



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

**Vezzaro, Luca**

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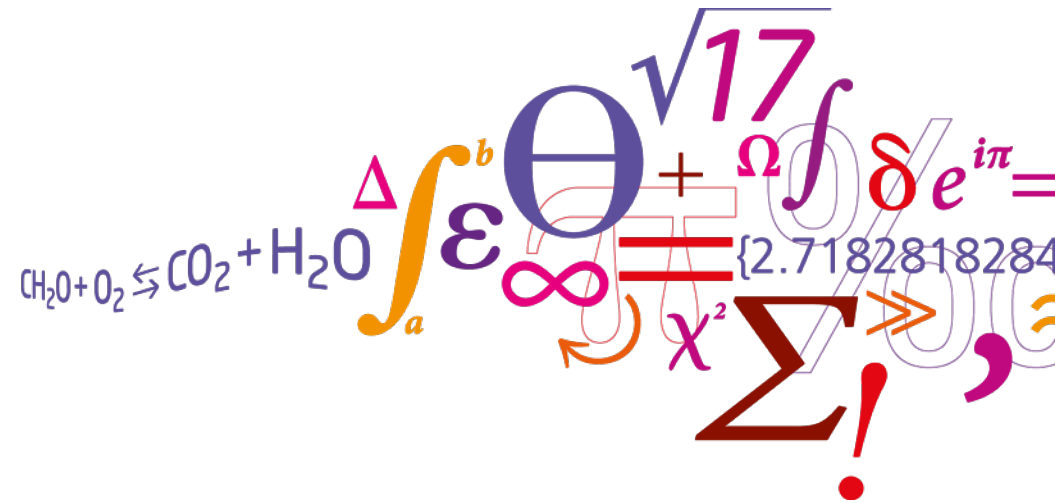
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# Kan vi få et bedre miljø med smartere kloakker?

Lektor Luca Vezzaro

# Forskning Døgn

Slagelse, d. 26. april 2018



**DTU Environment**  
Department of Environmental Engineering

# 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")

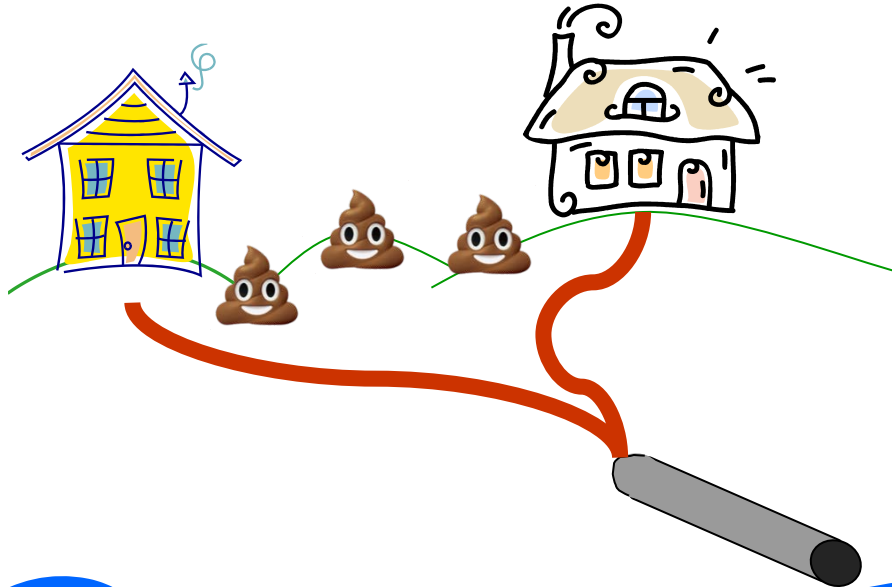




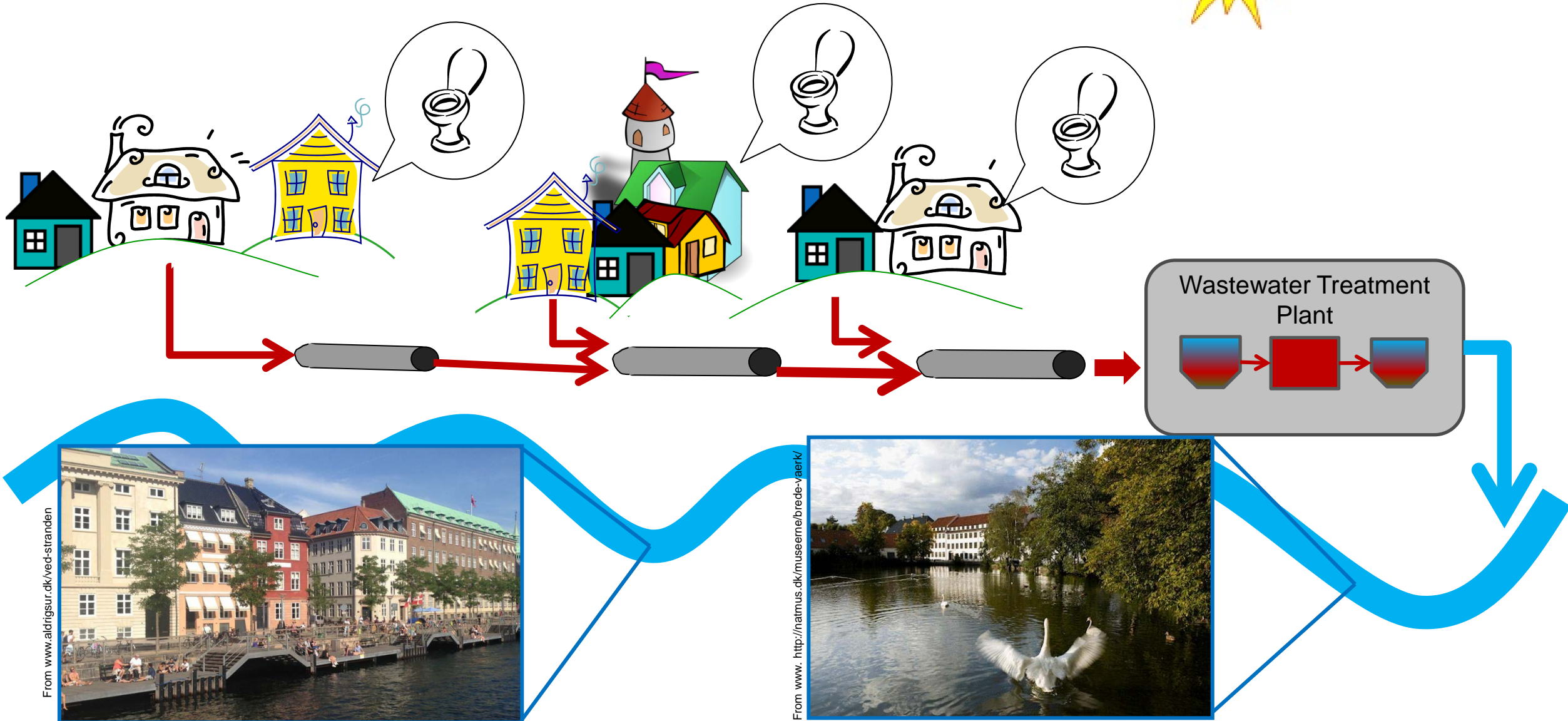
# Why do we have sewers?

# Why do we have sewers?

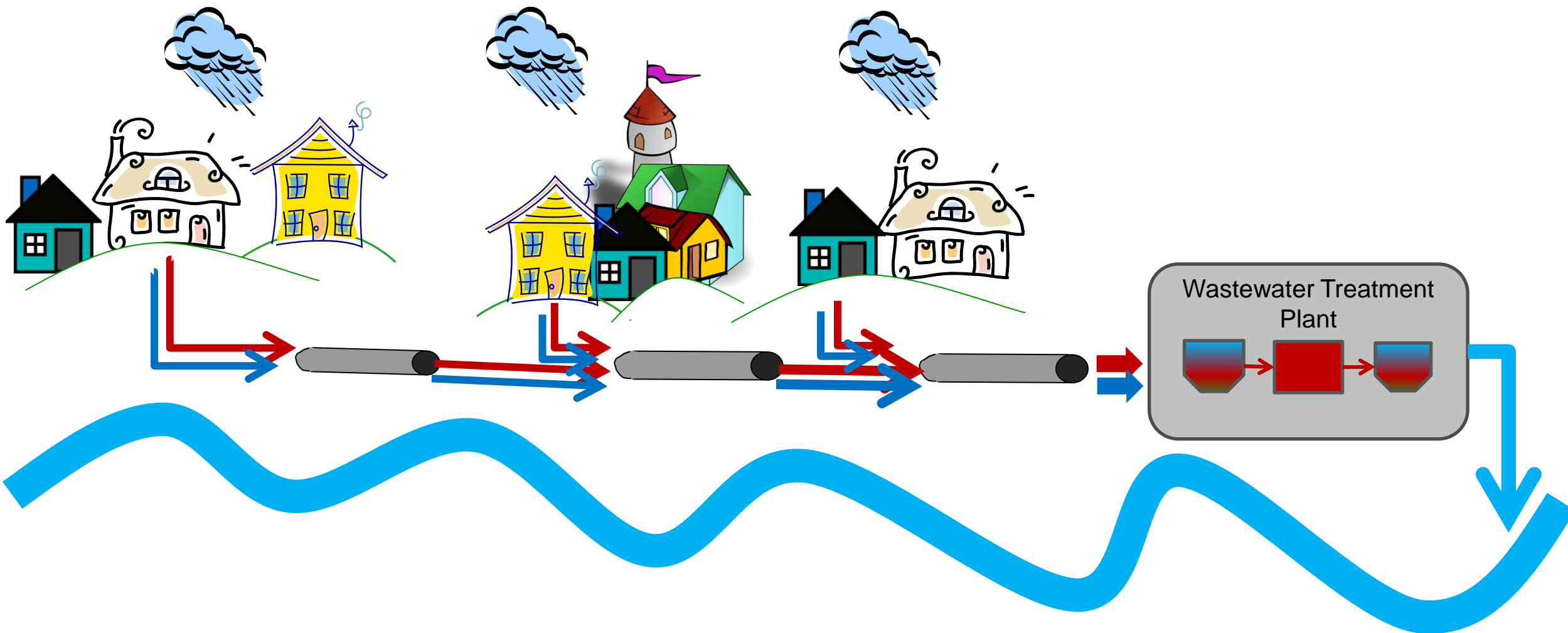
Before 1800  
(Western Cities)



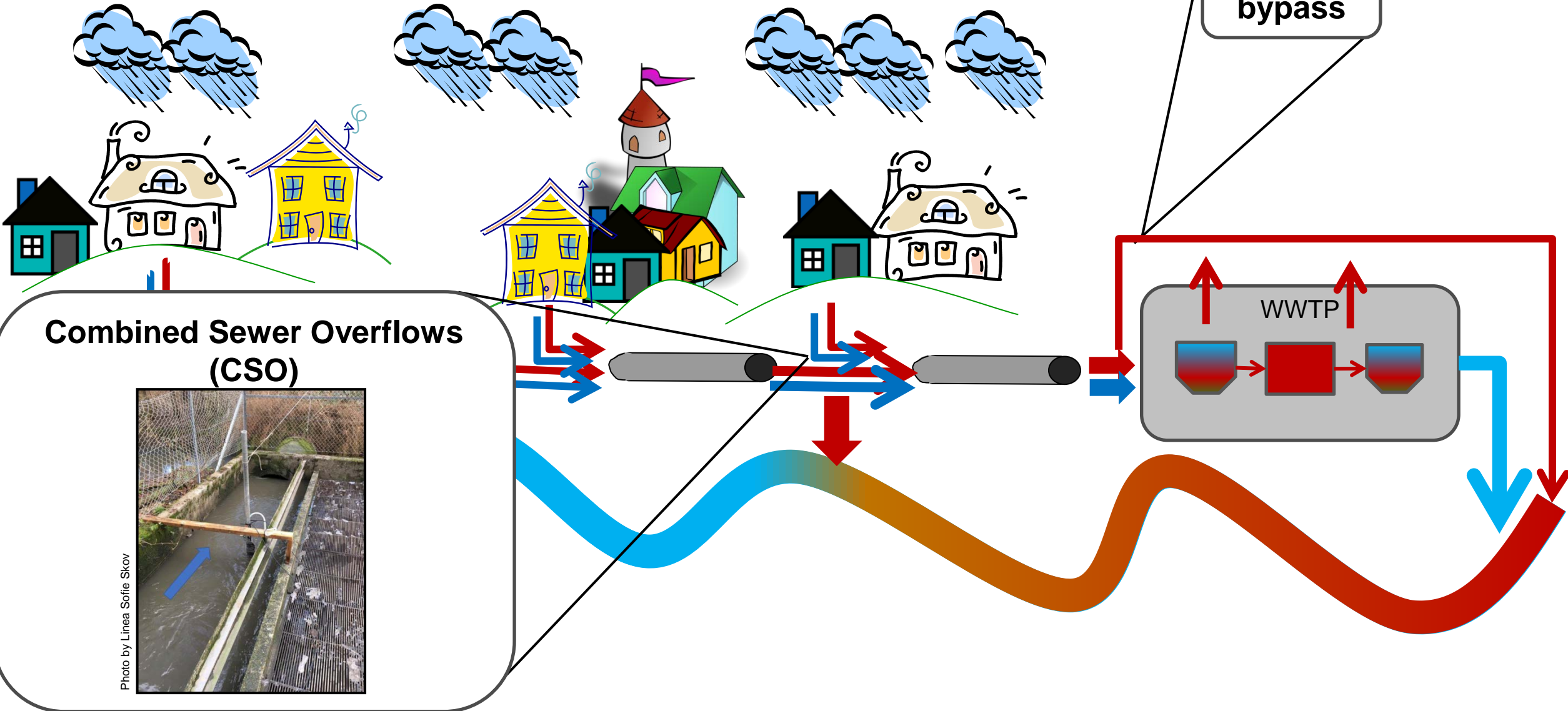
# Our cities when sun is shining...



...but sometimes it rains...



...and it rains more...



