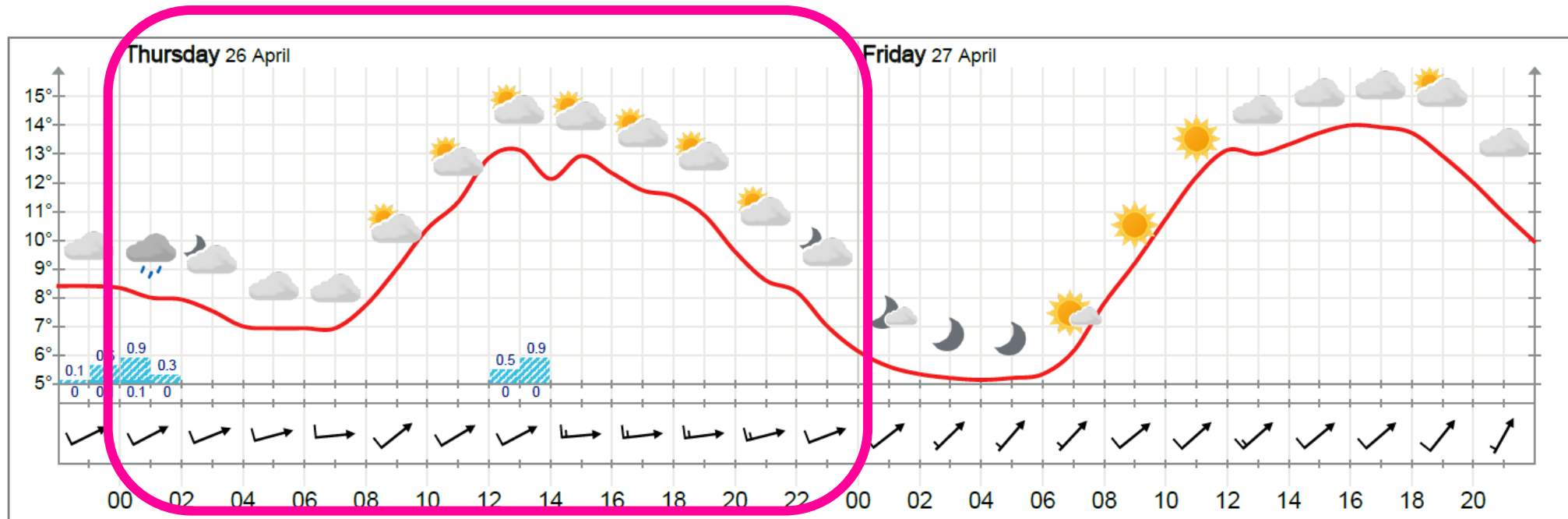
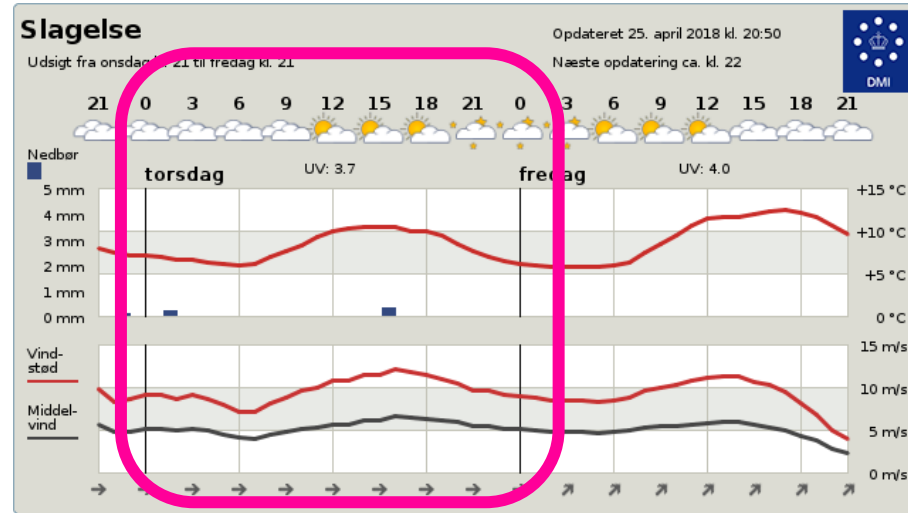
Tomorrow 24/04/2018	Wednesday 25/04/2018	Thursday 26/04/2018	Friday 27/04/2018	Saturday 28/04/2018	Sunday 29/04/2018	Monday 30/04/2018	Tuesday 01/05/2018	Wednesday 02/05/2018
10°	7°	11°	11°	10°	13°	16°	10°	10°
Cloudy. Fresh breeze, 8 m/s from southwest. 0 mm precipitation.	Partly cloudy. Light air, 1 m/s from south-southwest. 0 mm precipitation.	Rain showers. Moderate breeze, 7 m/s from west-southwest. 2 mm precipitation.	Partly cloudy. Moderate breeze, 7 m/s from west-southwest. 0 mm precipitation.	Clear sky. Light breeze, 3 m/s from north. 0 mm precipitation.	Cloudy. Light air, 1 m/s from south-southwest. 0 mm precipitation.	Partly cloudy. Moderate breeze, 7 m/s from south. 0 mm precipitation.	Cloudy. Gentle breeze, 5 m/s from west-southwest. 0 mm precipitation.	Partly cloudy. Gentle breeze, 5 m/s from west-southwest. 0 mm precipitation.



# Slagelse - 24/04

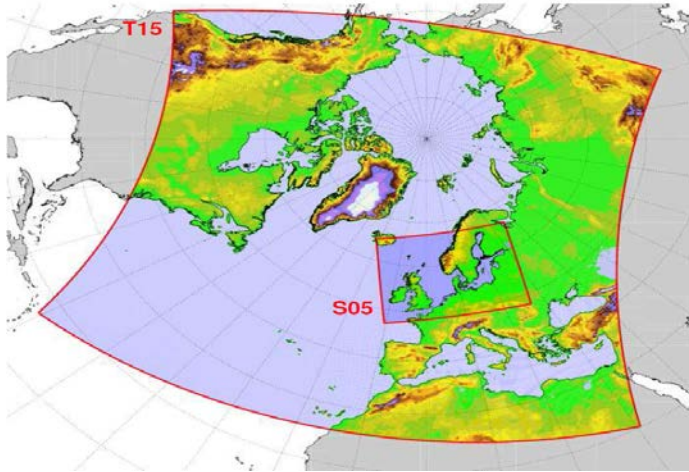


# Slagelse - 25/04



# 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

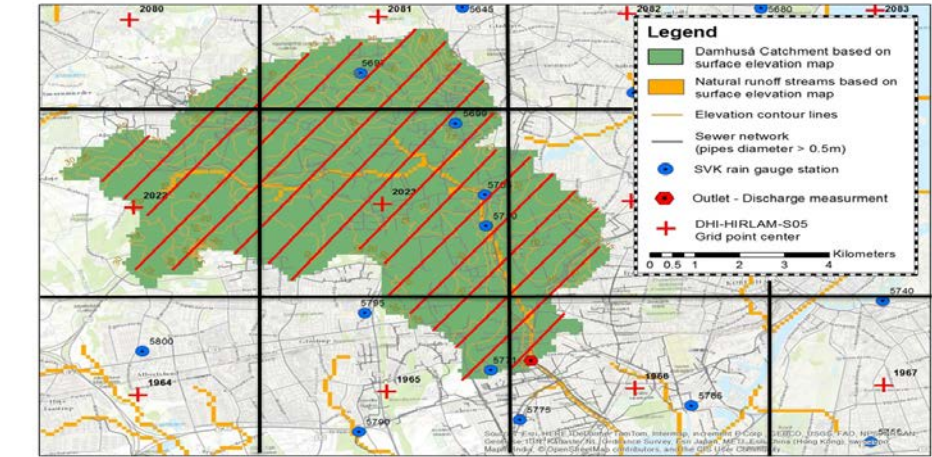
5 # initial condition

S

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



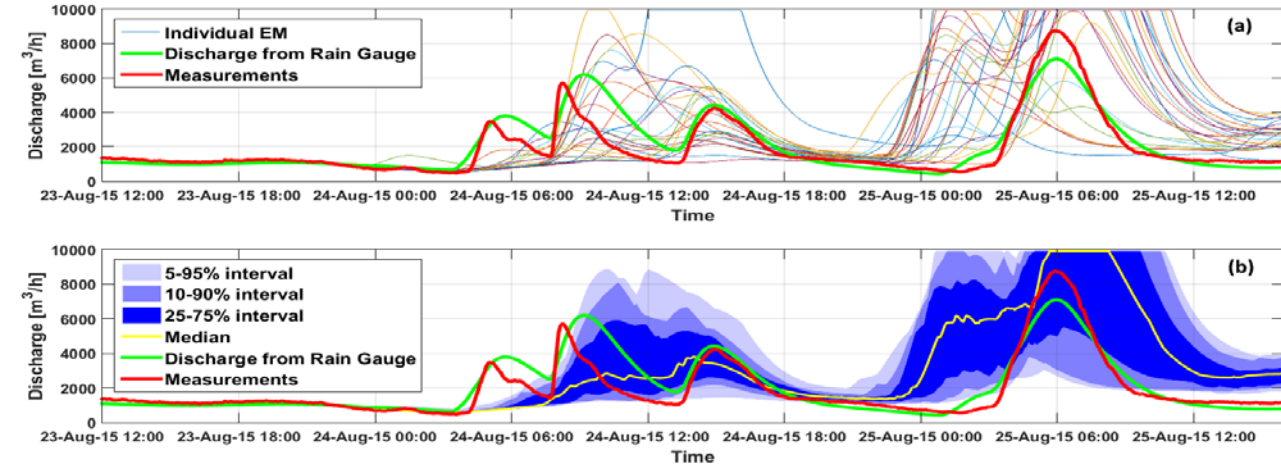
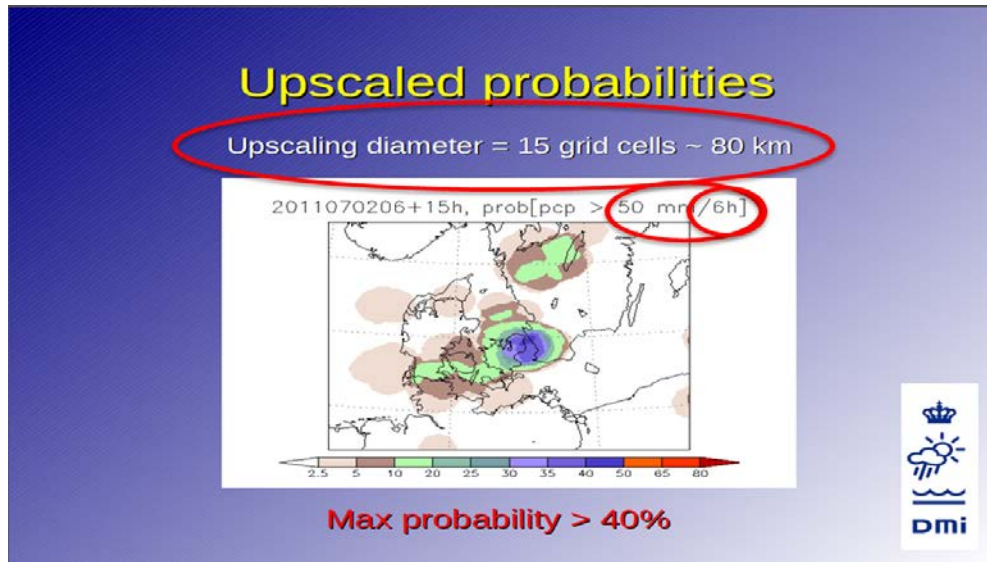
Local value with high resolution



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)

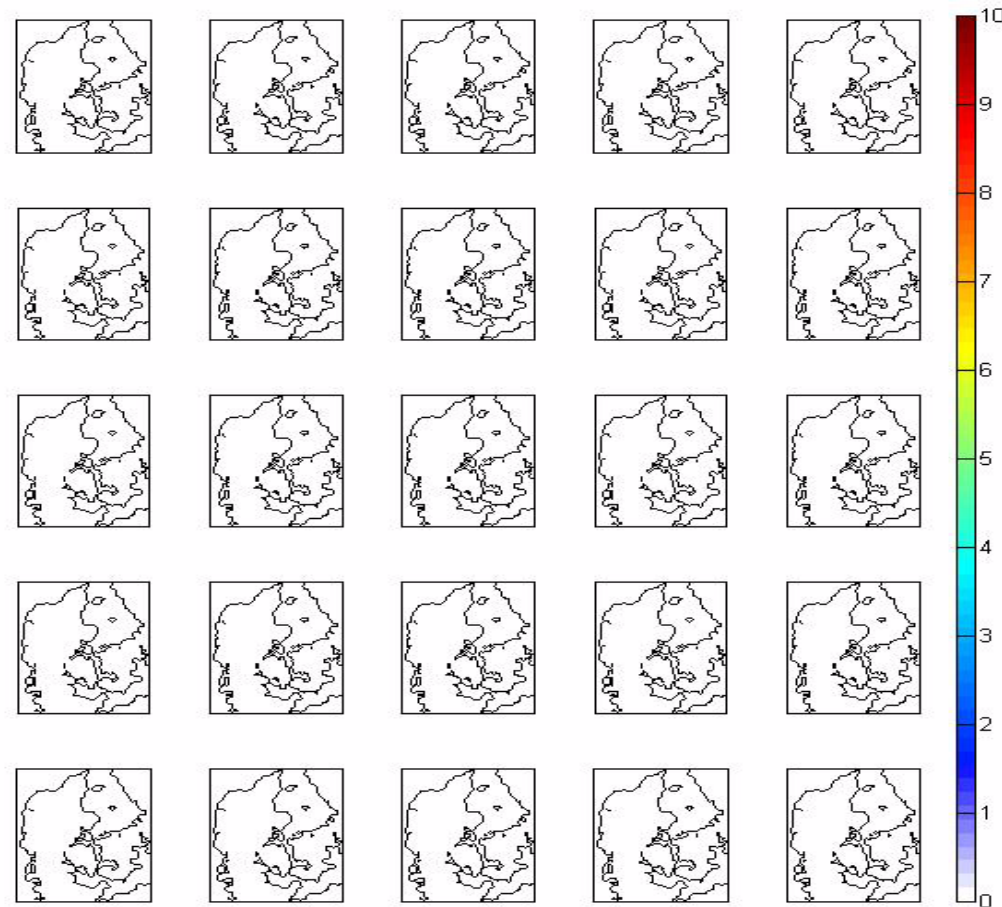
15-Jan-2015 - lead time 0 hours (in [mm/h])





# DMI model prediction (summer)

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

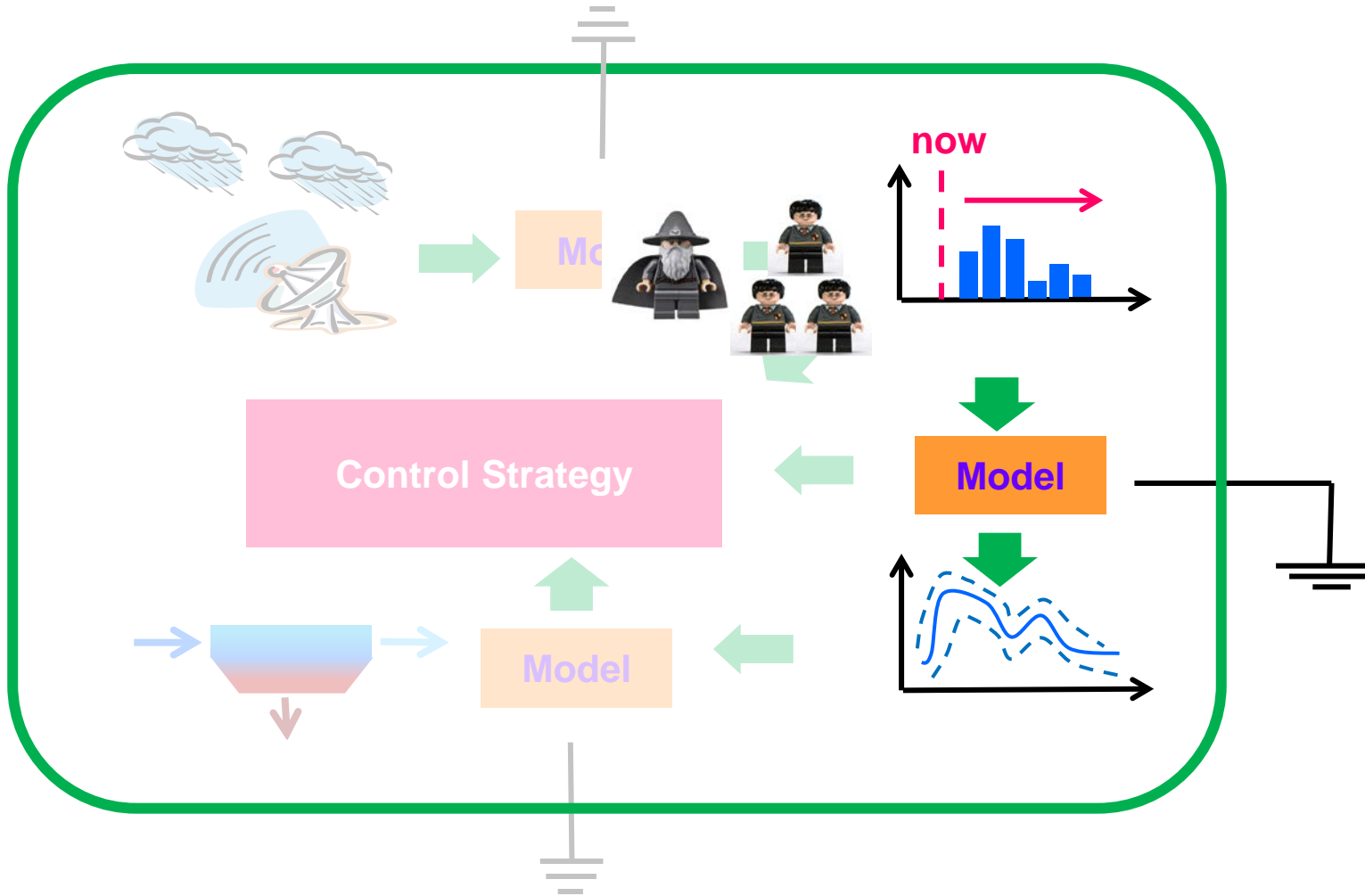


25 (physically based) models = 25 different results

# The fellowship of SWI – the long journey



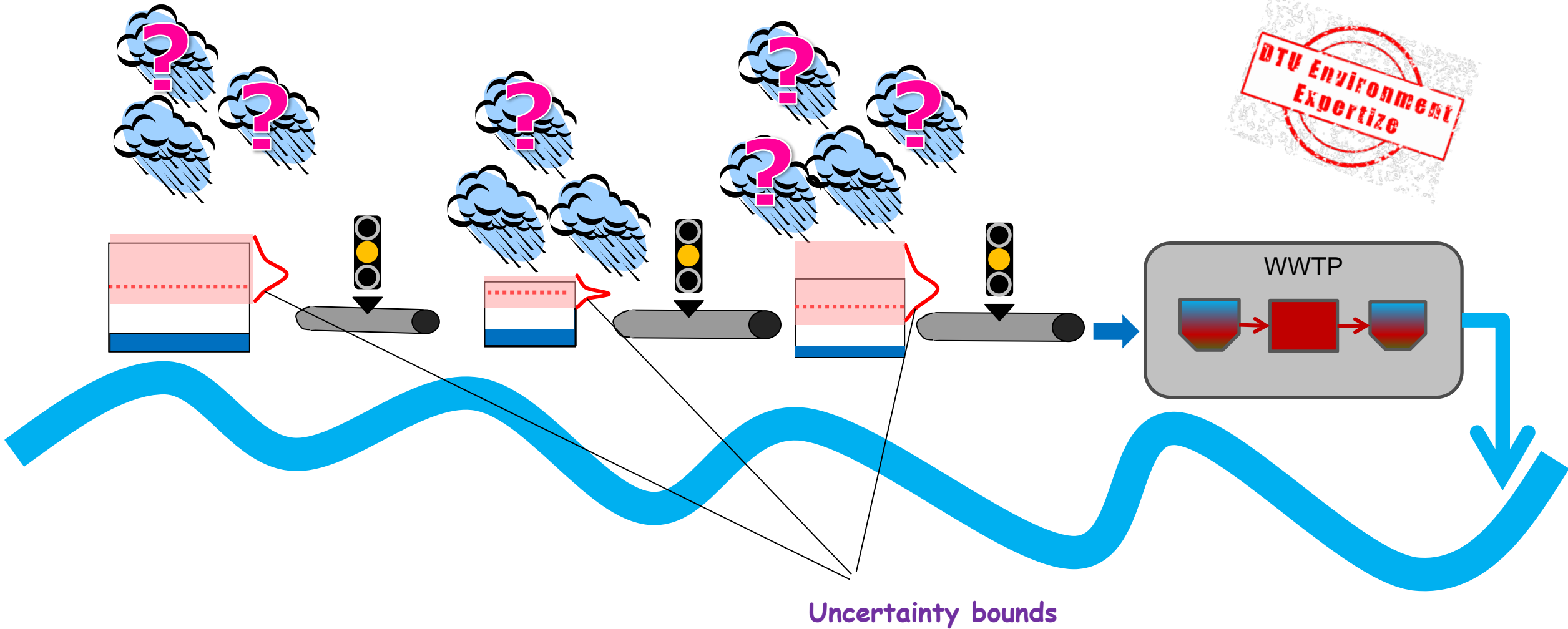
*The happy operator*



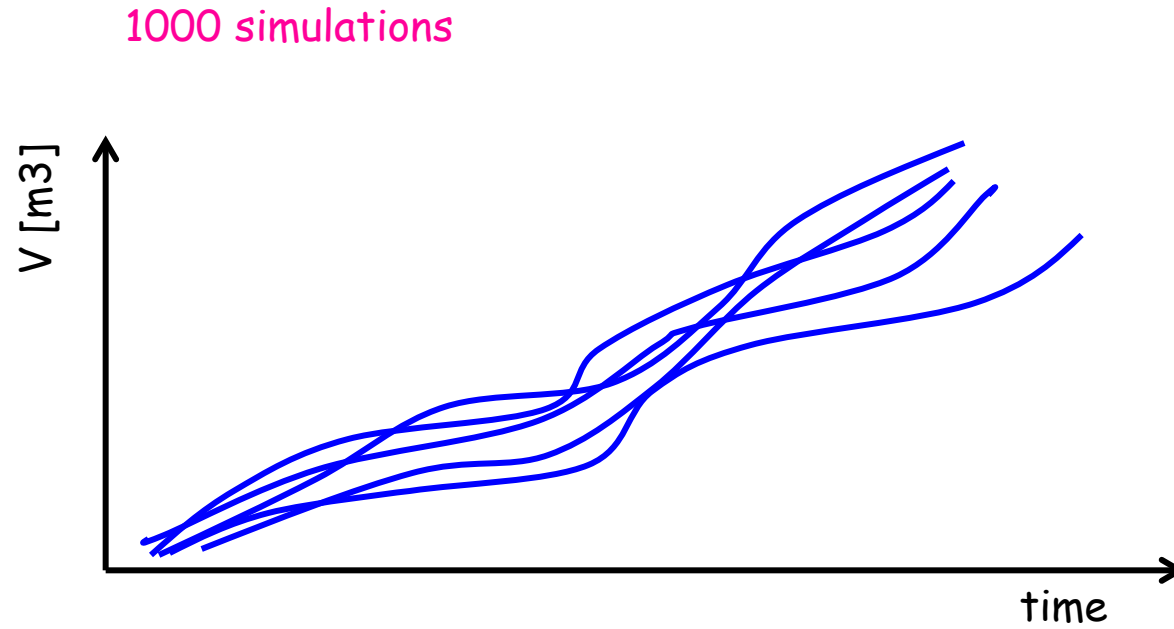
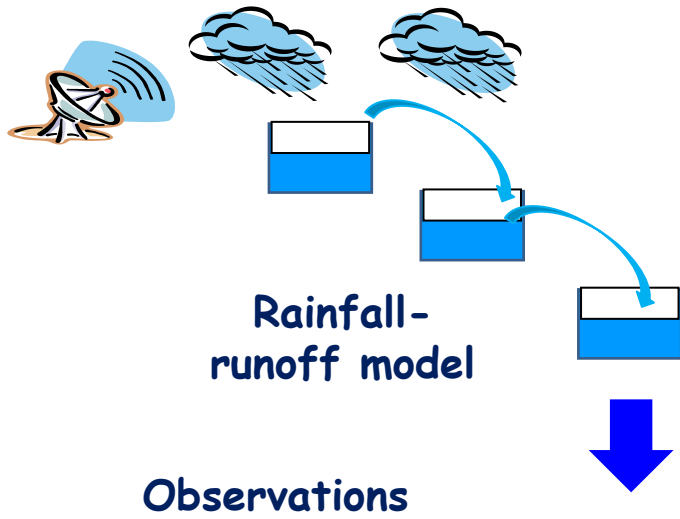
- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

# Model Predictive Control with uncertainty

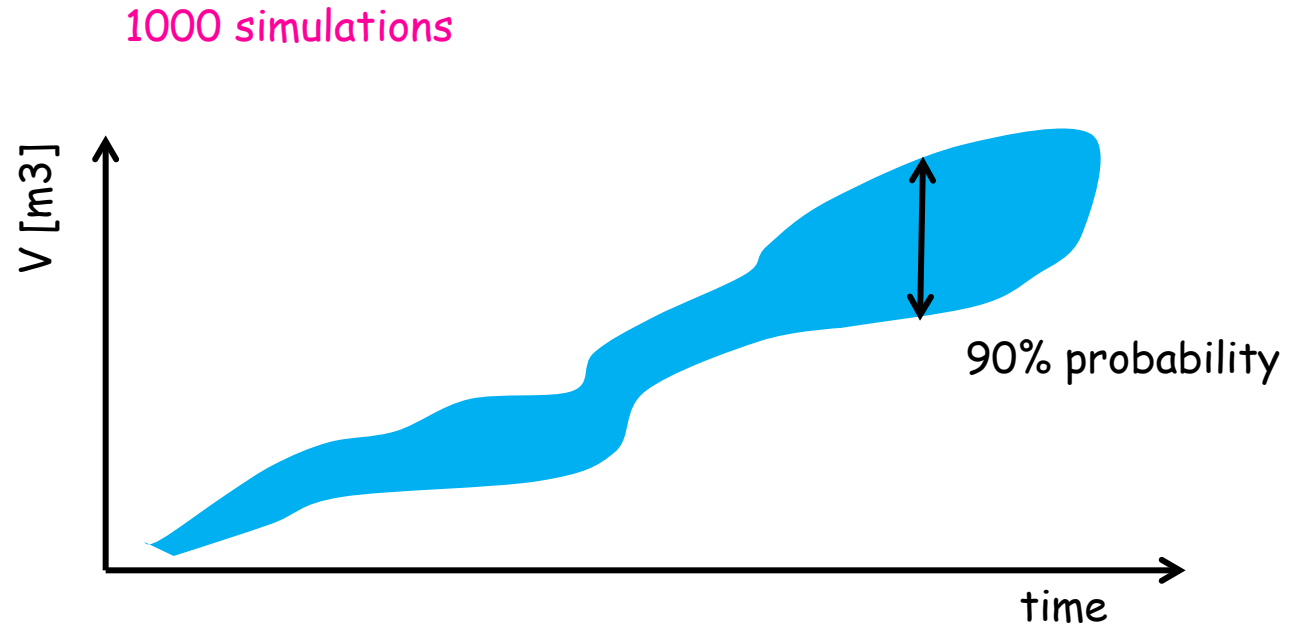
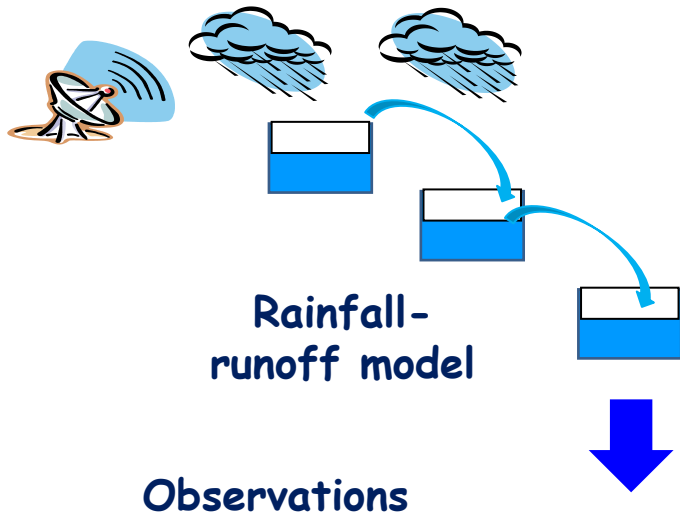
- Rainfall forecasts are uncertain →