Combined Sewer Overflows (CSO)



Photo by Linea Sofie Skov

WWTP bypass

WWTP



# ...and it rains more...



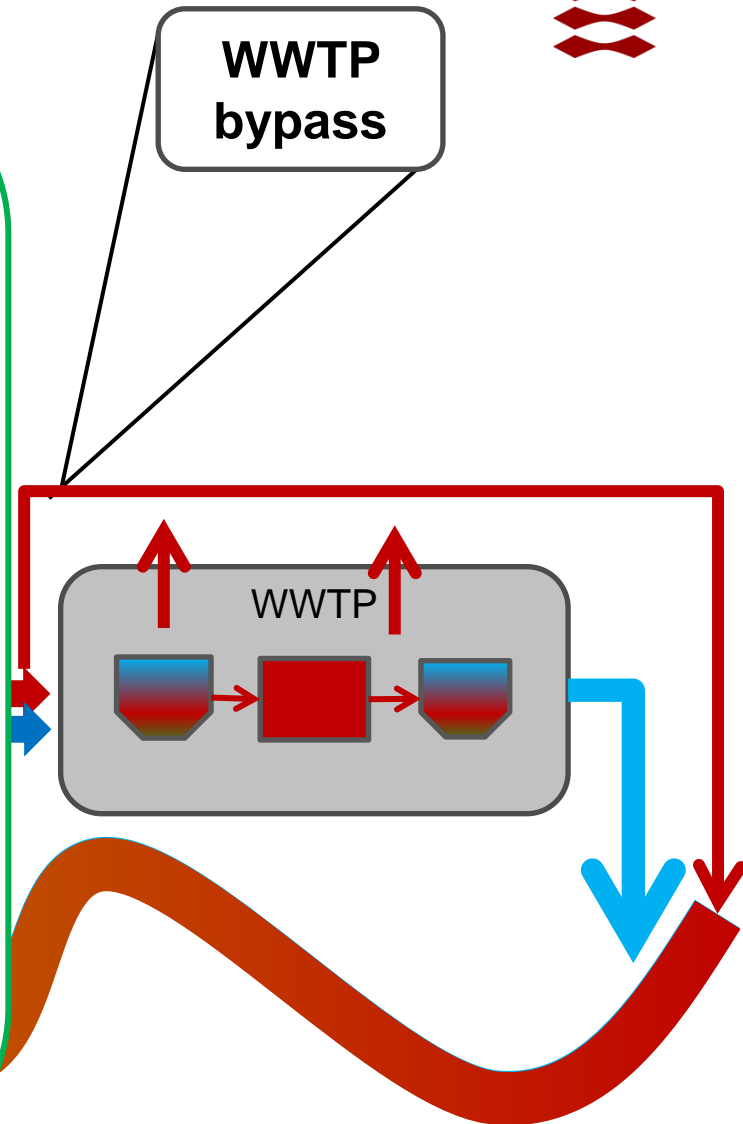
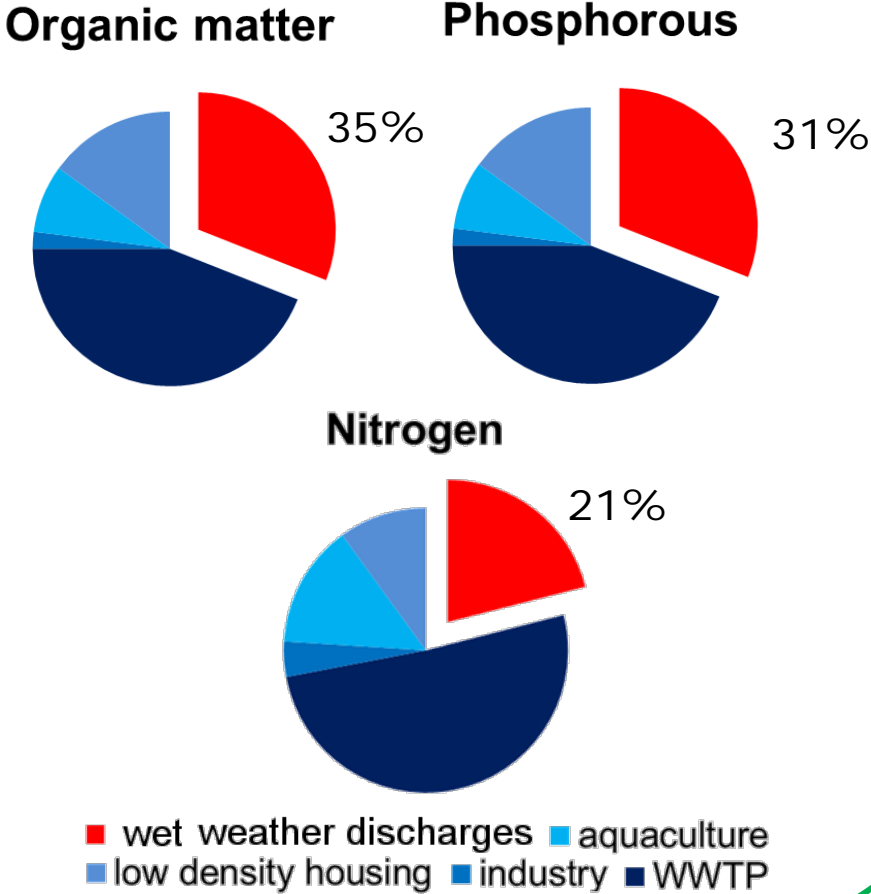
## Combined Sewer Overflows (CSO)



Photo by Linea Sofie Skov

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

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



# ...and it rains more...



## Combined Sewer Overflows (CSO)

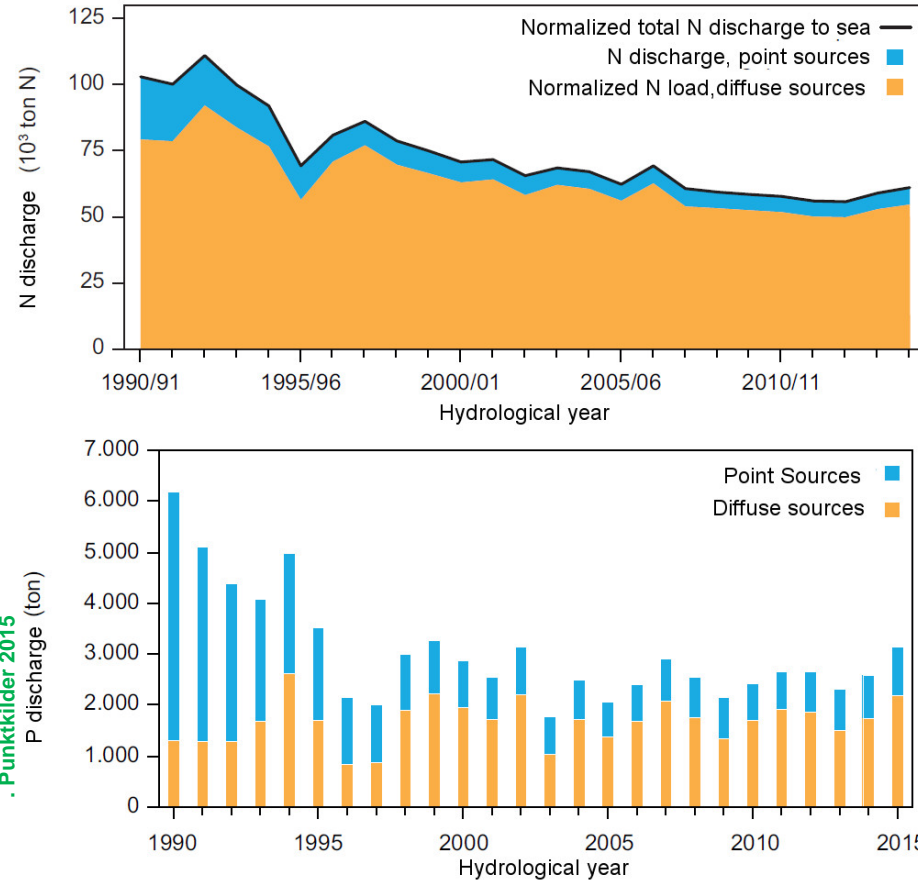


Photo by Linea Sofie Skov

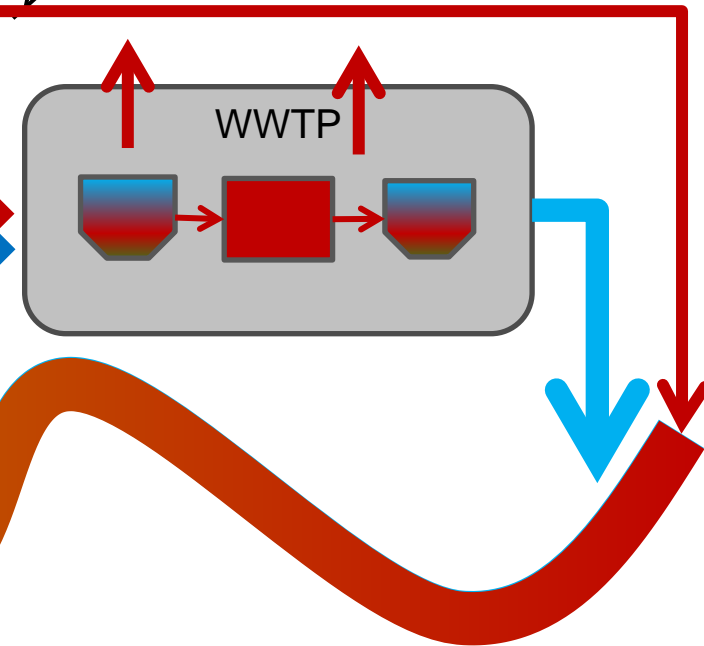
Source: Miljø- og Fødevarerministeriet Styrelsen for Vand- og Naturforvaltning (2017)

. Punktkilder 2015

## Pollutant contribution from point discharges in DK



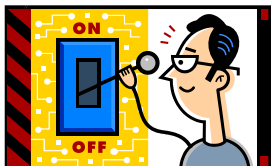
WWTP bypass



# 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

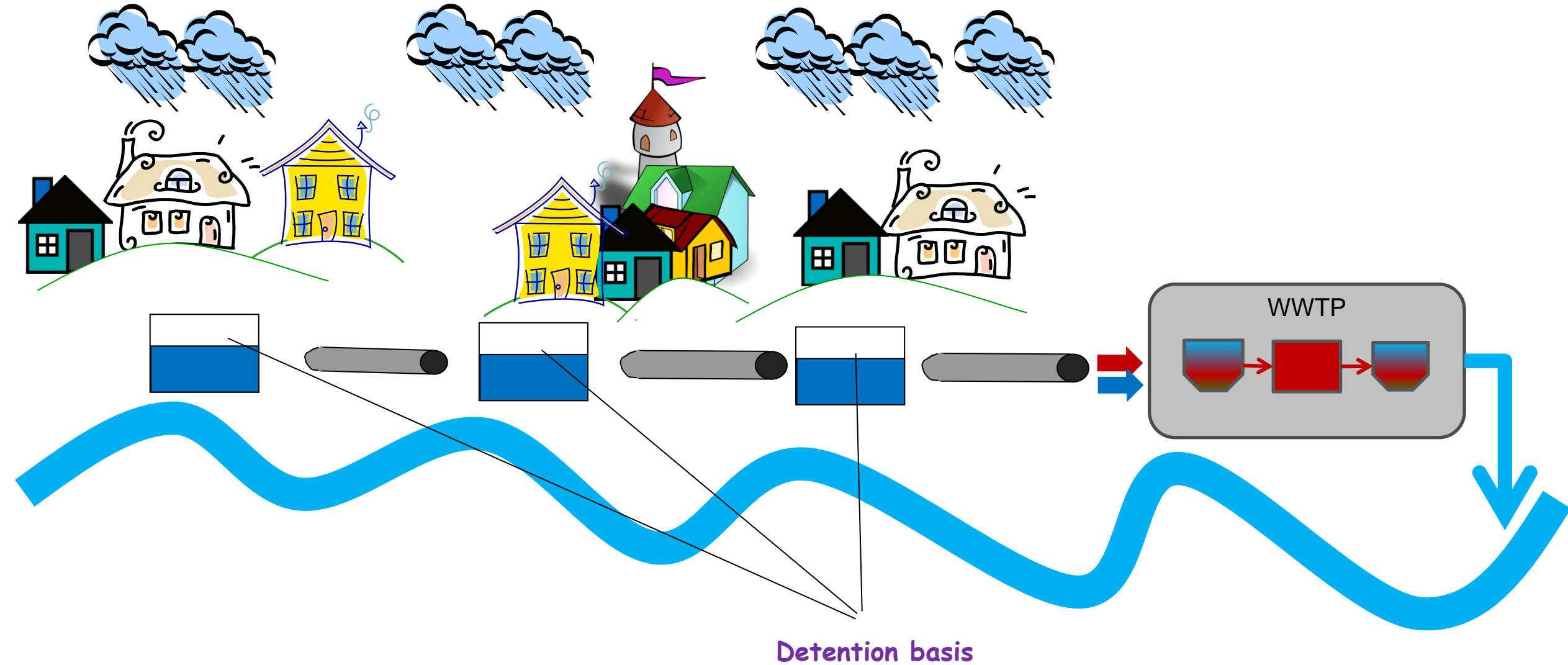
- Many projects
  - Storm- and Wastewater Informatics (SWI)
  - Klimaspring
  - Prepared
  - AMOK
  - Water Smart Cities



- Industrial PhDs
- Industrial postdocs
- Many MSc theses



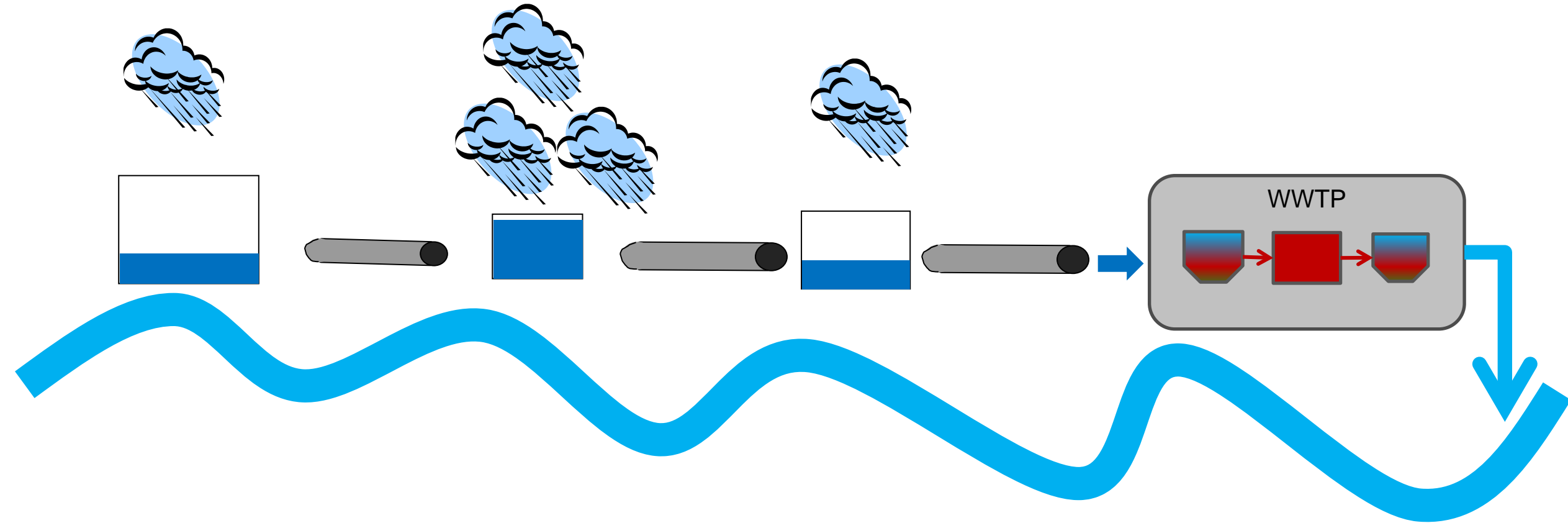
# One option to avoid overflow...





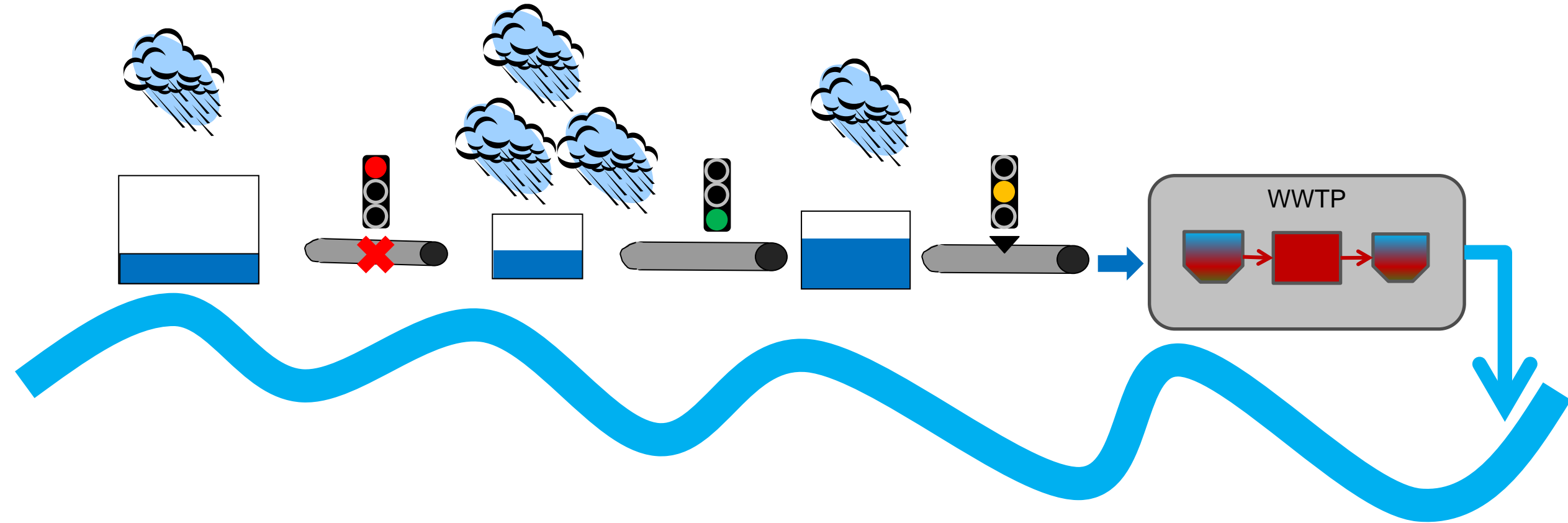
# Real Time Control of drainage network

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



# Real Time Control of drainage network

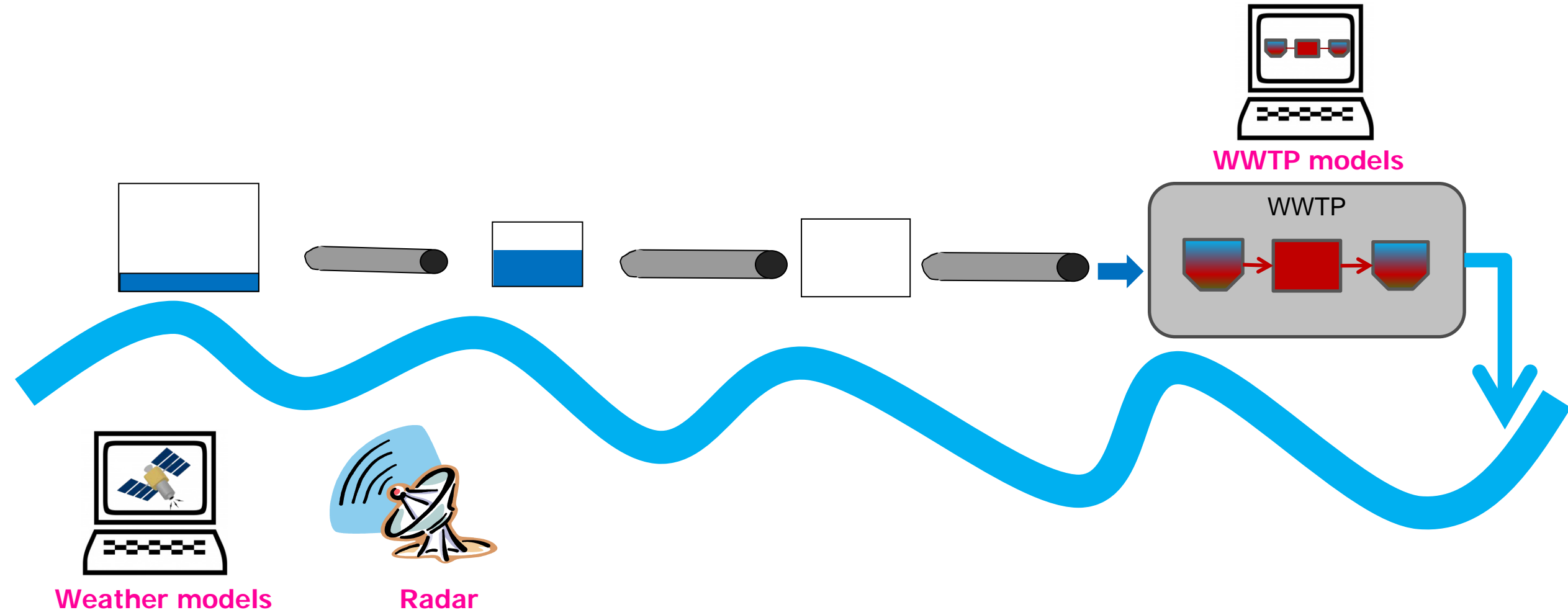
- Rain is not uniform → we can optimize the storage across the system → less overflow
- WWTP doesn't like high flows → we can regulate the inlet flow to the WWTP → less bypass





# Model Predictive Control

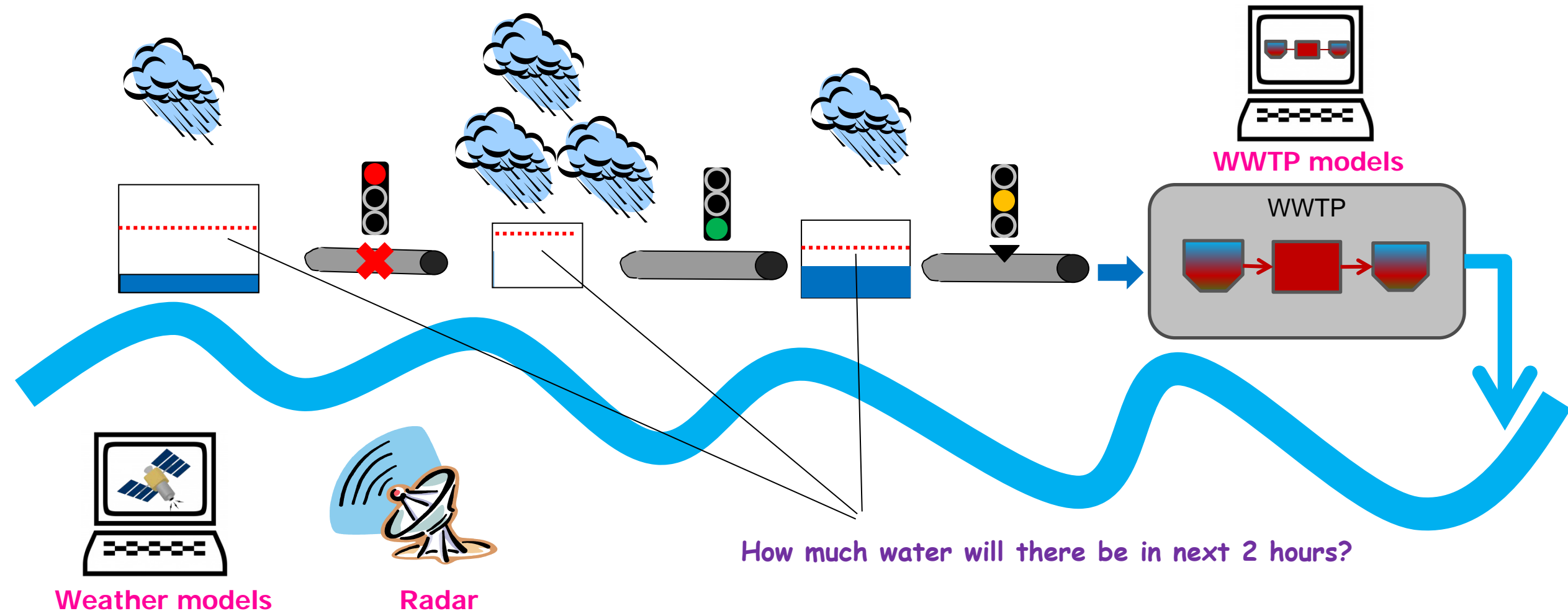
- We can forecast rainfall → where and how much is going to rain → even less CSO
- We can forecast WWTP status → how much water the WWTP can treat → even less bypass