# Stochastic runoff forecasts



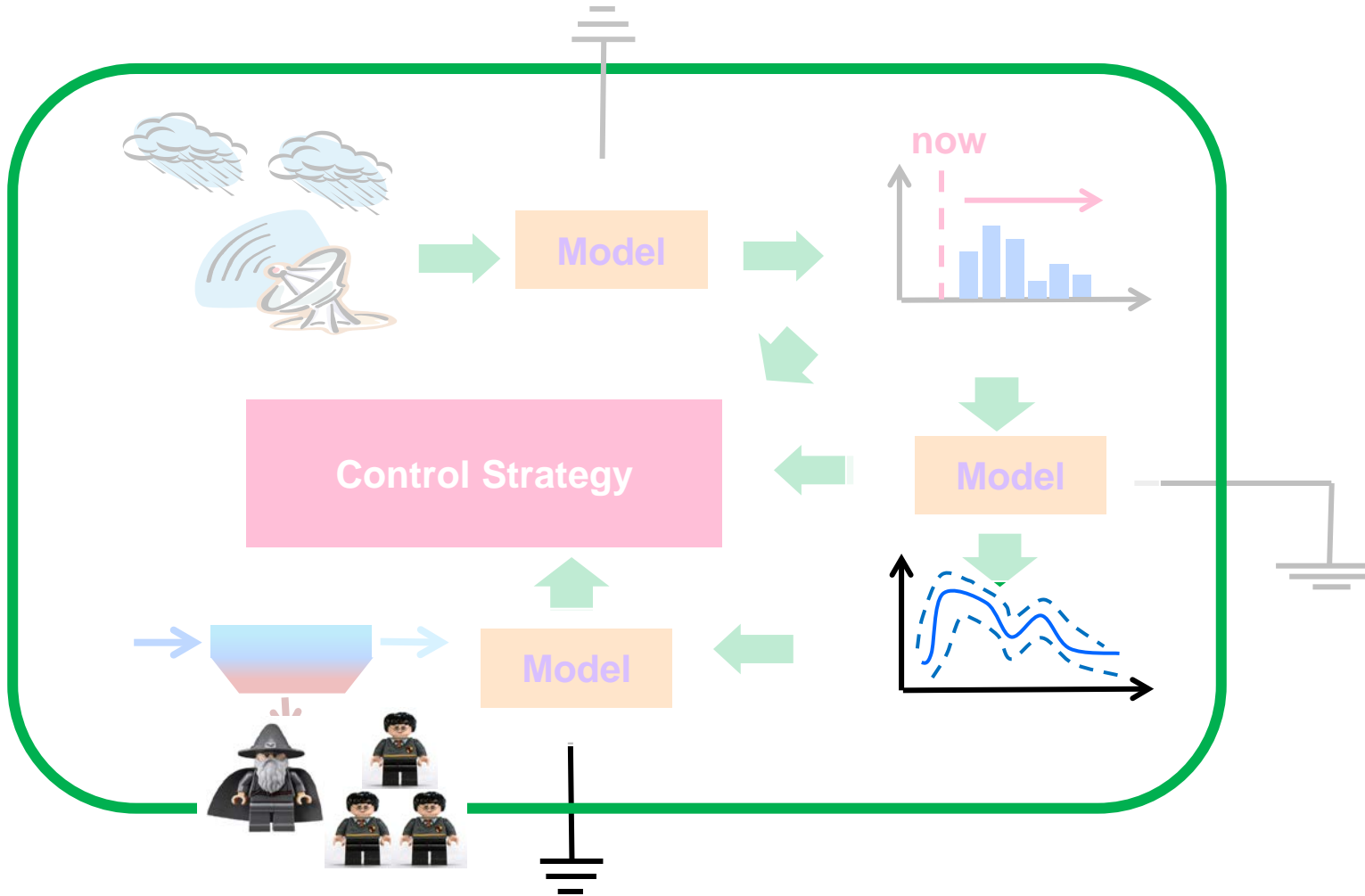
# Stochastic runoff forecasts



# The fellowship of SWI – the long journey



*The happy operator*

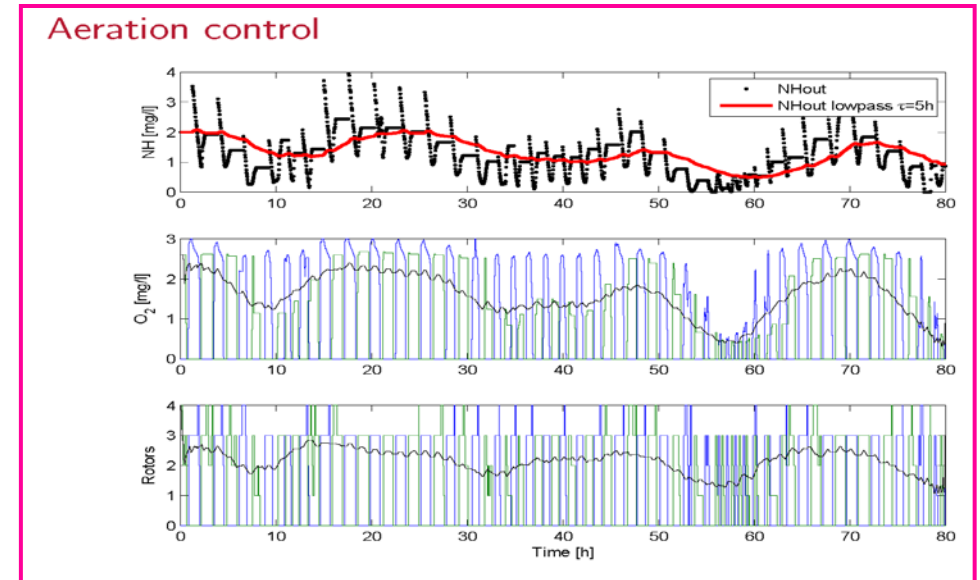
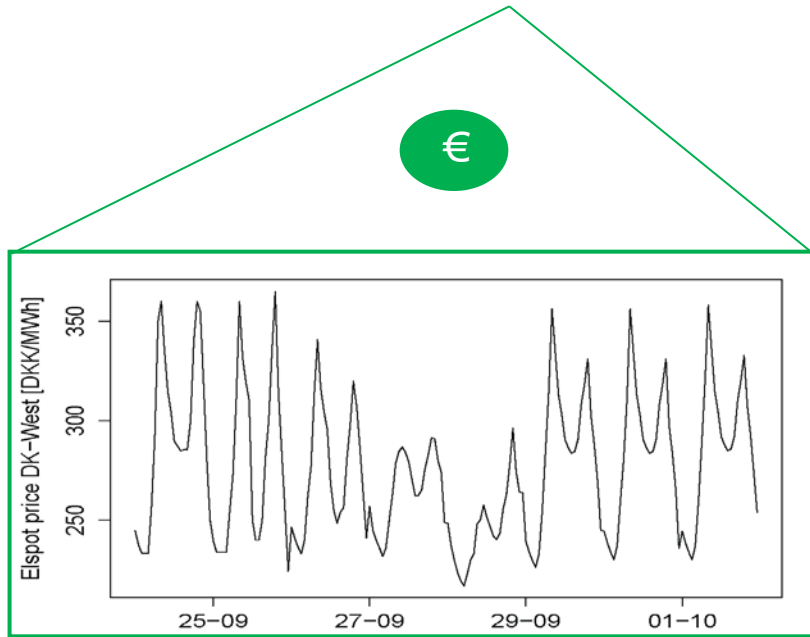
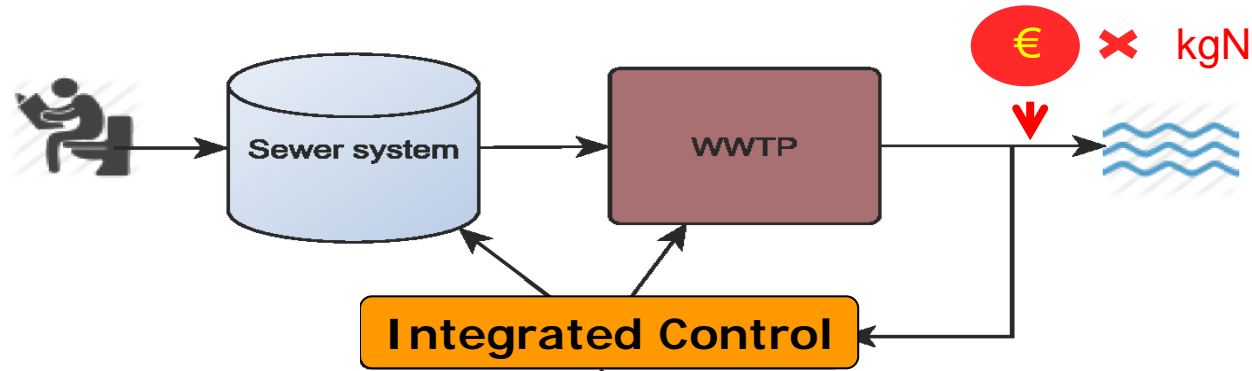


- Rainfall measurements
- Short-term rainfall forecasts
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- WWTP forecast models
- MPC strategy addressing uncertainty



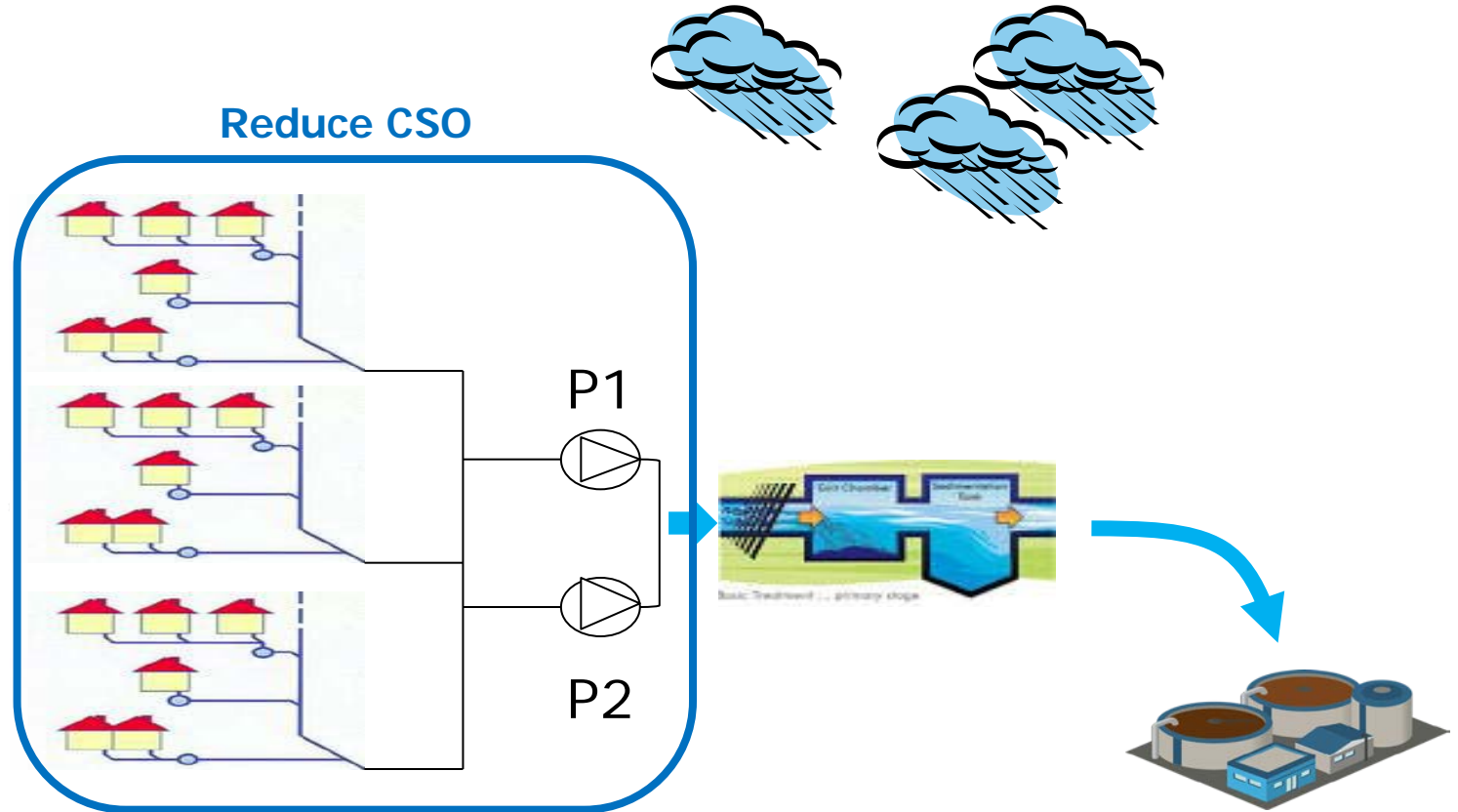
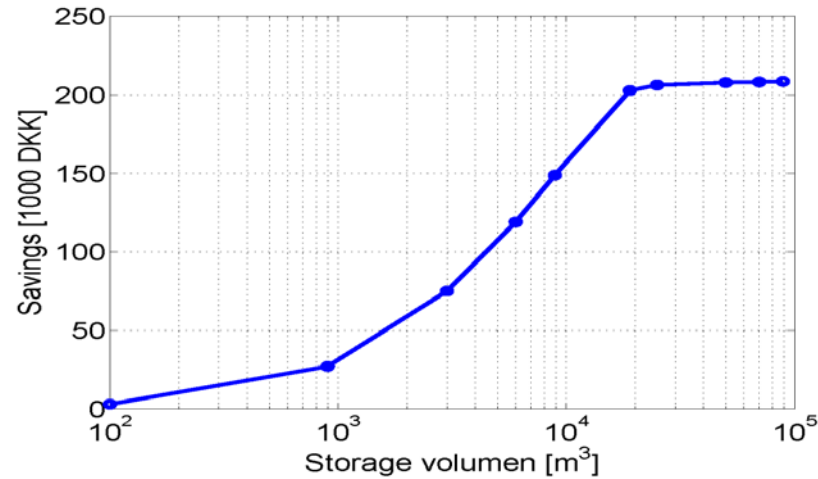
# Controlling the WWTP based on energy prices

## the Blue Kolding example



# Controlling the WWTP based on energy prices – moving upstream

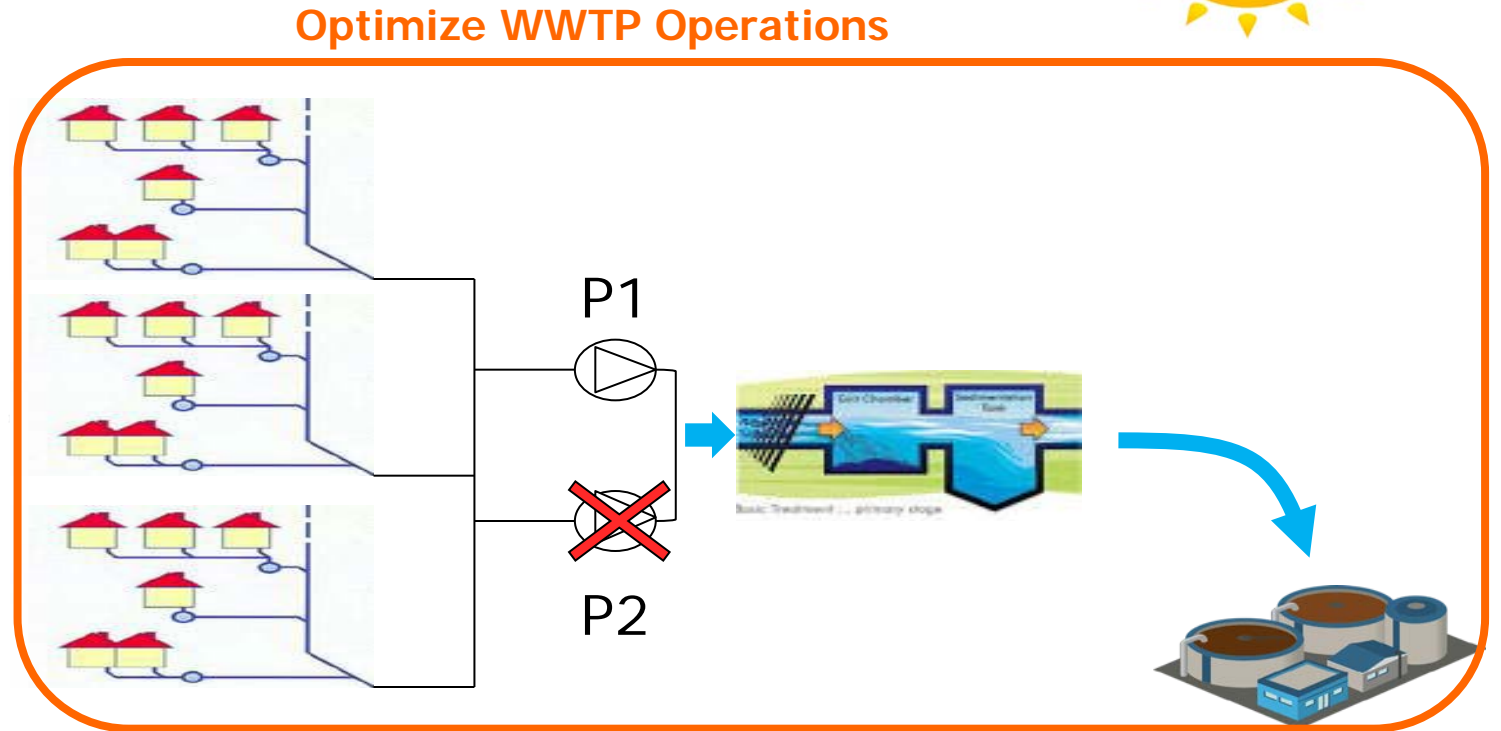
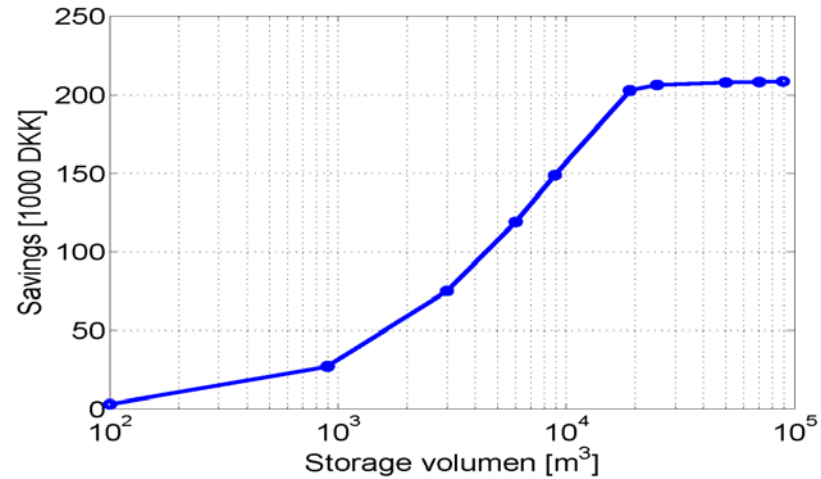
Sewer system annual Elspot savings



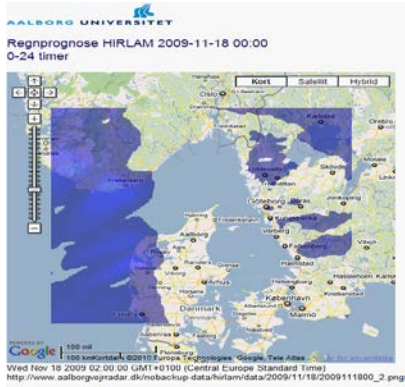
# Controlling the WWTP based on energy prices – moving upstream