# 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

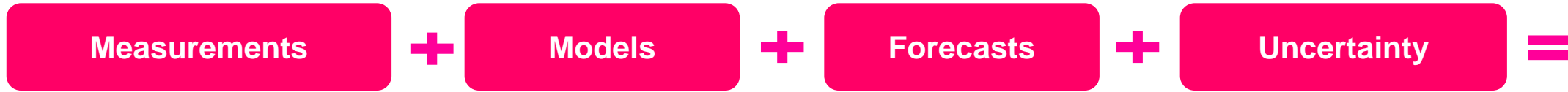


# The SWI concept

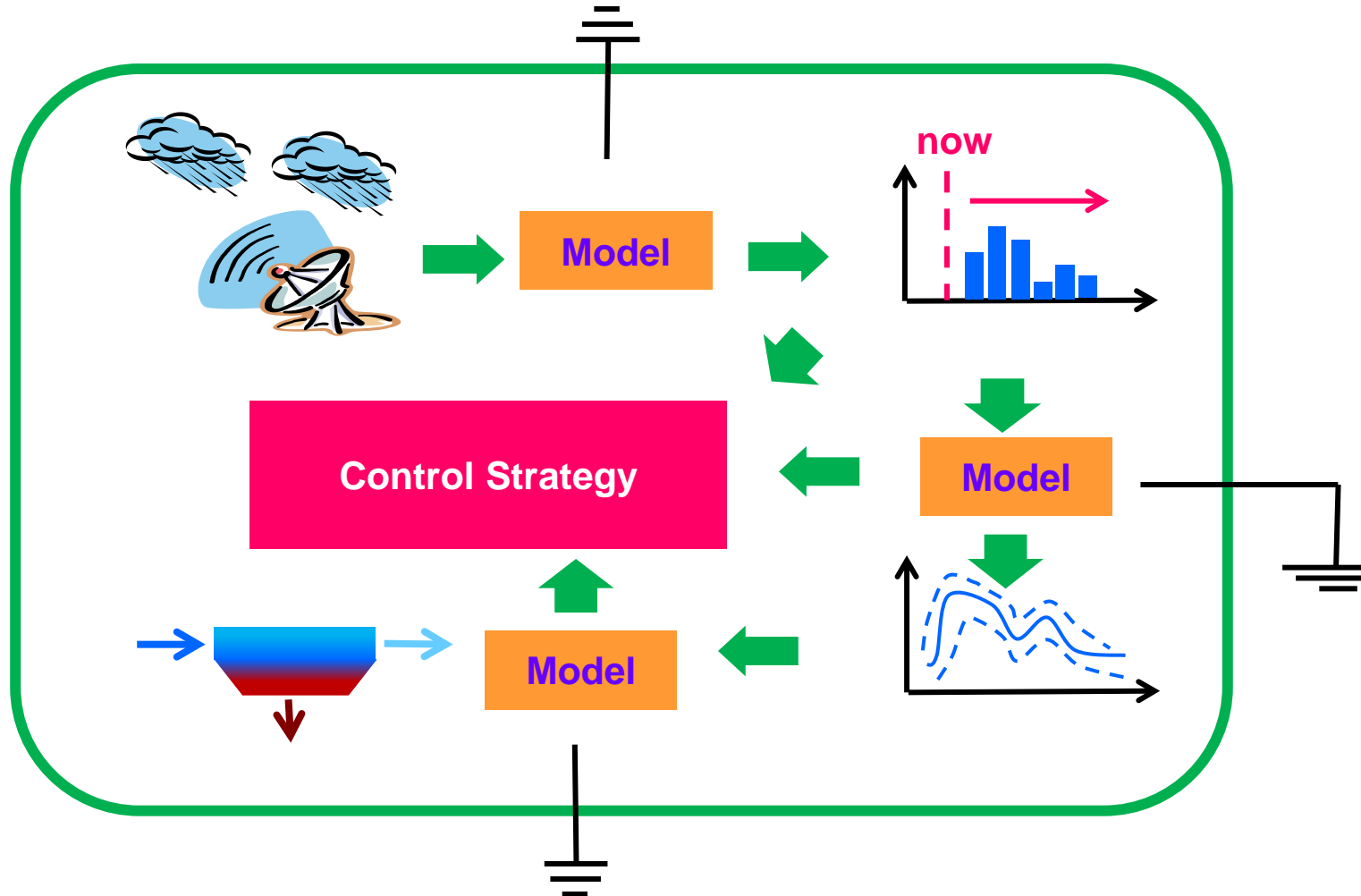


*The happy operator*

# The fellowship of SWI – the long journey

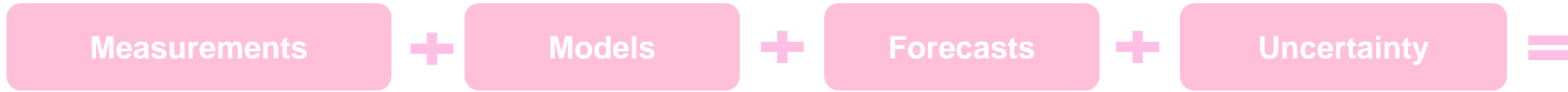


*The happy operator*

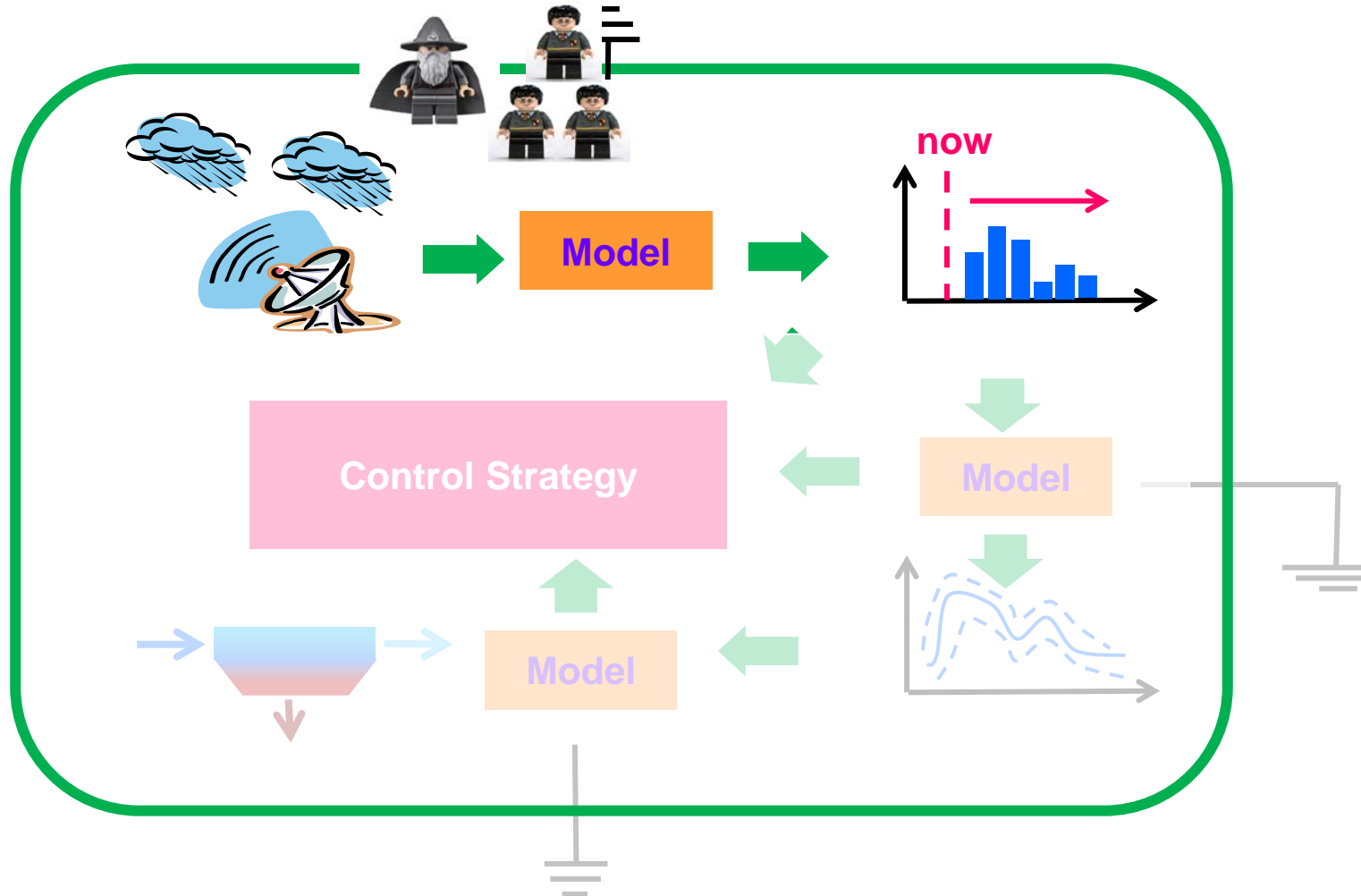


- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

# The fellowship of SWI – the long journey



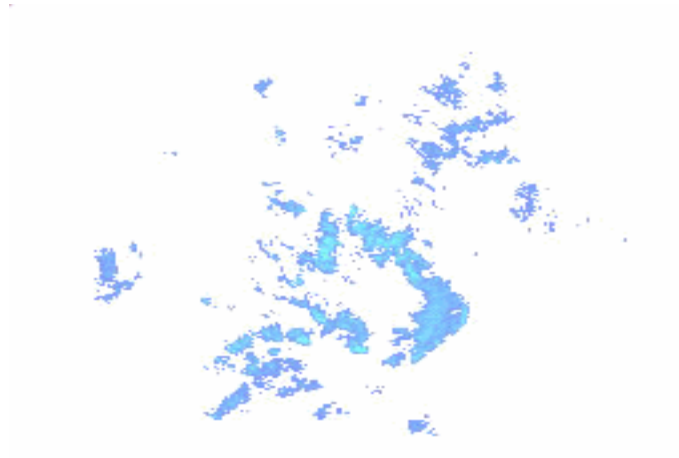
*The happy operator*



- 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

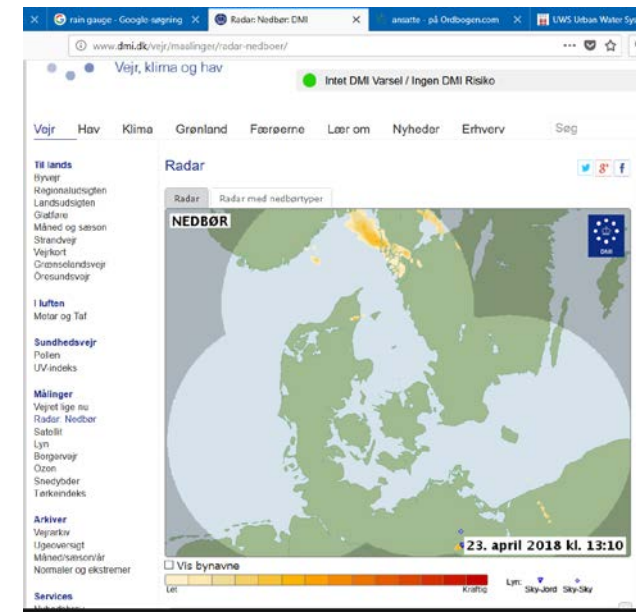


Slagelse Pumpestation (5485)



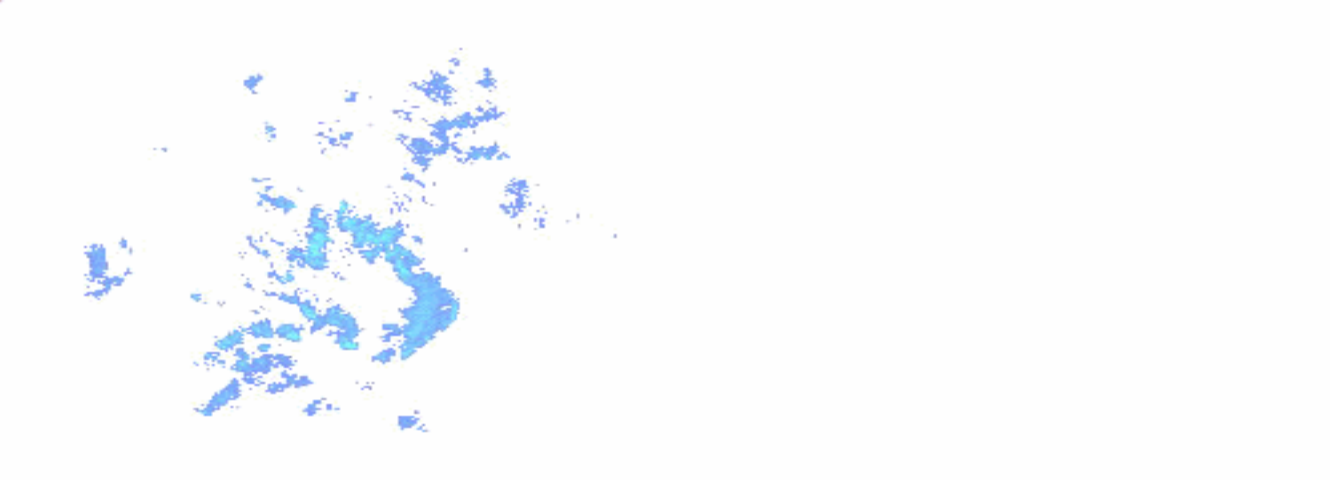
Slagelse centralrenseanlæg (5490)

Radar



# Rainfall input

Where is it raining?  
And how much?