Sewer system annual Elspot savings

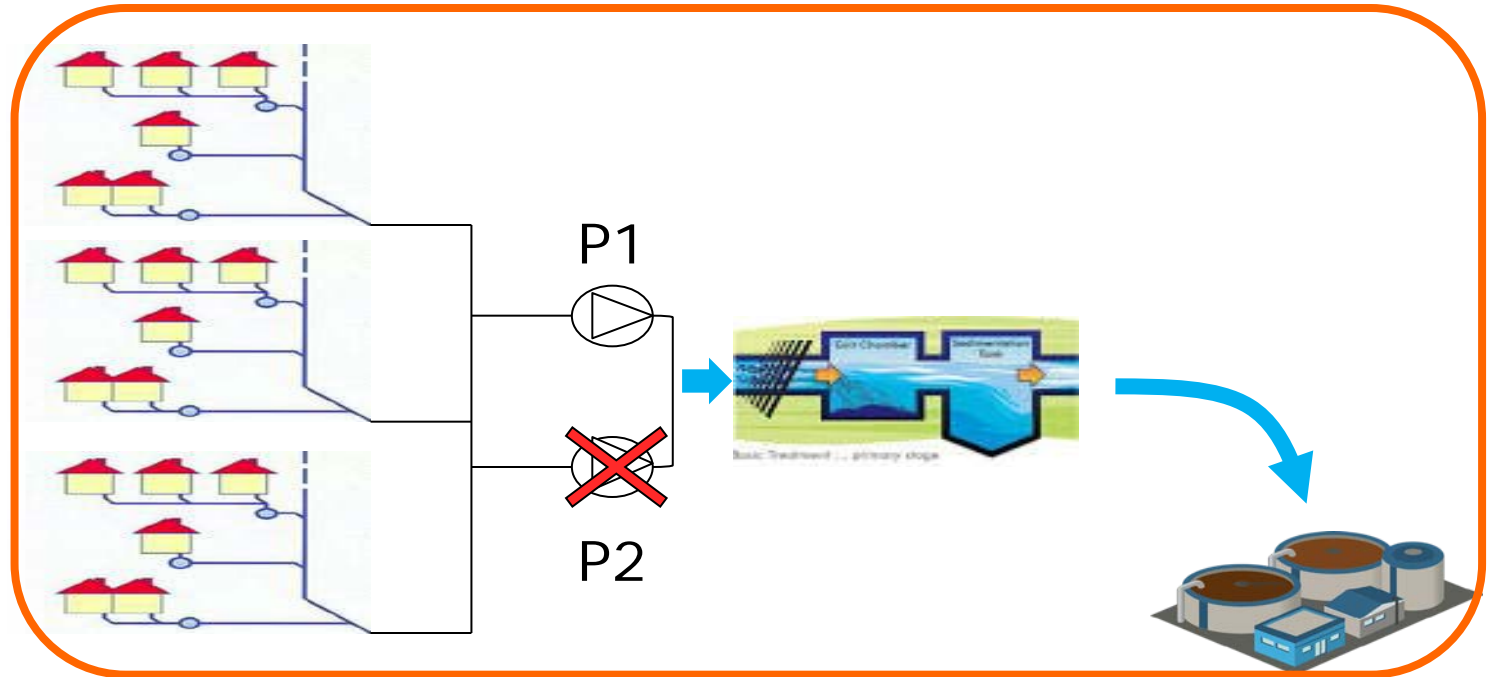


# Controlling the WWTP based on energy prices – moving upstream



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

## Optimize WWTP Operations

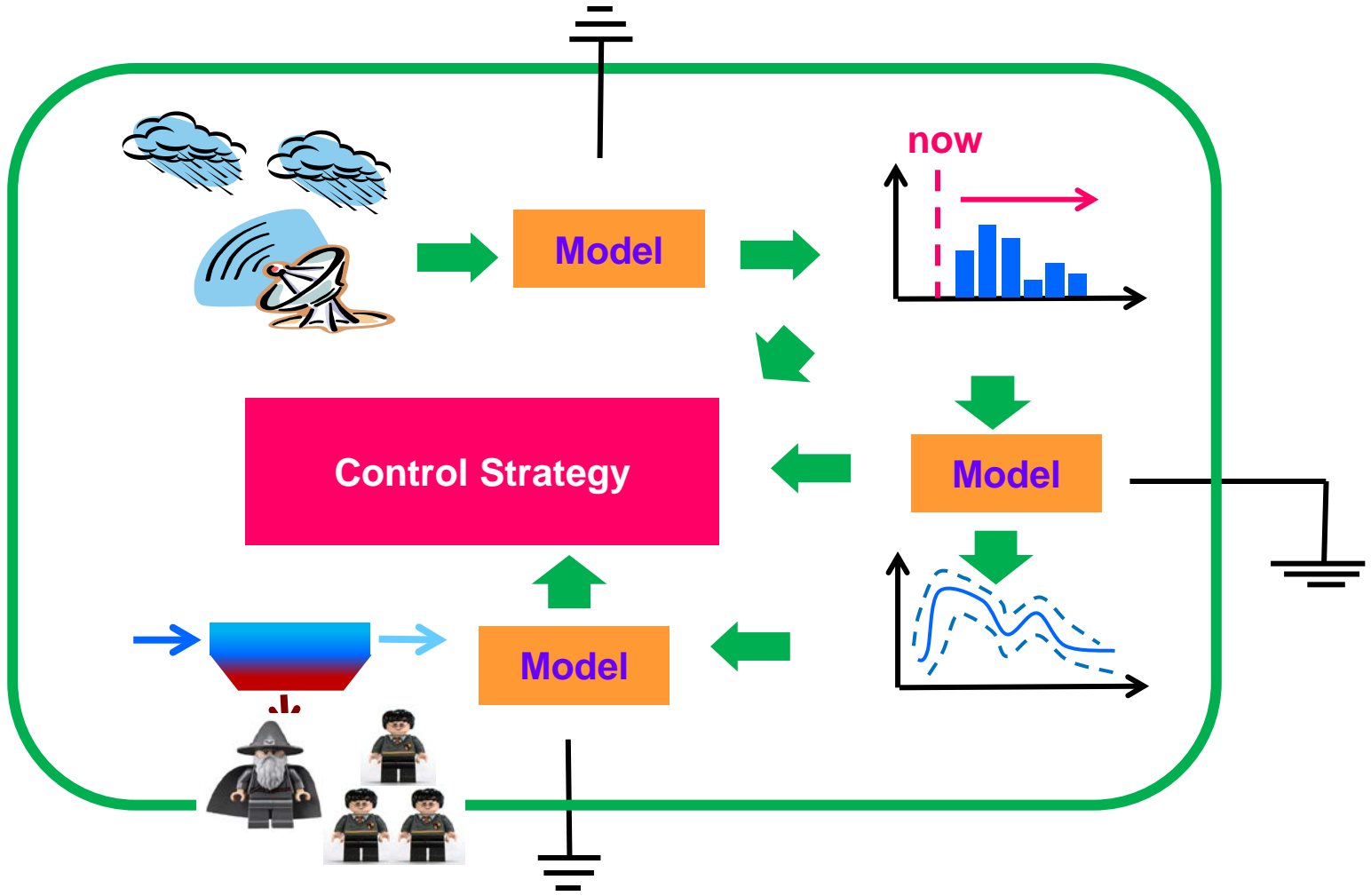


# The fellowship of SWI – the long journey



*The happy operator*

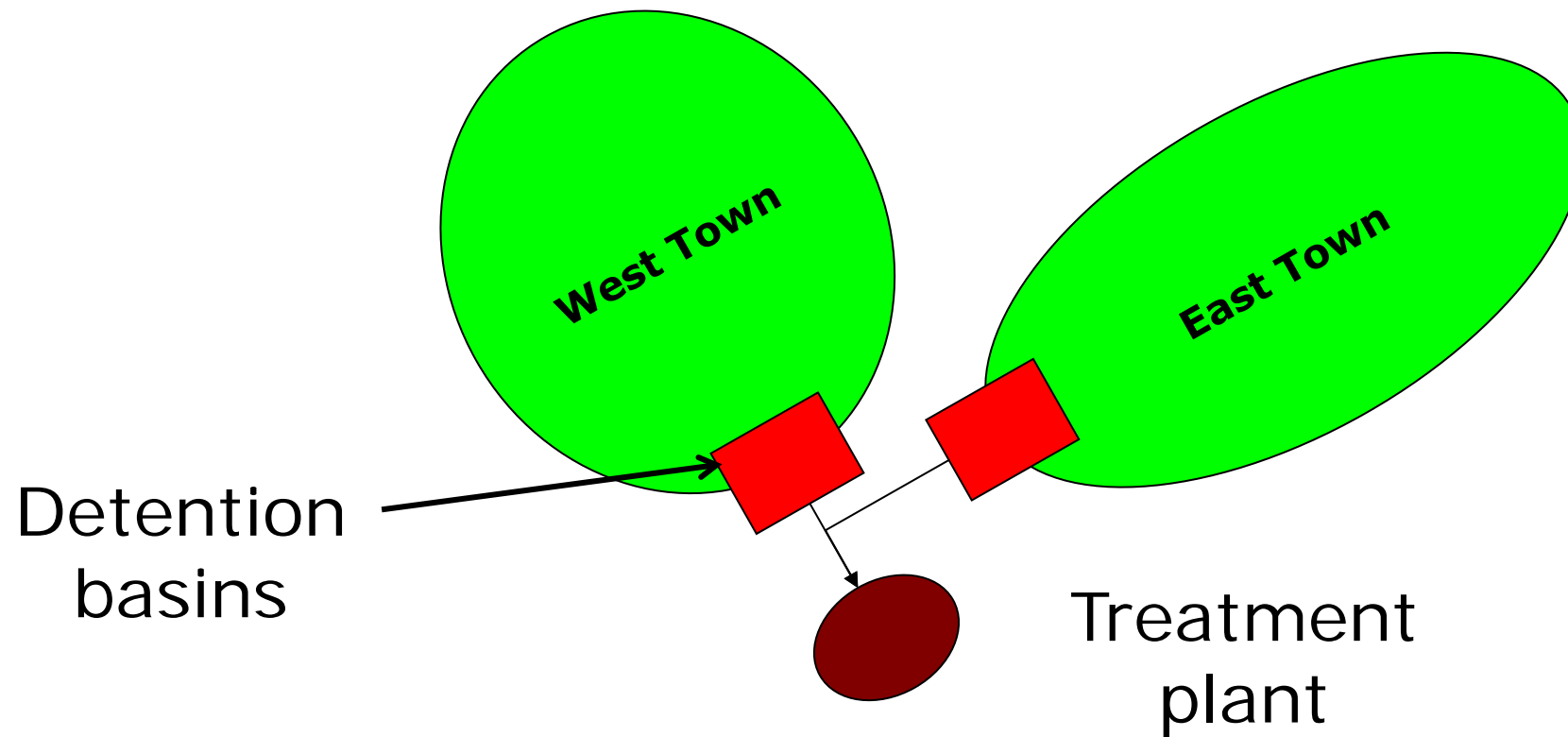
Measurements + Models + Forecasts + Uncertainty =



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

# Why uncertainty matters

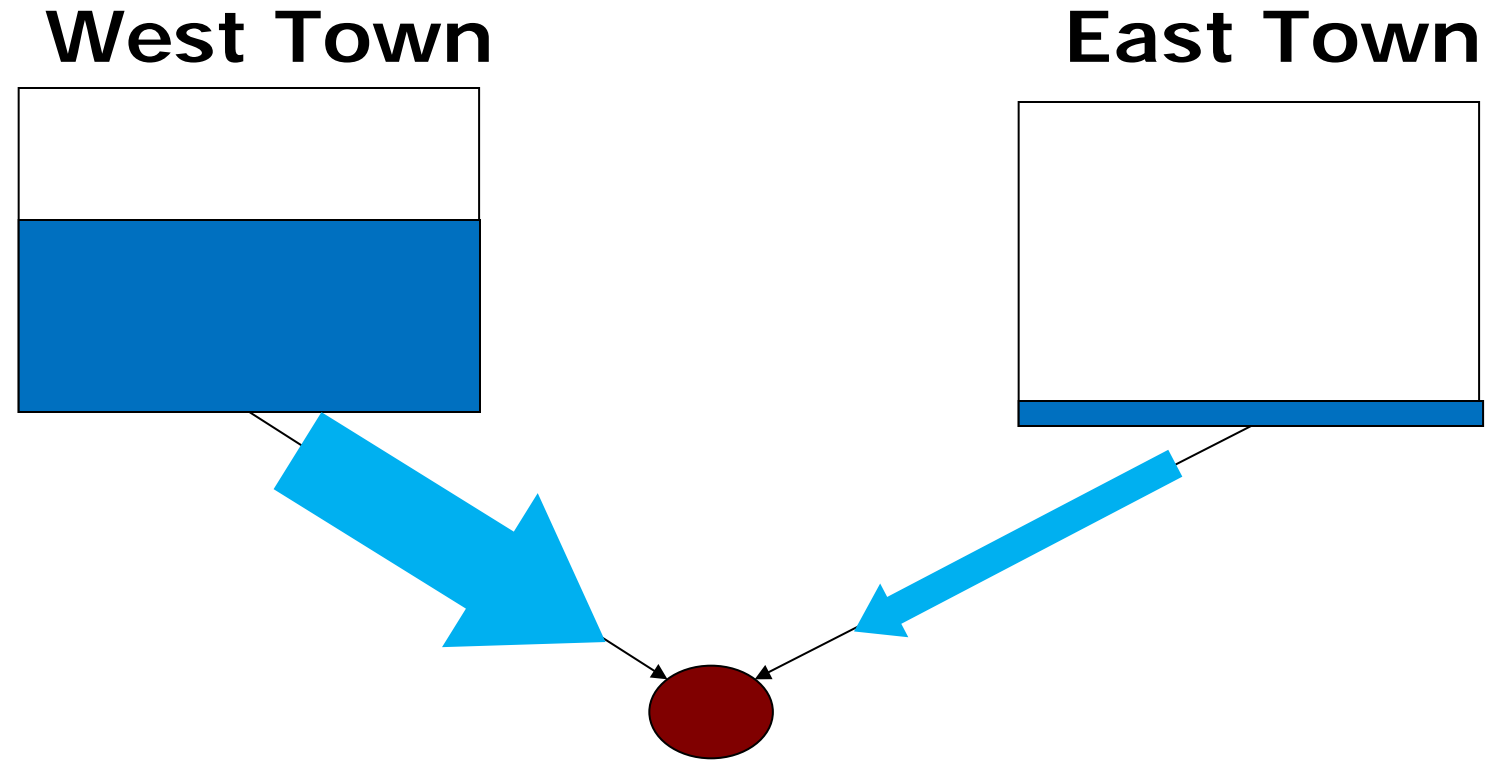
## Didactical example





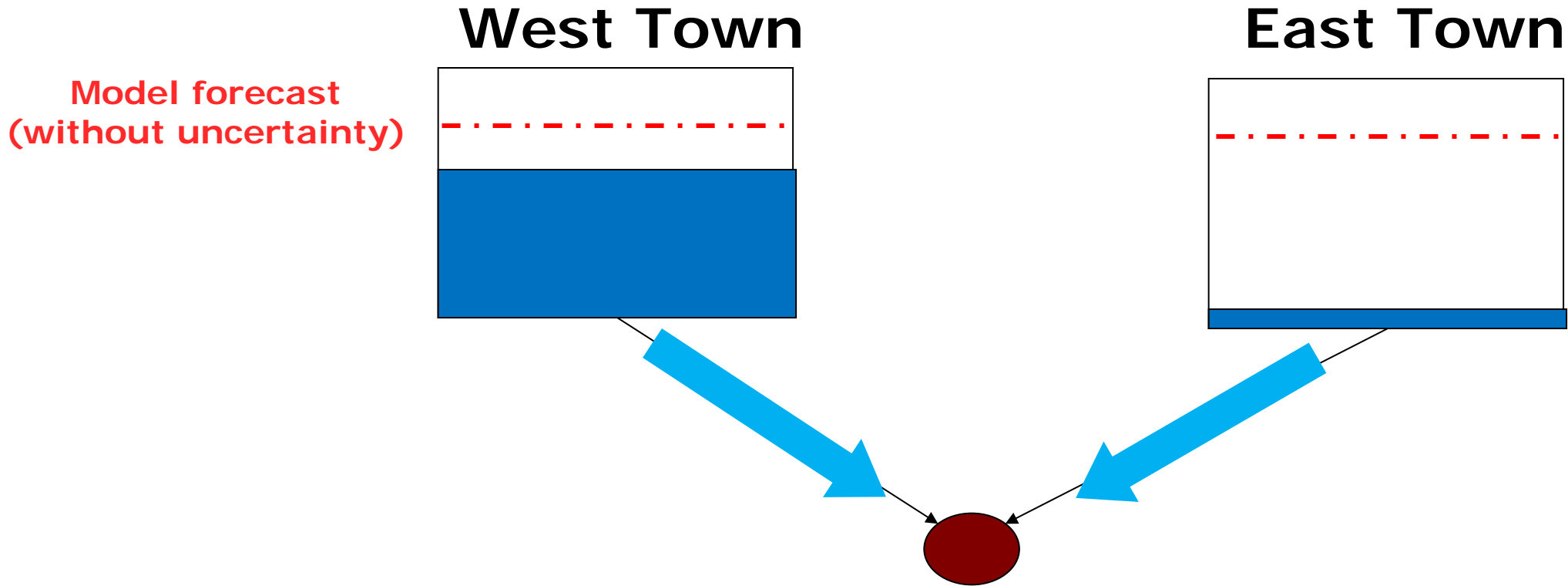
# Real Time Control

Objective:  
Maximize storage

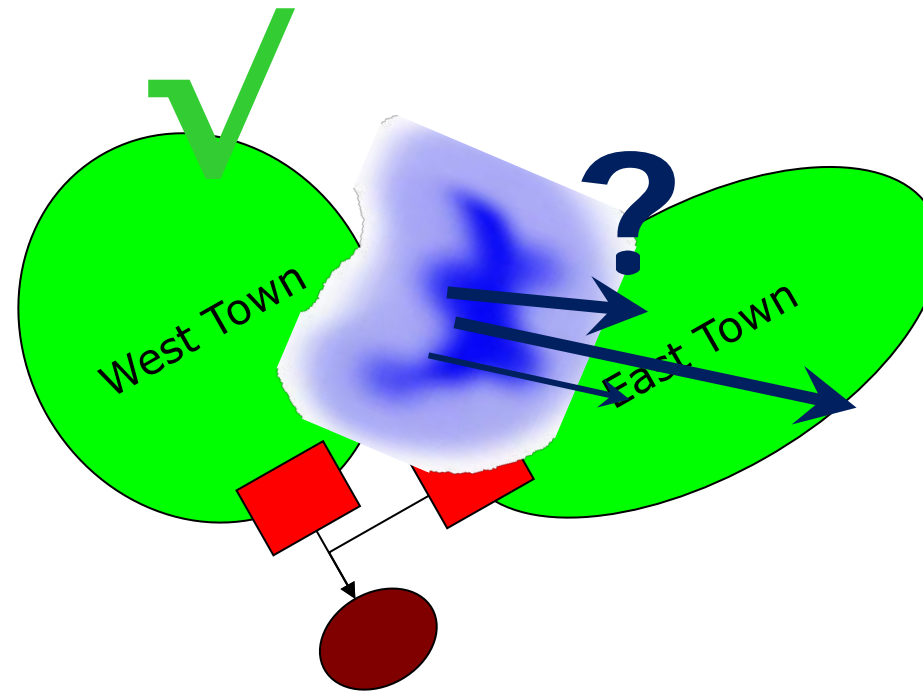


# "Traditional" MPC

Objective:  
Maximize future storage

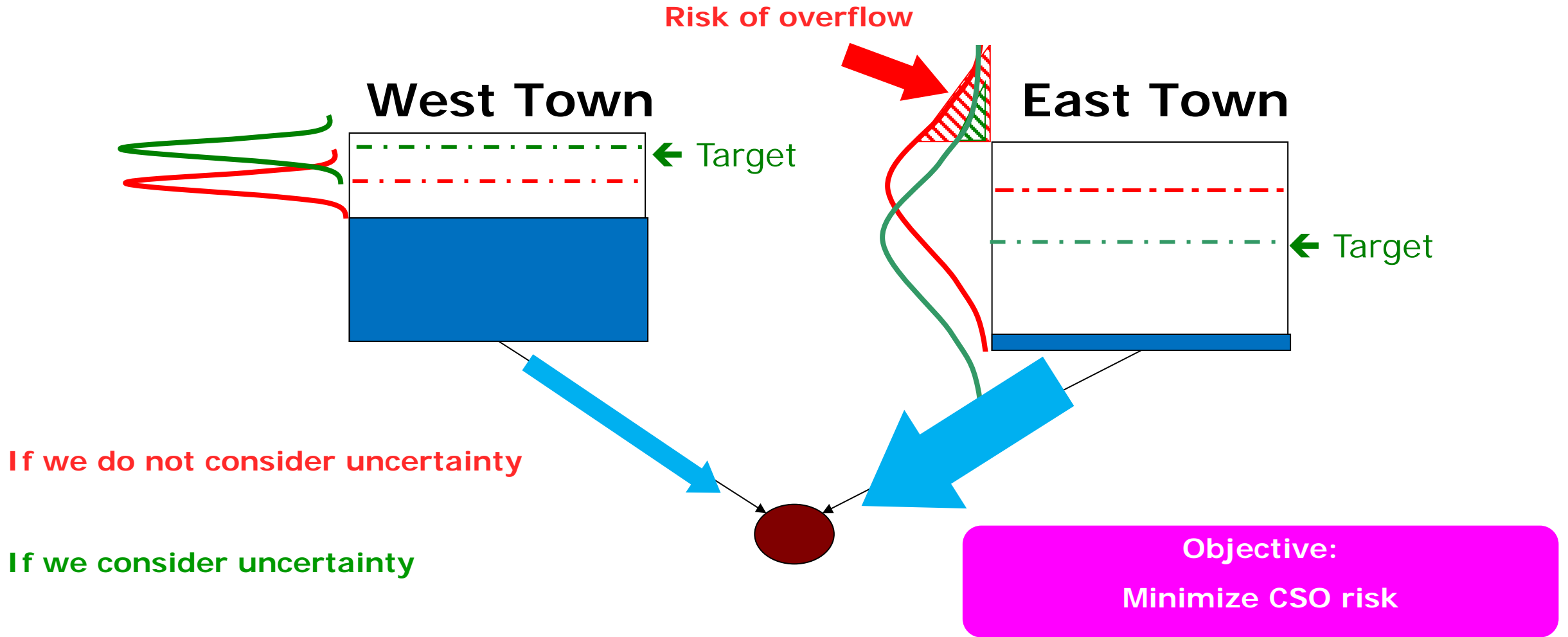


# Risk-based Model Predictive Control

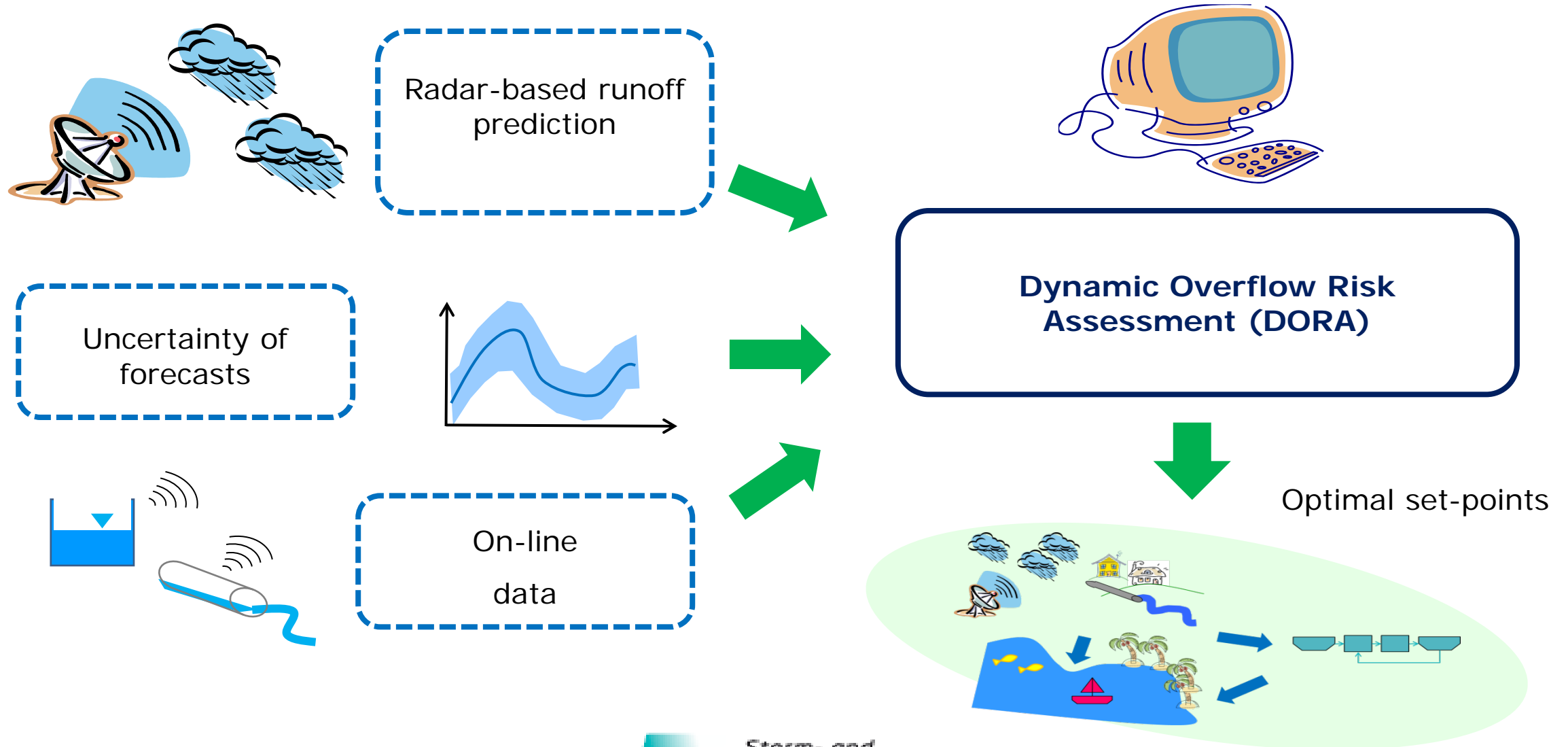


Rainfall evolution is  
uncertain

# Risk-based Model Predictive Control

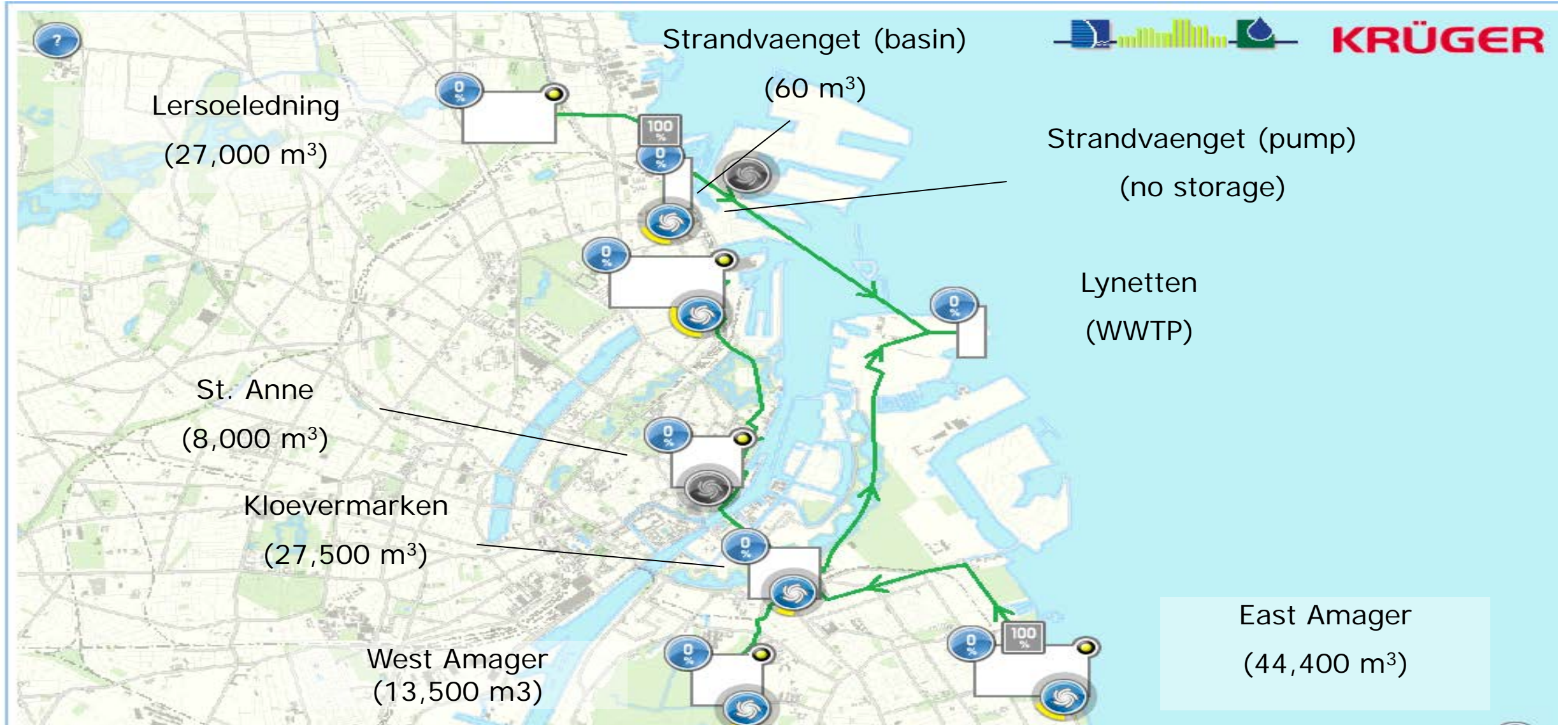


# The Dynamic Overflow Risk Analysis (DORA)



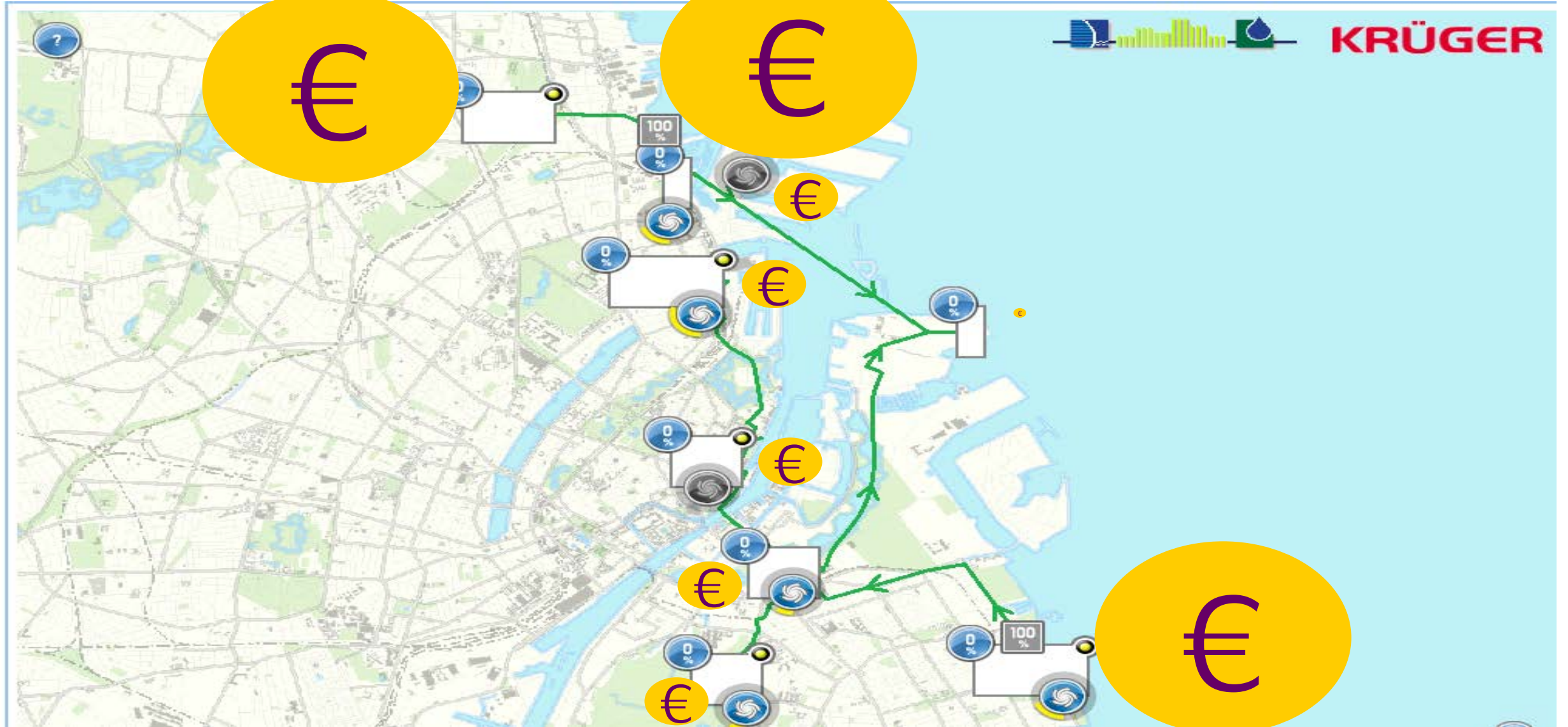
# The Lynetten catchment

## Central Copenhagen, Denmark

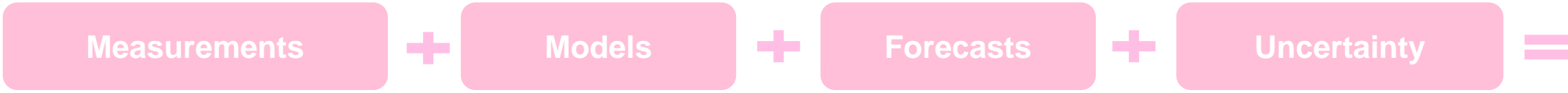