- Rainfall is not easy to measure

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

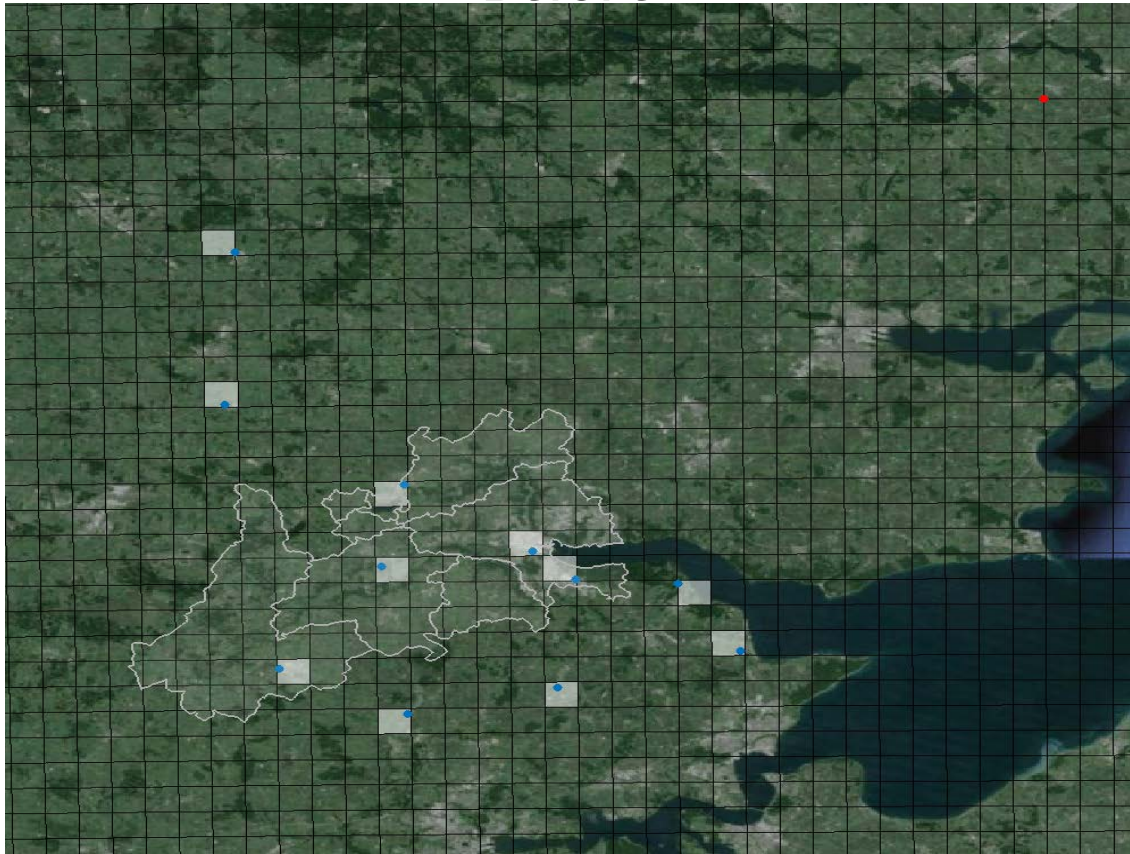
- But you can combine them



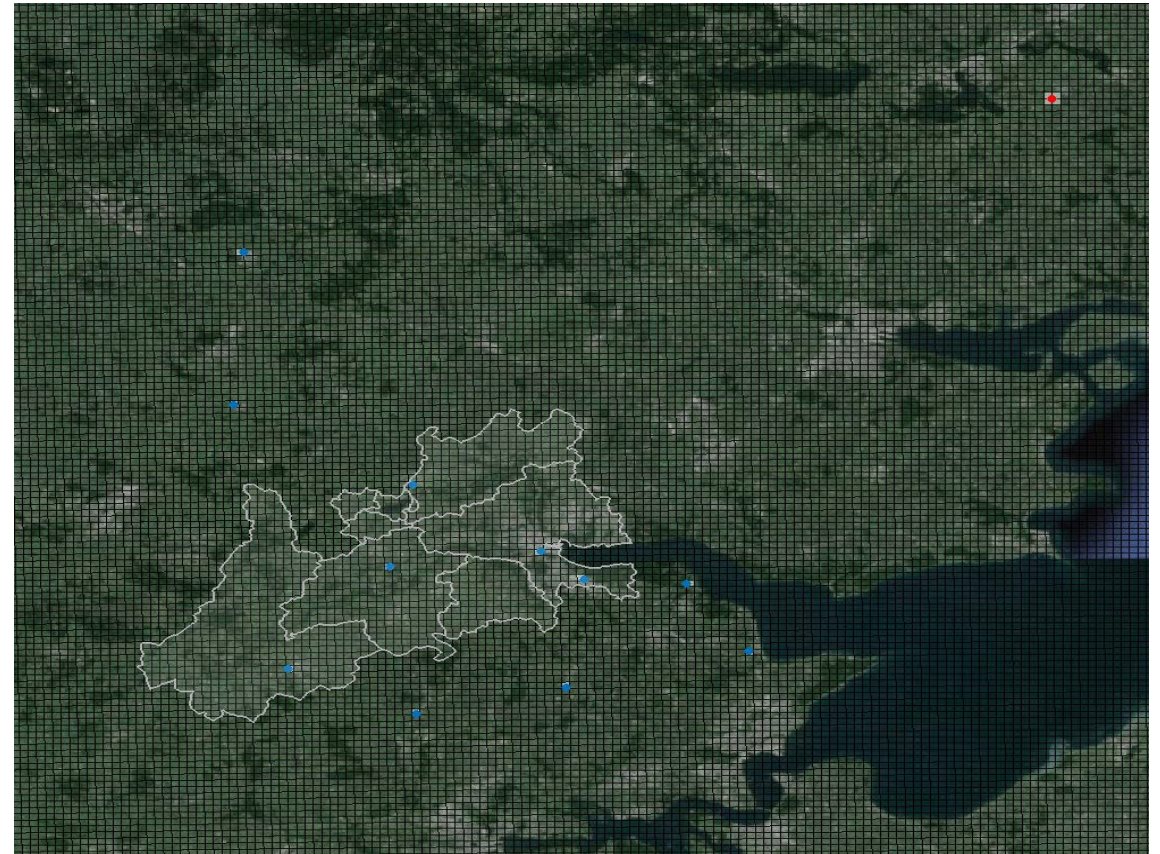
# The new AAU Nowcaster

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

Before



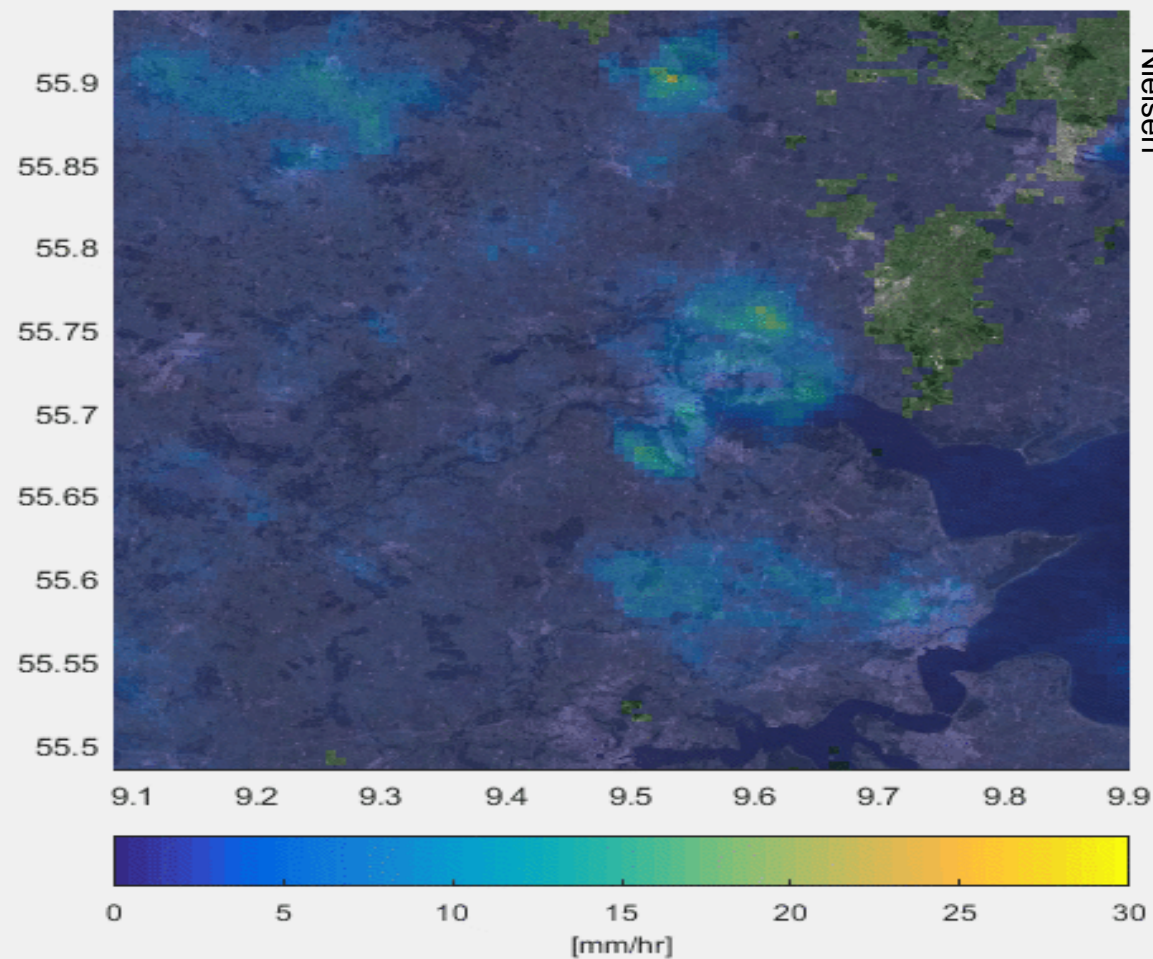
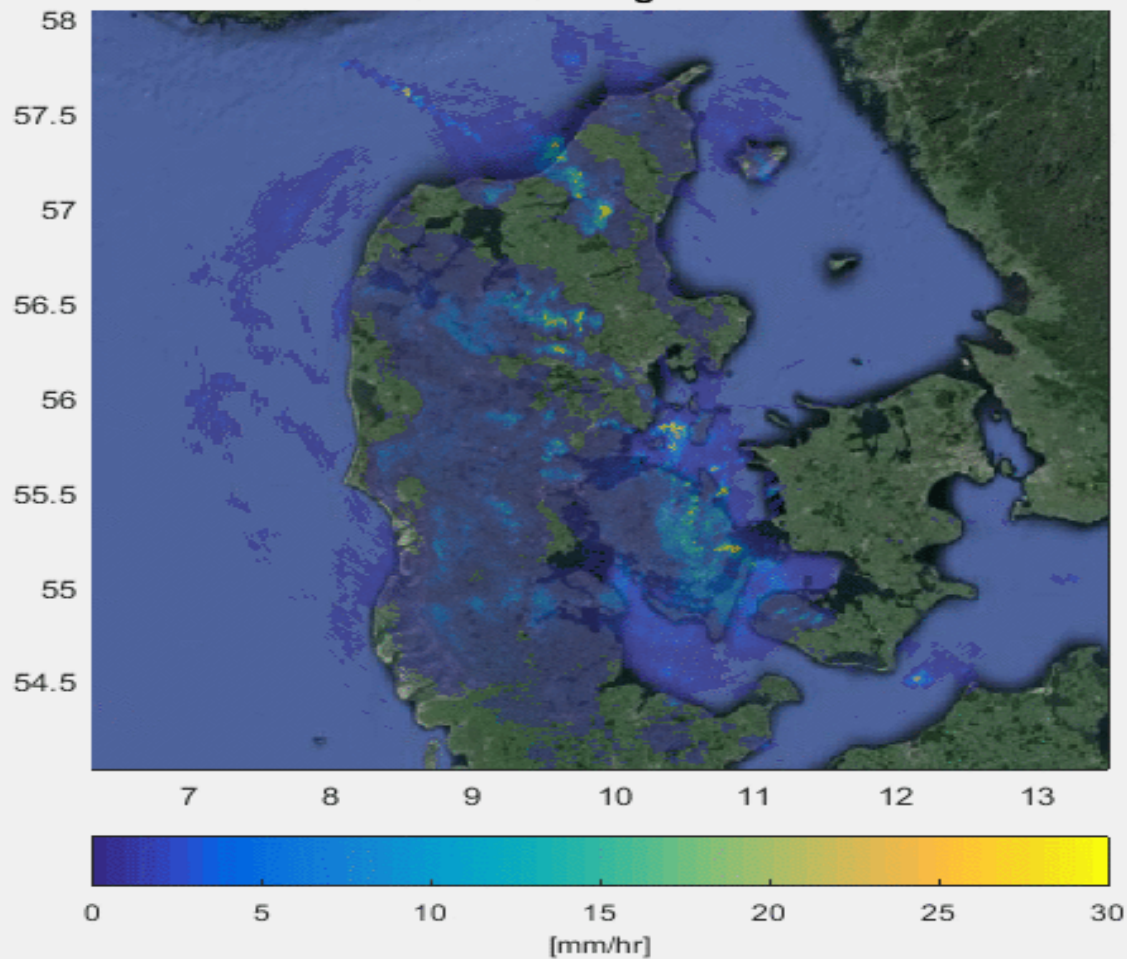
After





# Demonstration af online nowcaster (WP-3)

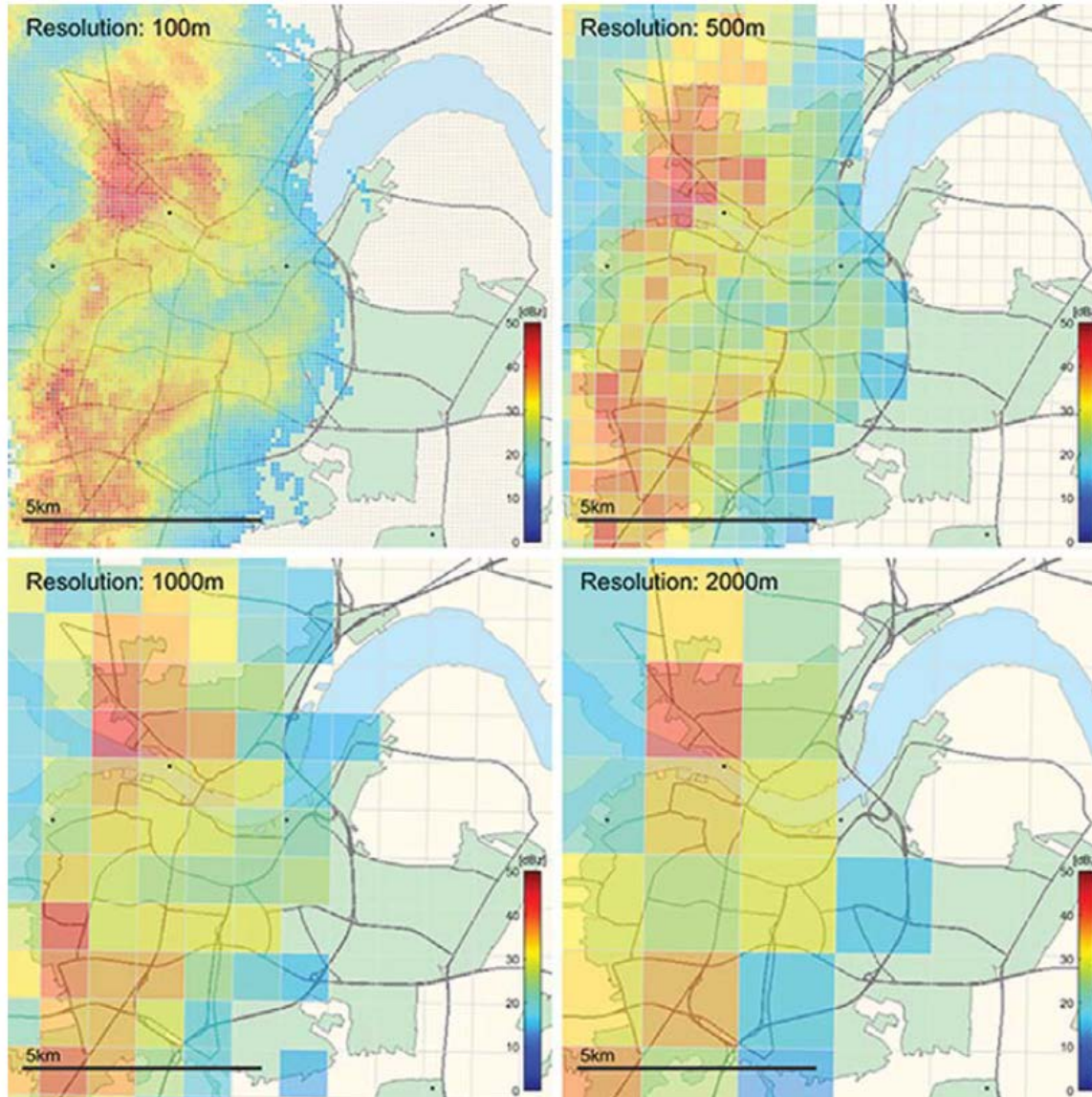
Observation: 04-Aug-2015 16:51:00



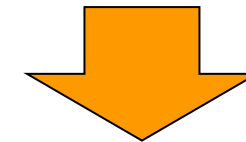
Slide courtesy of Jesper Ellerbæk Nielsen



# Radar resolution

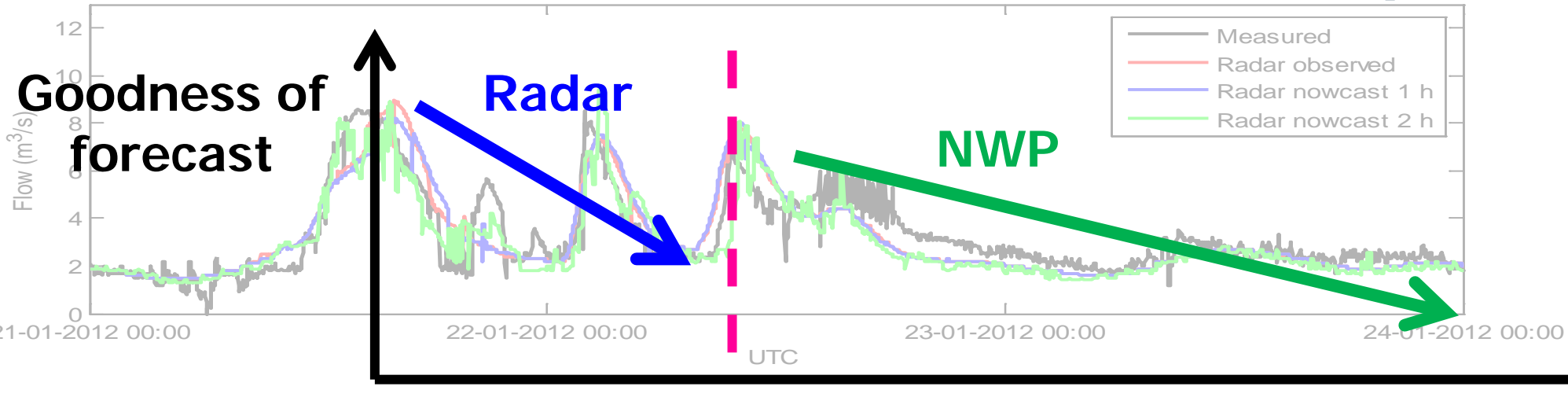


- Which one is the good one for the urban scale?
- Radar can are only useful to predict up to 2 hrs in the future
- What about longer horizons?



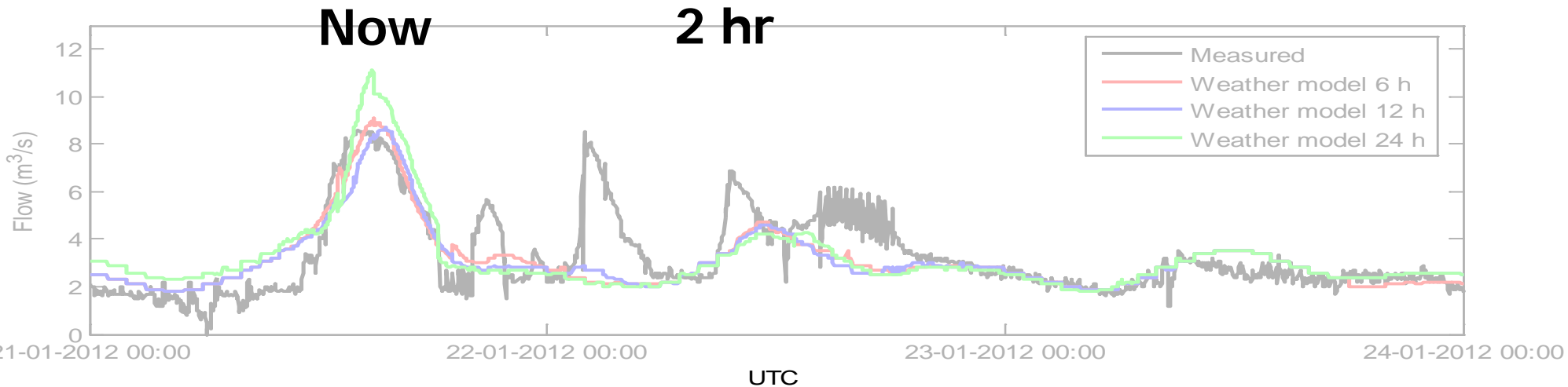
- Numerical Weather Prediction (NWP) models