# Sensitivity of overflow recipient CSO "price"

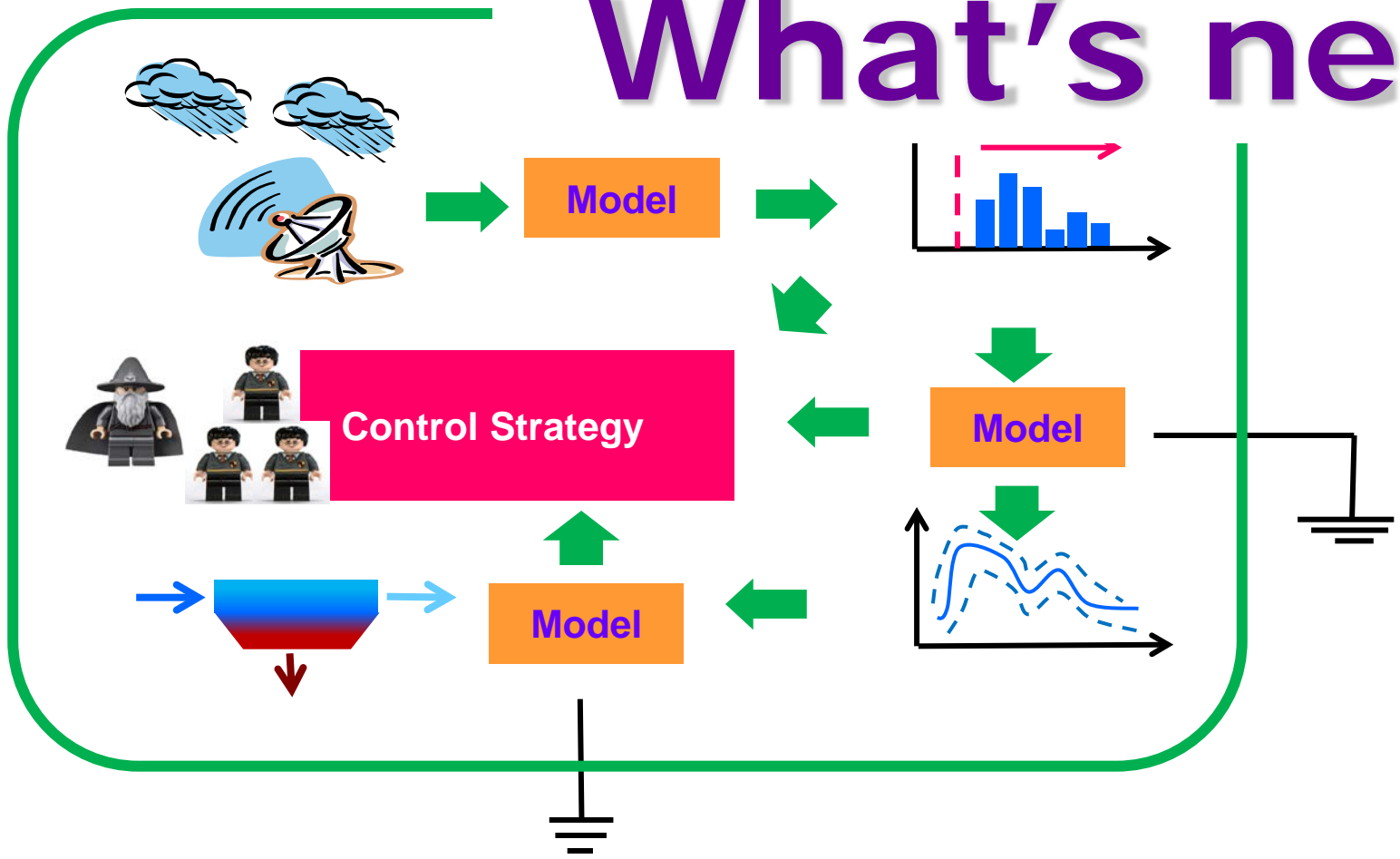


# The fellowship of SWI – the long journey



*The happy operator*

## What's next?



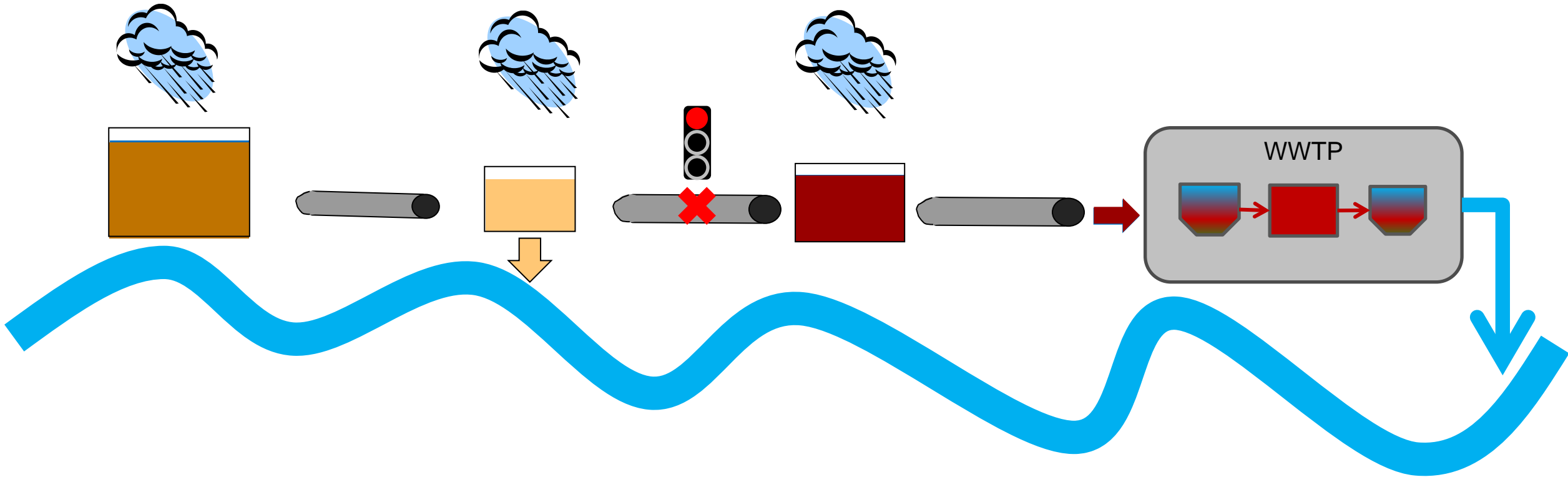
measurements  
in rainfall forecasts

- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
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# Water Quality-based control

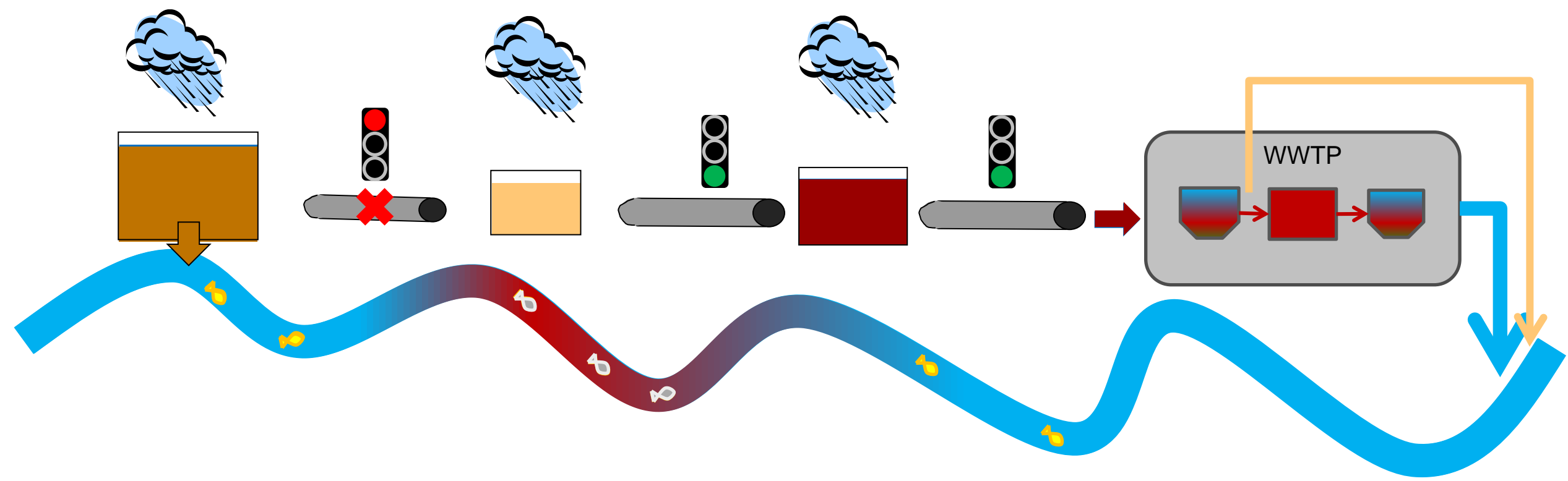


- Pollutant concentrations are not uniform →



# Water Quality-based control

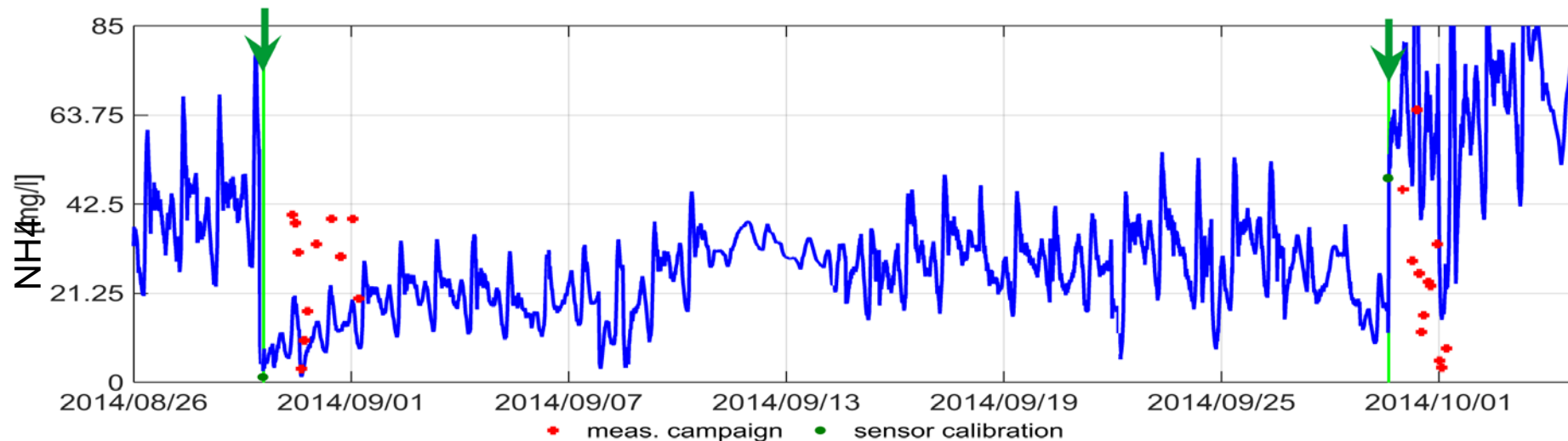
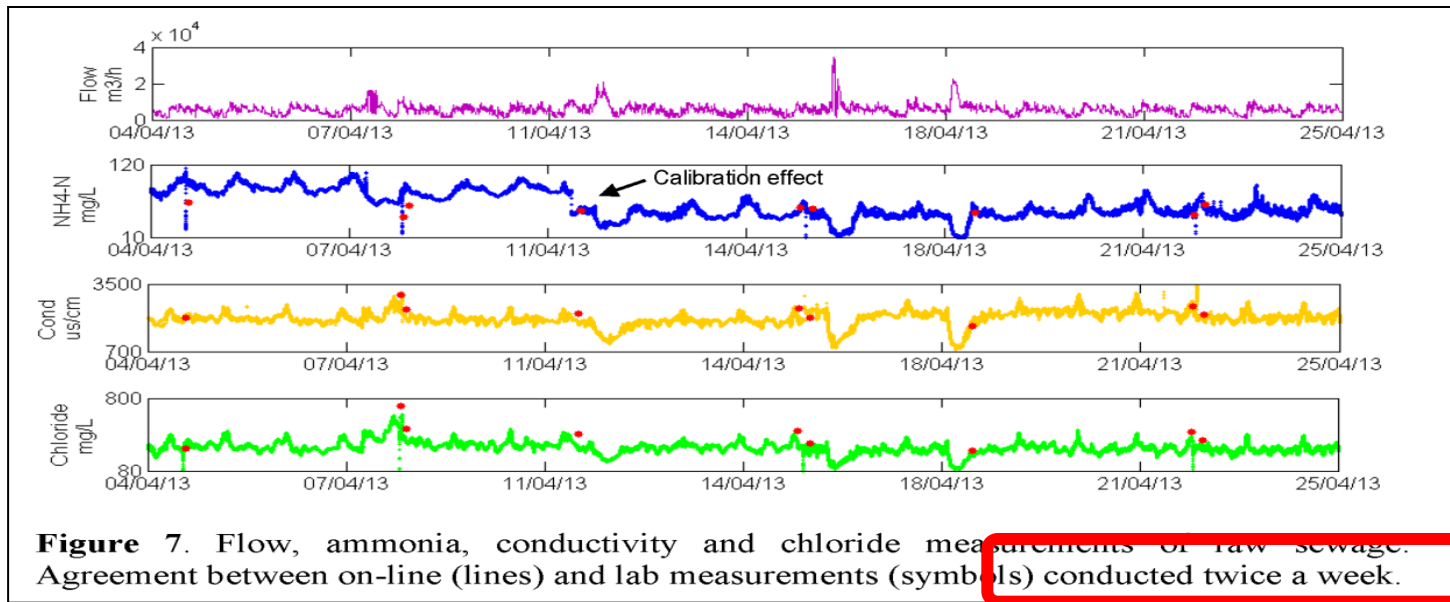
- Pollutant concentrations are not uniform → we can control the system based on Water Quality (instead of water quantity)
- The natural waters have not all the same status →