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



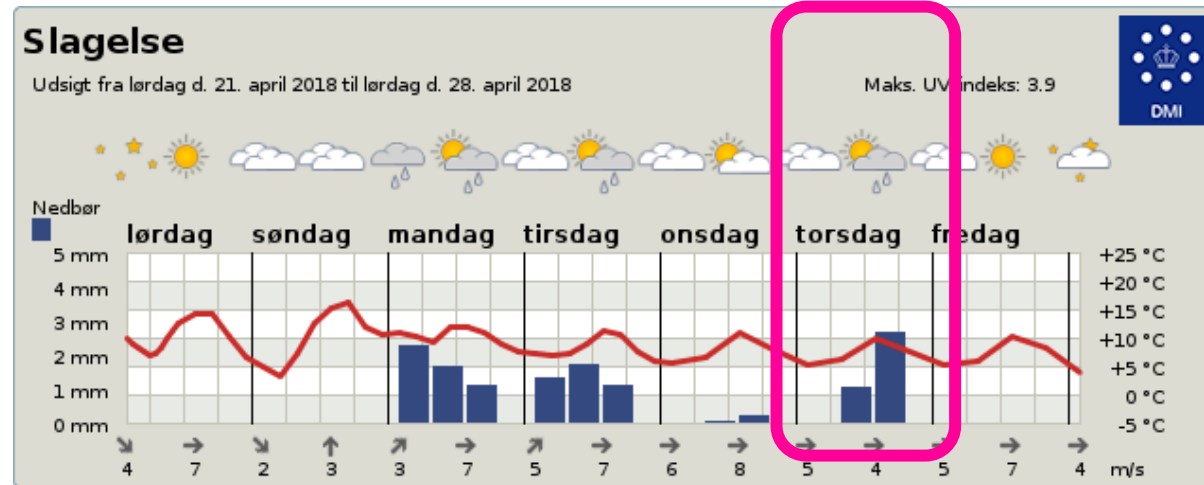
Mean rain gauge  
accum.: 8.6 mm

Mean obs. radar  
accum.: 7.3 mm



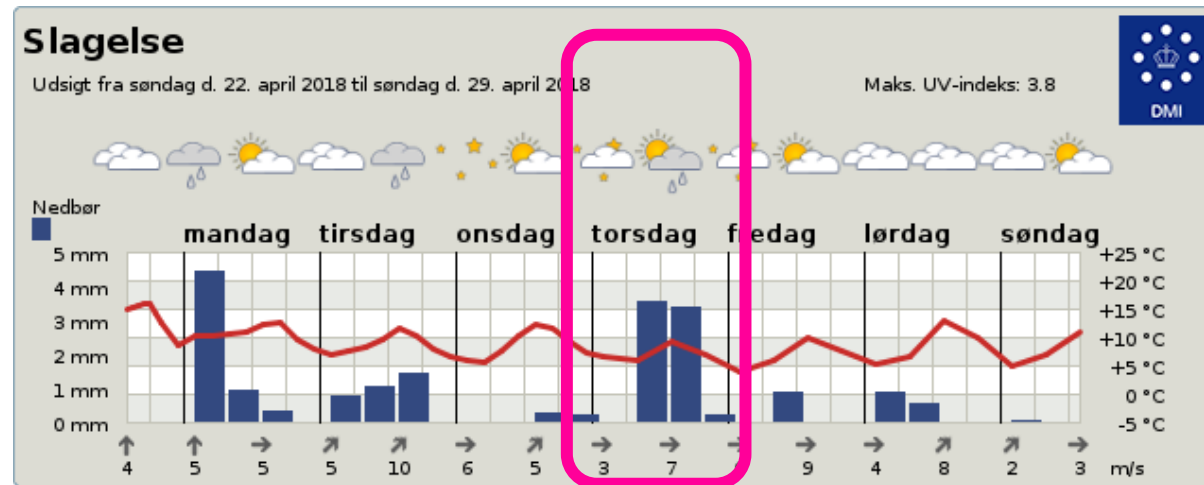
**Hvordan er vejret i dag?**

# Slagelse - 19/04



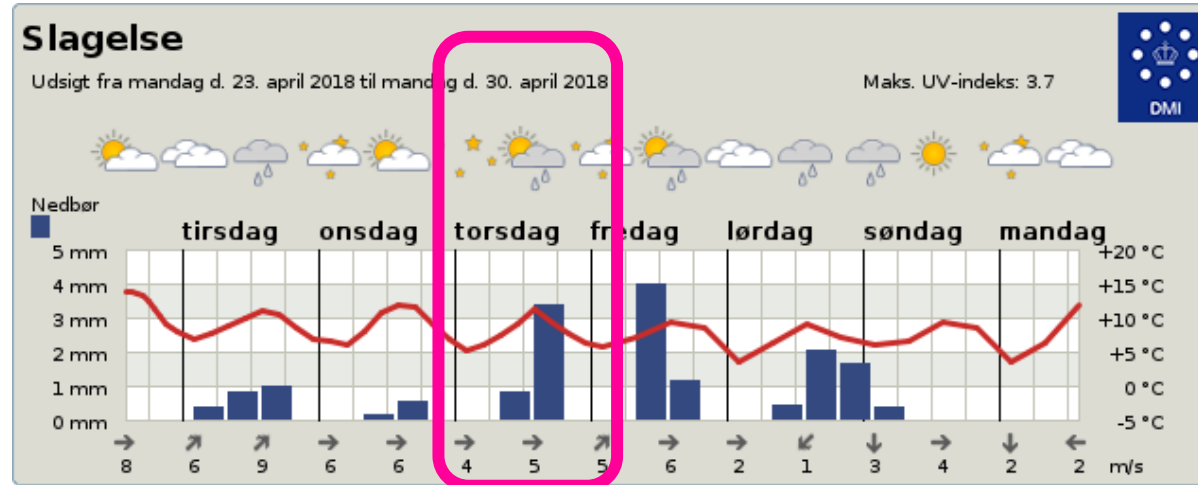
I morgen 20.04.2018	Lørdag 21.04.2018	Søndag 22.04.2018	Mandag 23.04.2018	Tirsdag 24.04.2018	Onsdag 25.04.2018	Torsdag 26.04.2018	Fredag 27.04.2018	Lørdag 28.04.2018
20°	14°	15°	12°	11°	11°	10°	10°	8°
Klarvær. Lett bris, 5 m/s fra sør. 0 mm nedbør.	Klarvær. Lett bris, 5 m/s fra vest-nordvest. 0 mm nedbør.	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.

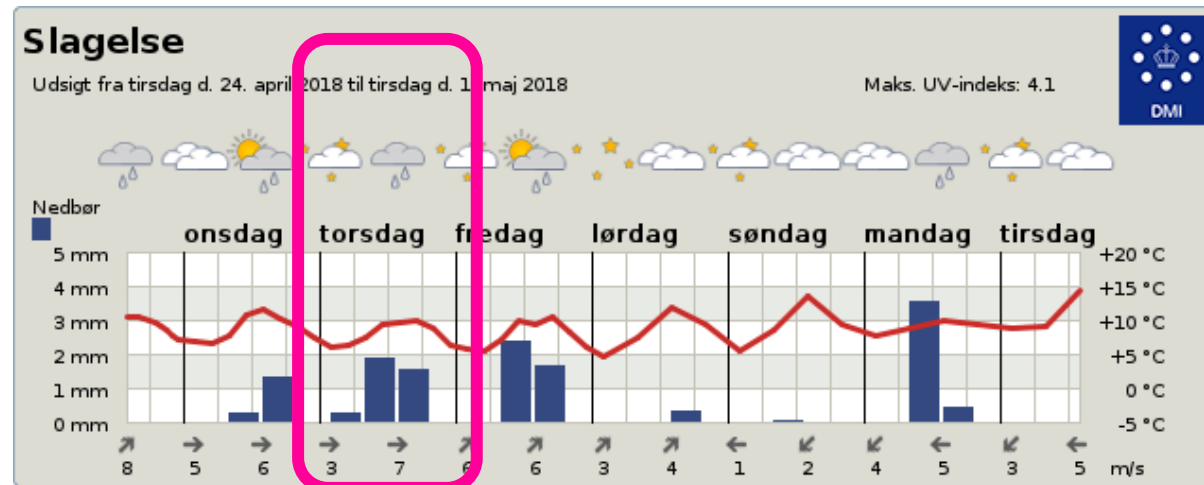
# Slagelse - 21/04



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. Lager bris, 6 m/s fra vest. 0 mm nedbør.	Regnbyger. Lager bris, 6 m/s fra vest- sørvest. 1,9 mm nedbør.	Regnbyger. Lager 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.

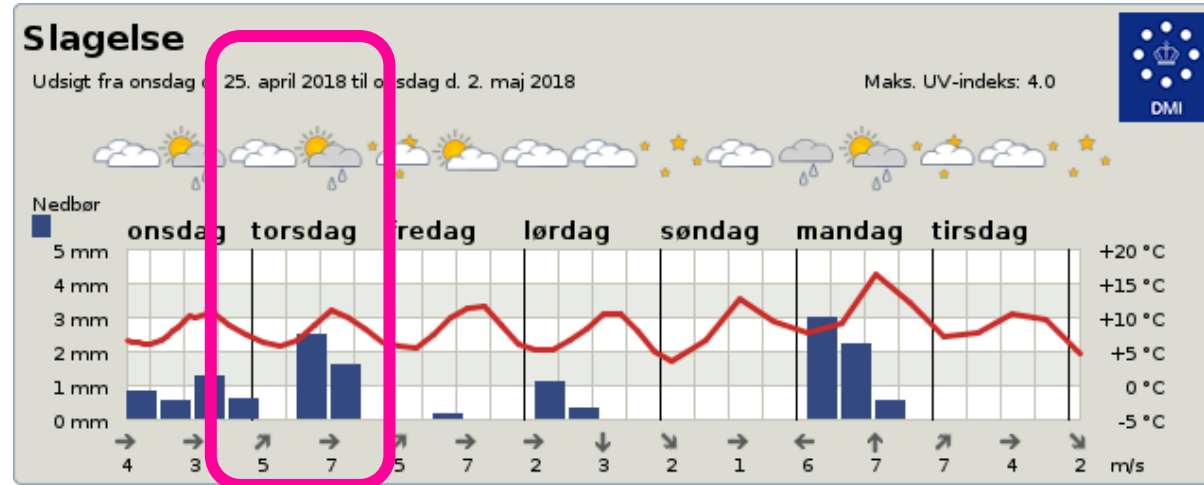


# Slagelse - 22/04



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.	Lettskyet. 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.

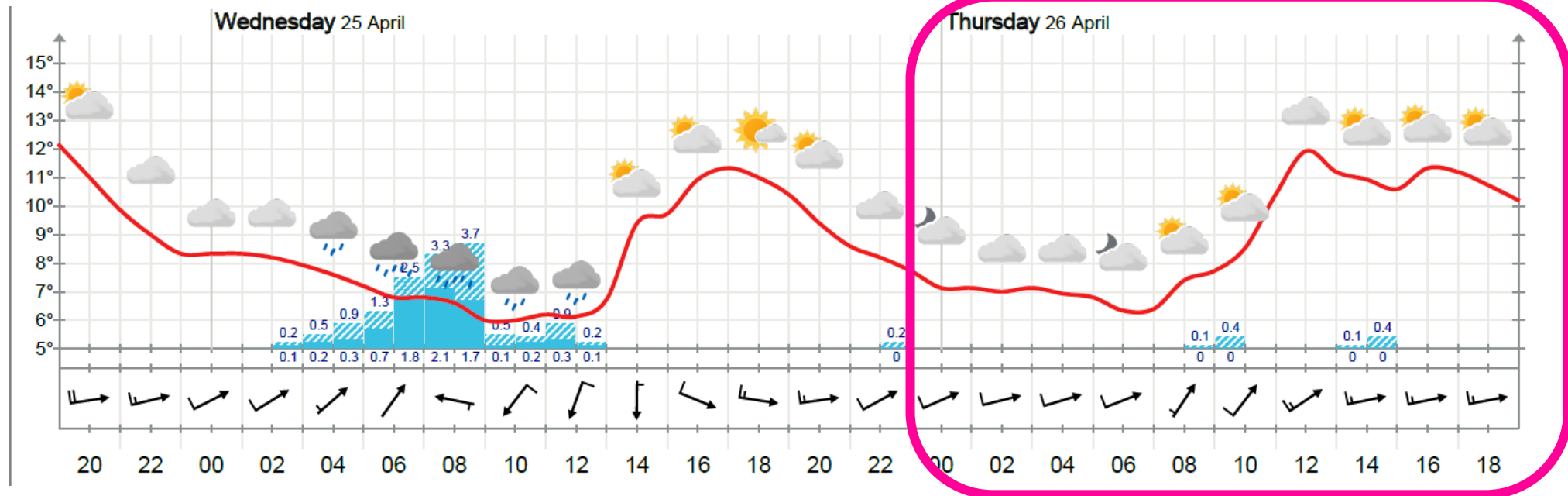
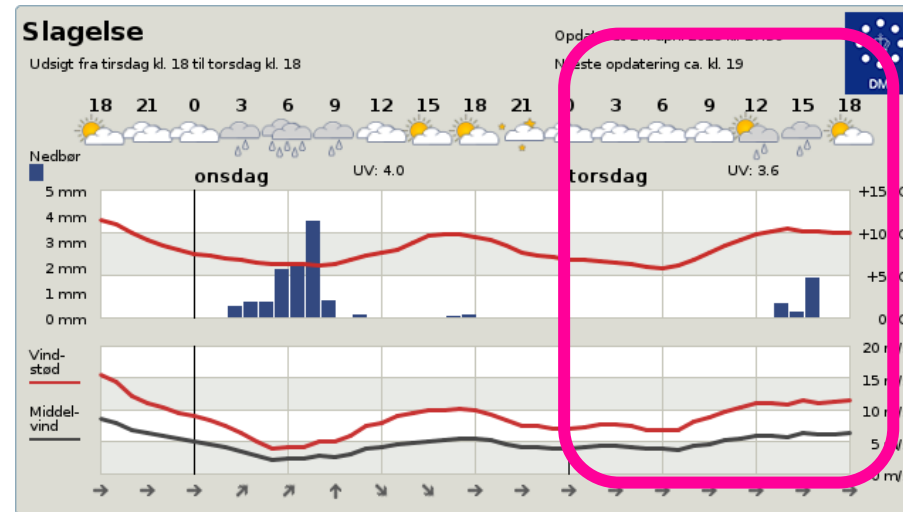
# Slagelse - 23/04