# 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

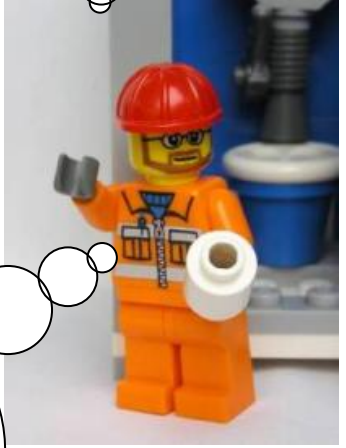
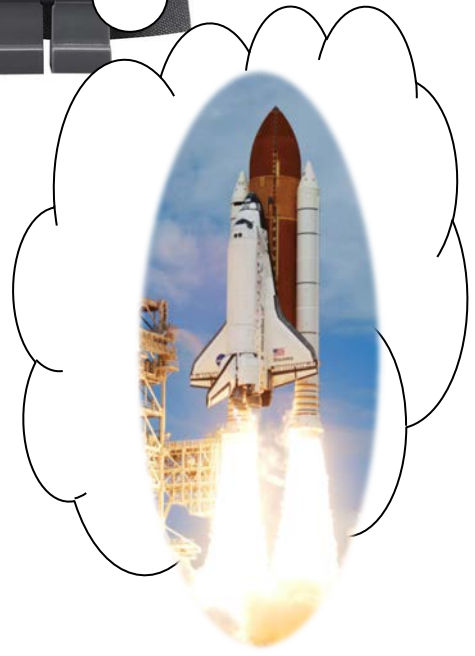


Photo by Ravi Kumar Chhetri



Sensor  
Maintenance  
Multivariate DQC  
Software Sensors  
...

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



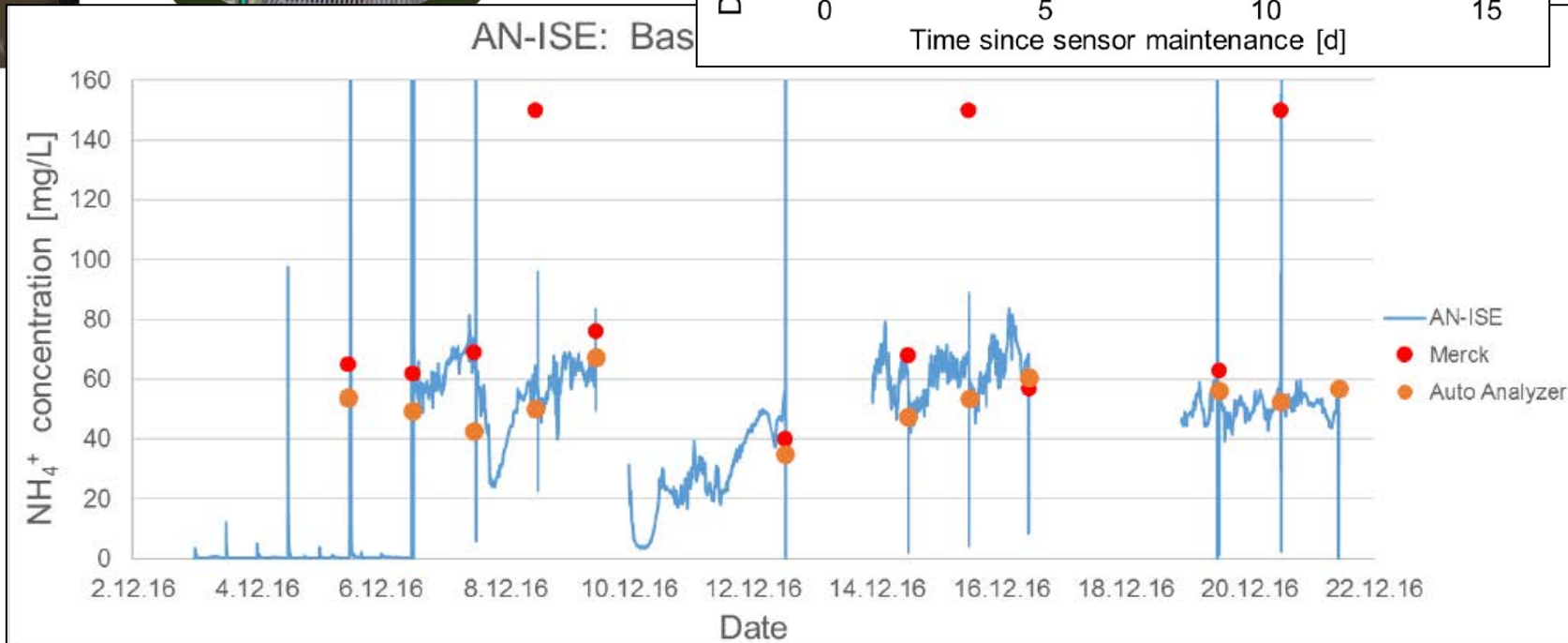
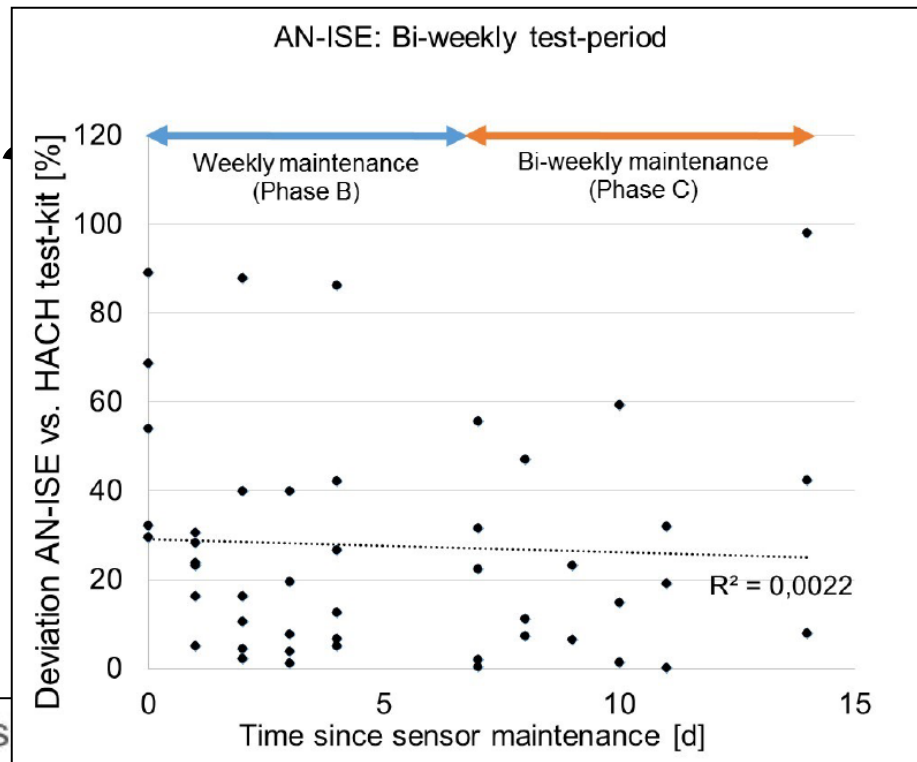
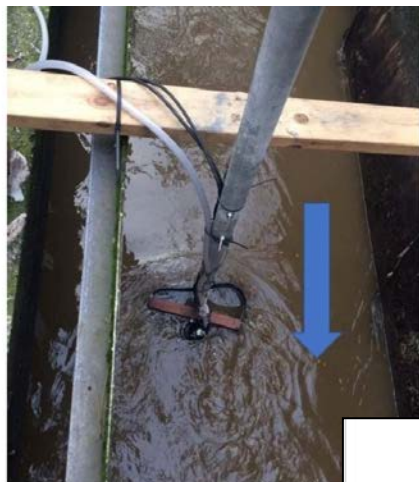


# The Ålebækken "playground"



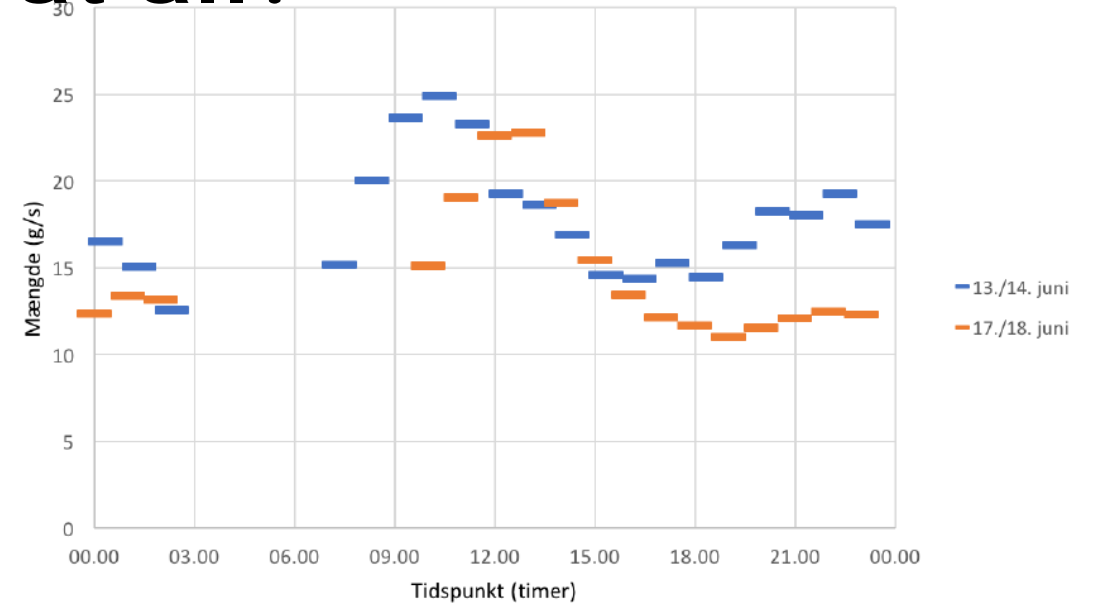


# How much can we trust sensors

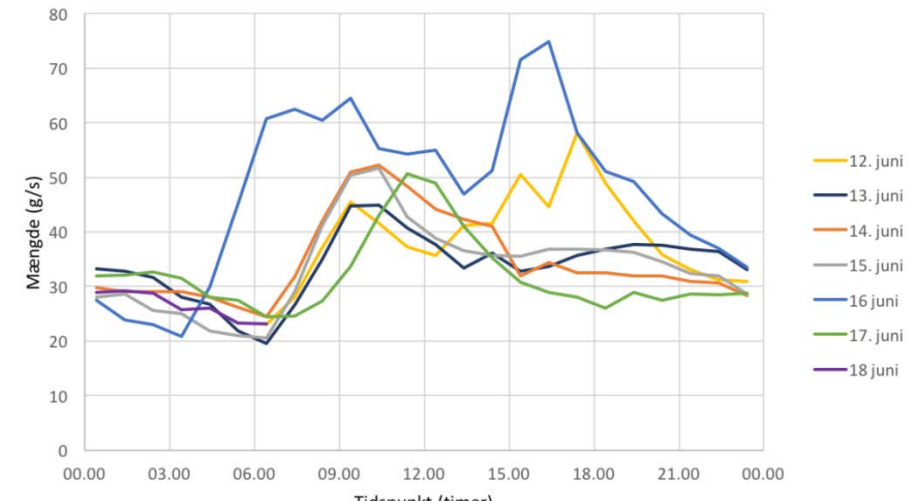


# Do we need fancy sensors at all?

Daglig variation (autosampler)



Daglig variation JUNI



# 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



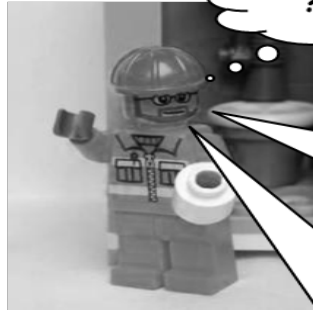
Dear smart people from university, what wonderful tool did you prepare for me?



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