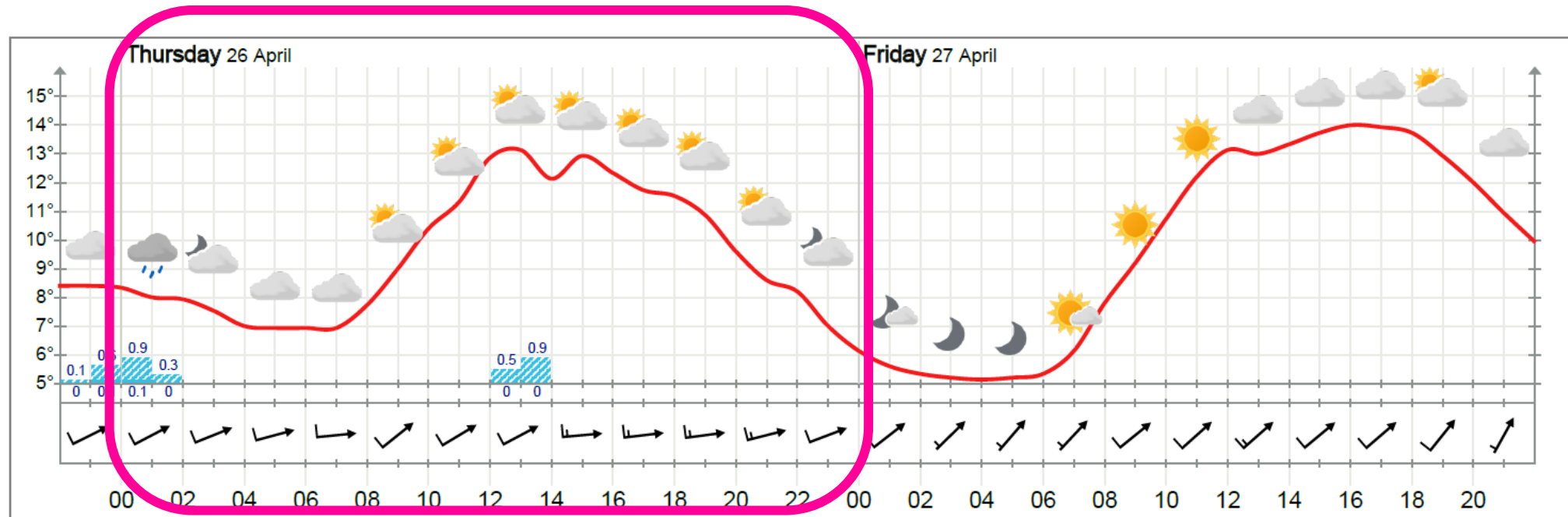
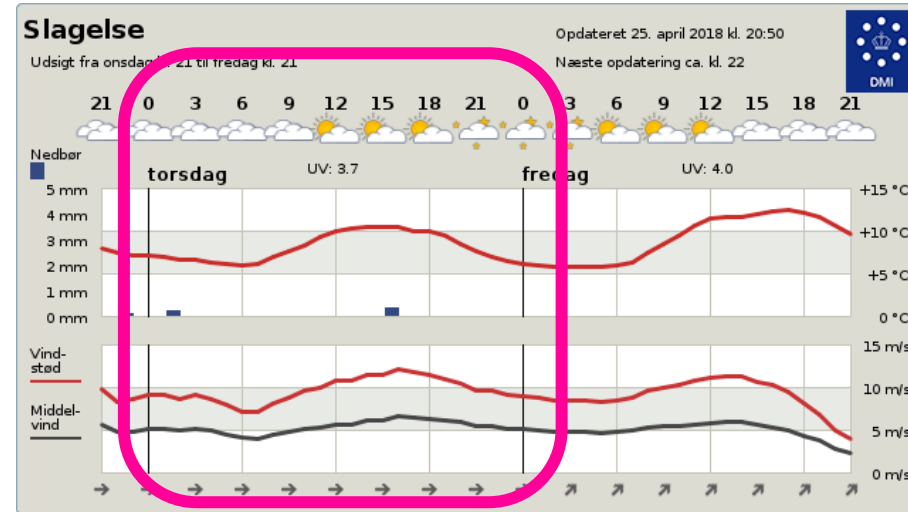
Tomorrow 24/04/2018	Wednesday 25/04/2018	Thursday 26/04/2018	Friday 27/04/2018	Saturday 28/04/2018	Sunday 29/04/2018	Monday 30/04/2018	Tuesday 01/05/2018	Wednesday 02/05/2018
10°	7°	11°	11°	10°	13°	16°	10°	10°
Cloudy. Fresh breeze, 8 m/s from southwest. 0 mm precipitation.	Partly cloudy. Light air, 1 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

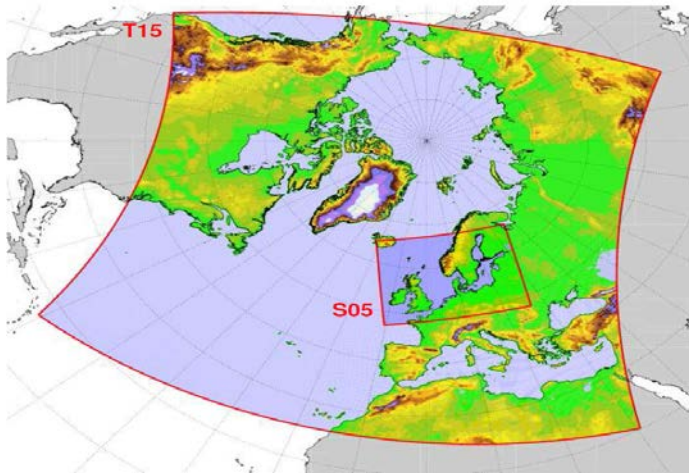


# Slagelse - 25/04



# 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

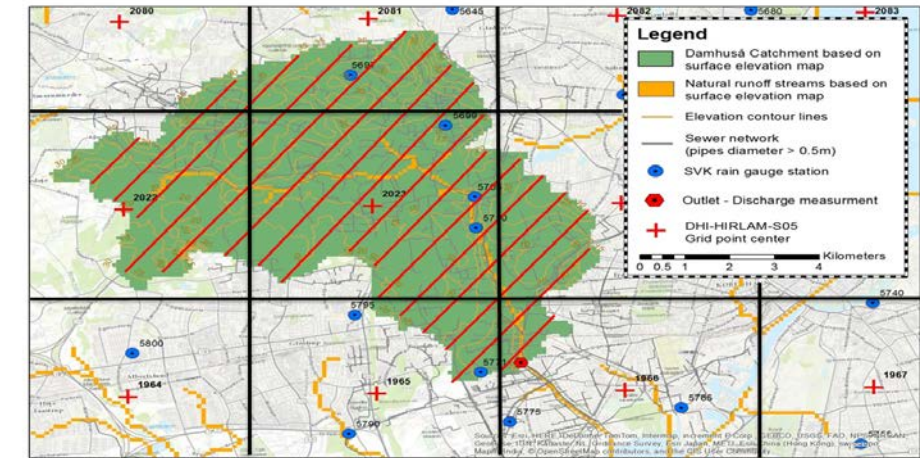
5 # initial  
condition

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

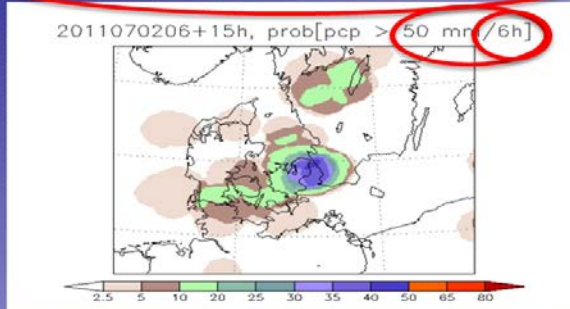
# Context vs. Model Uncertainty

## what do we ask to the model?

### Upscaled probabilities

Upscaling diameter = 15 grid cells ~ 80 km

2011070206+15h, prob[pcp > 50 mm/6h]



Max probability > 40%

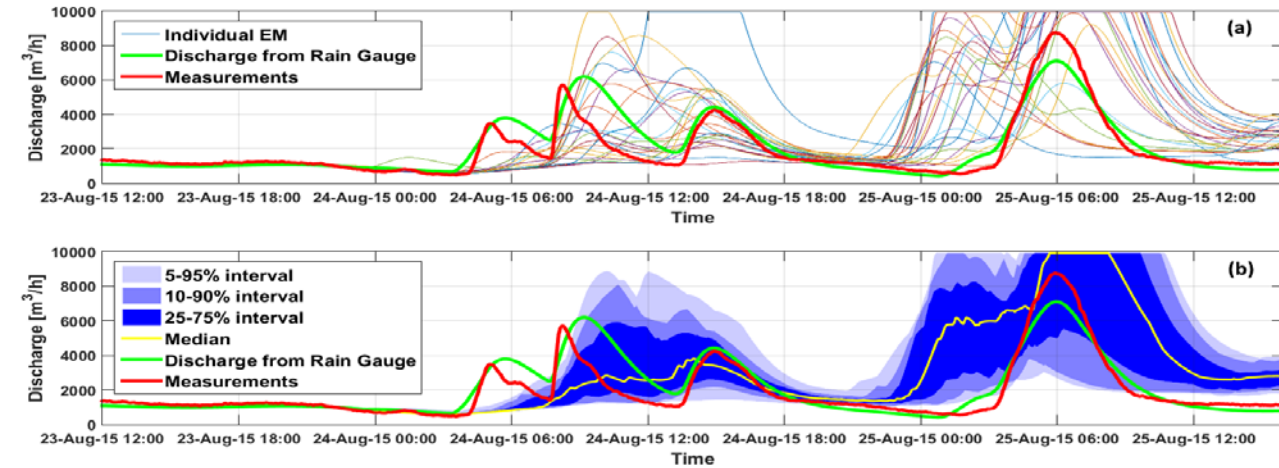


Meteorological perspective

These weather  
forecast are great!

Urban hydrology perspective

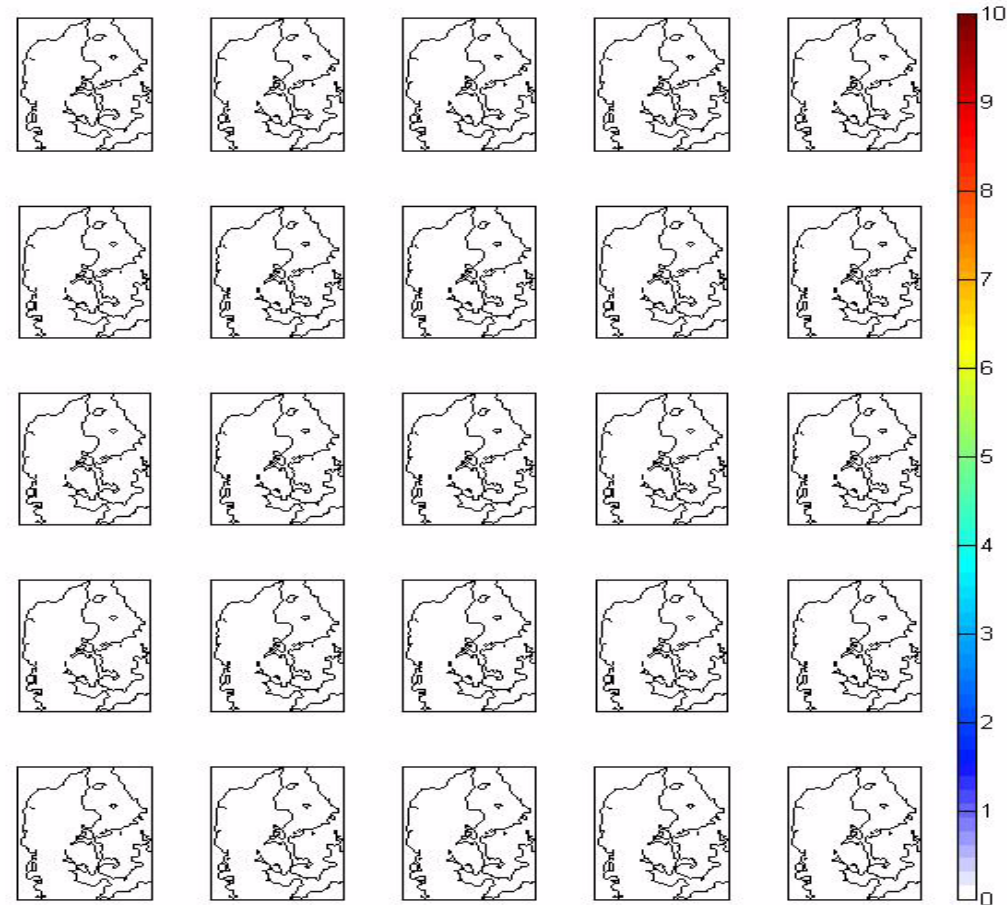
These weather  
forecast are crap





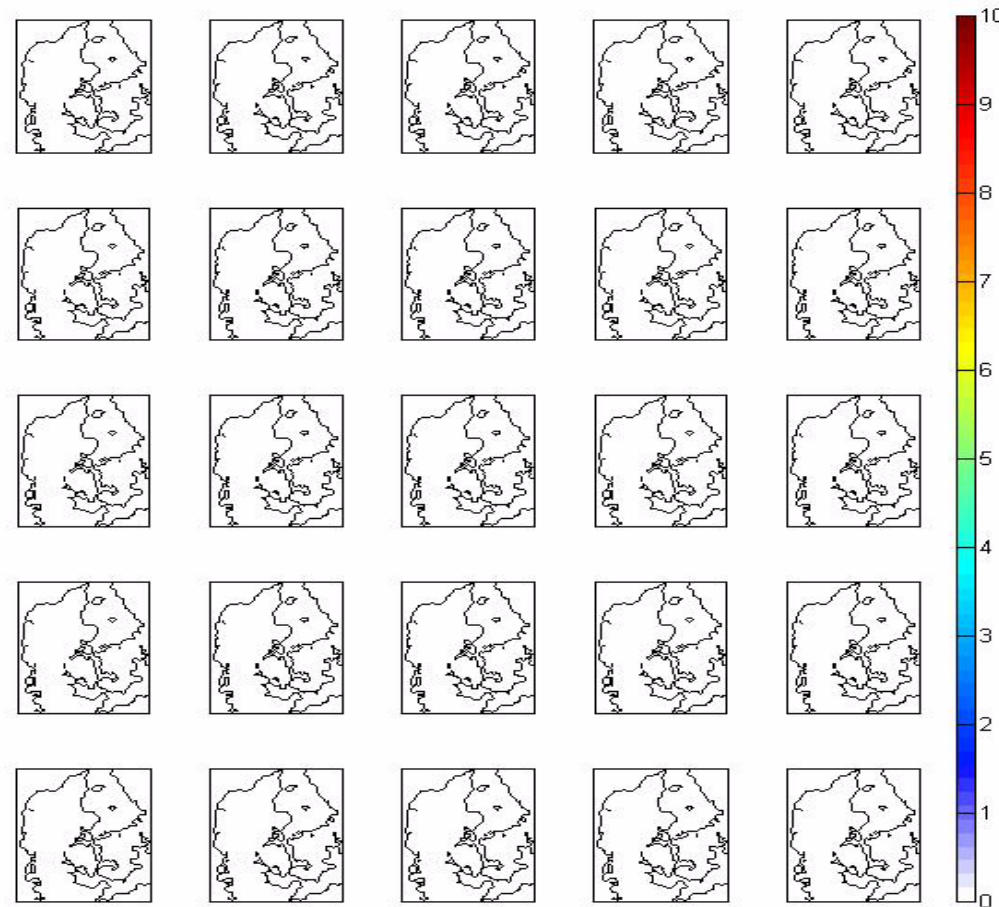
# DMI model prediction (winter)

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



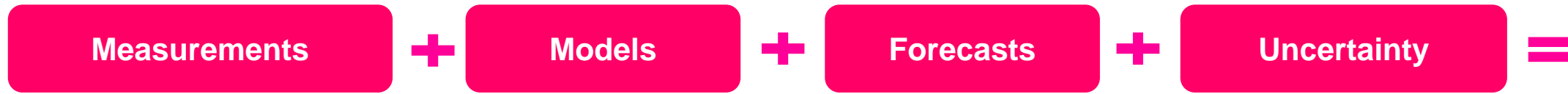
# DMI model prediction (summer)

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

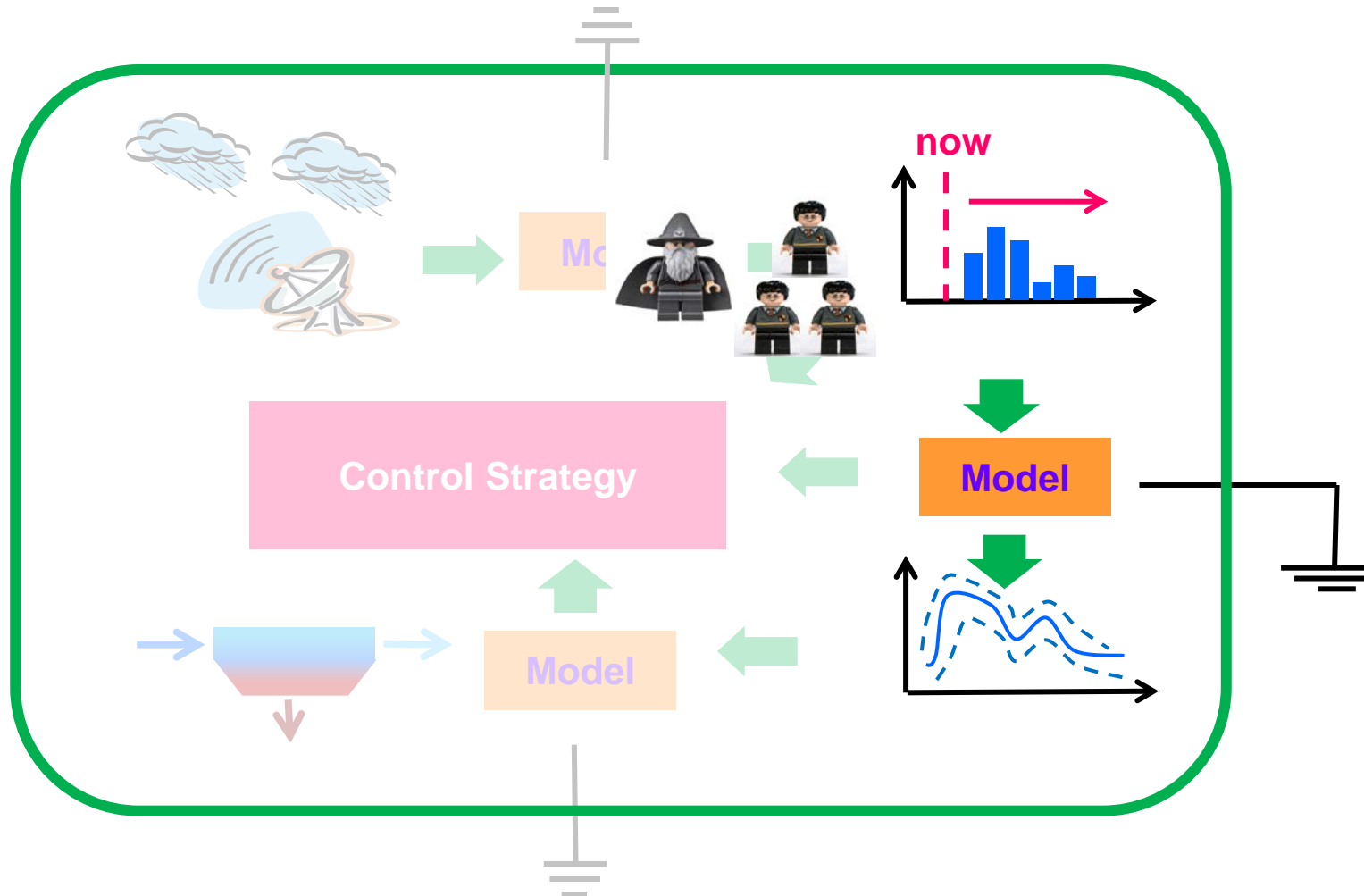


25 (physically based)  
models = 25 different  
results

# The fellowship of SWI – the long journey



*The happy operator*

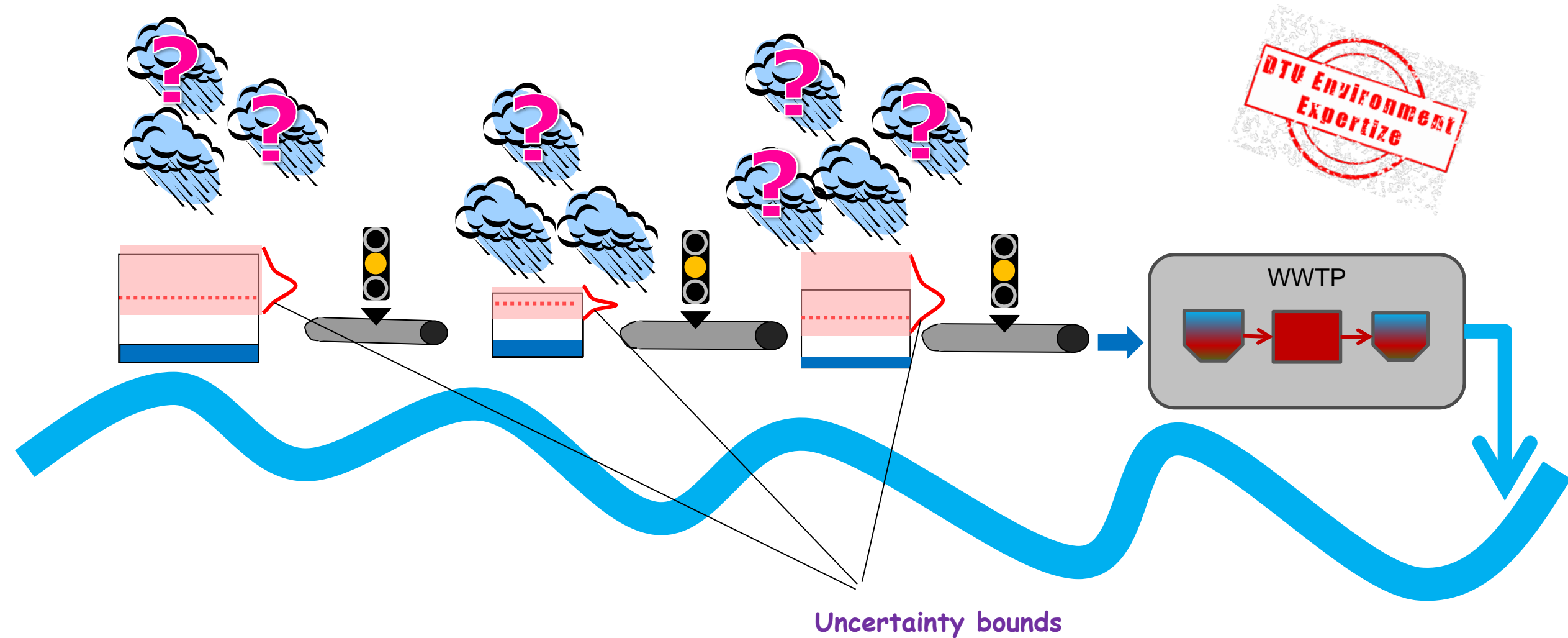


- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

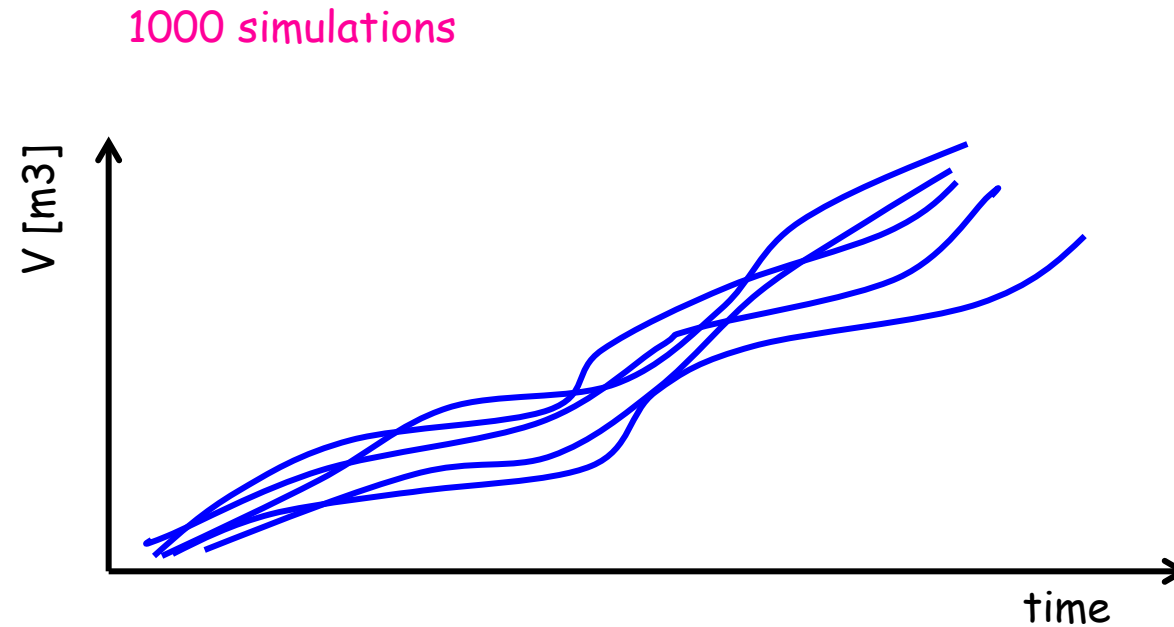
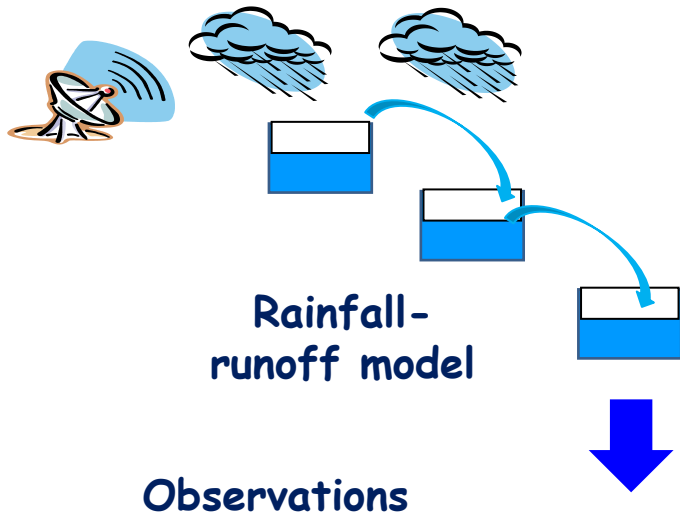


# Model Predictive Control with uncertainty

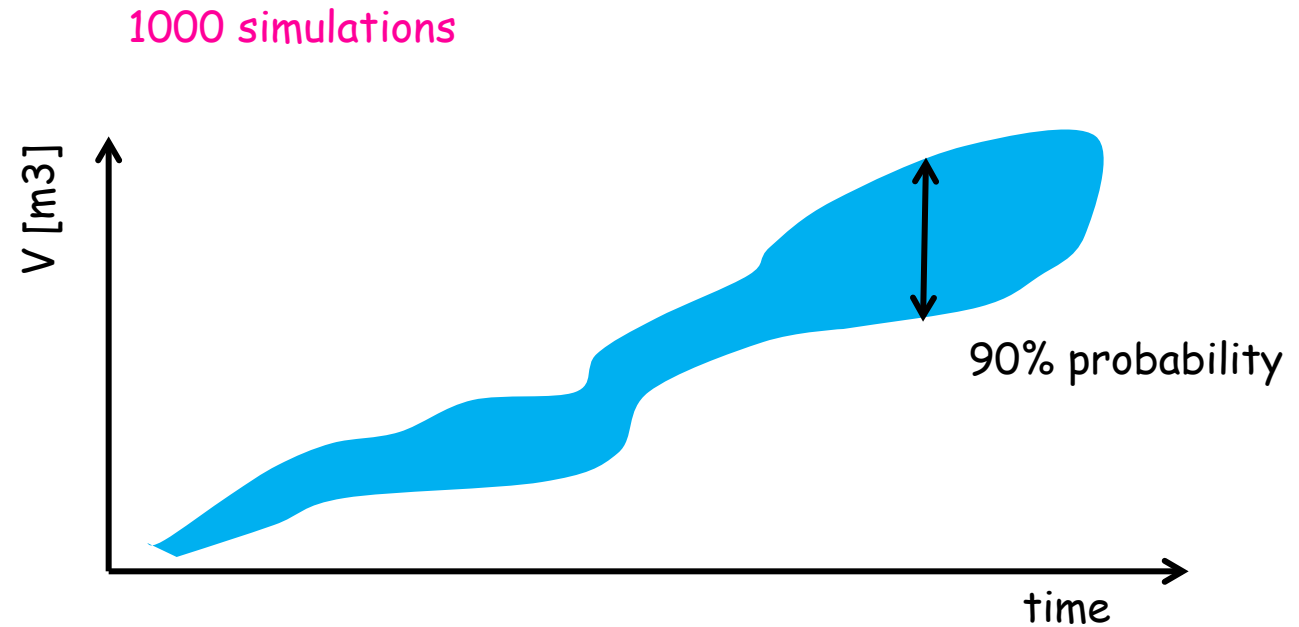
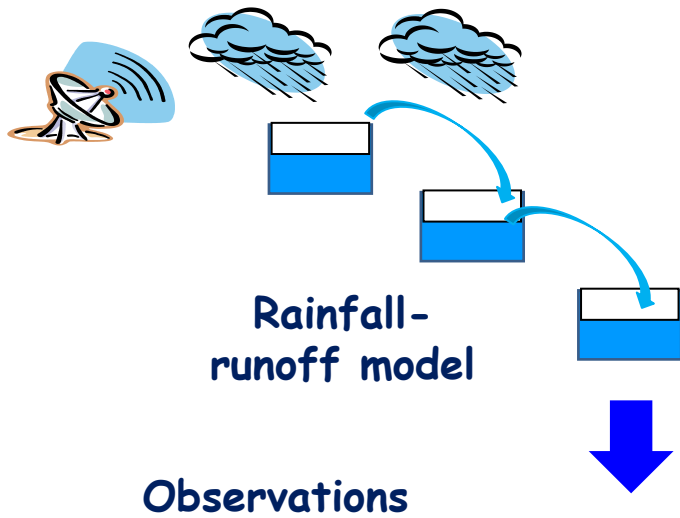
- Rainfall forecasts are uncertain →



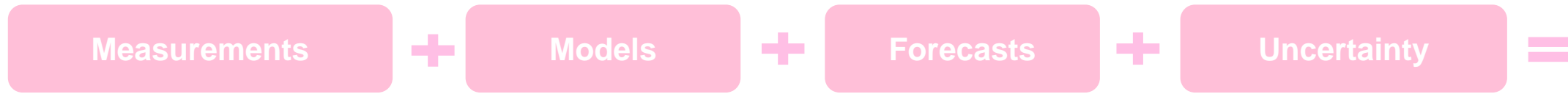
# Stochastic runoff forecasts



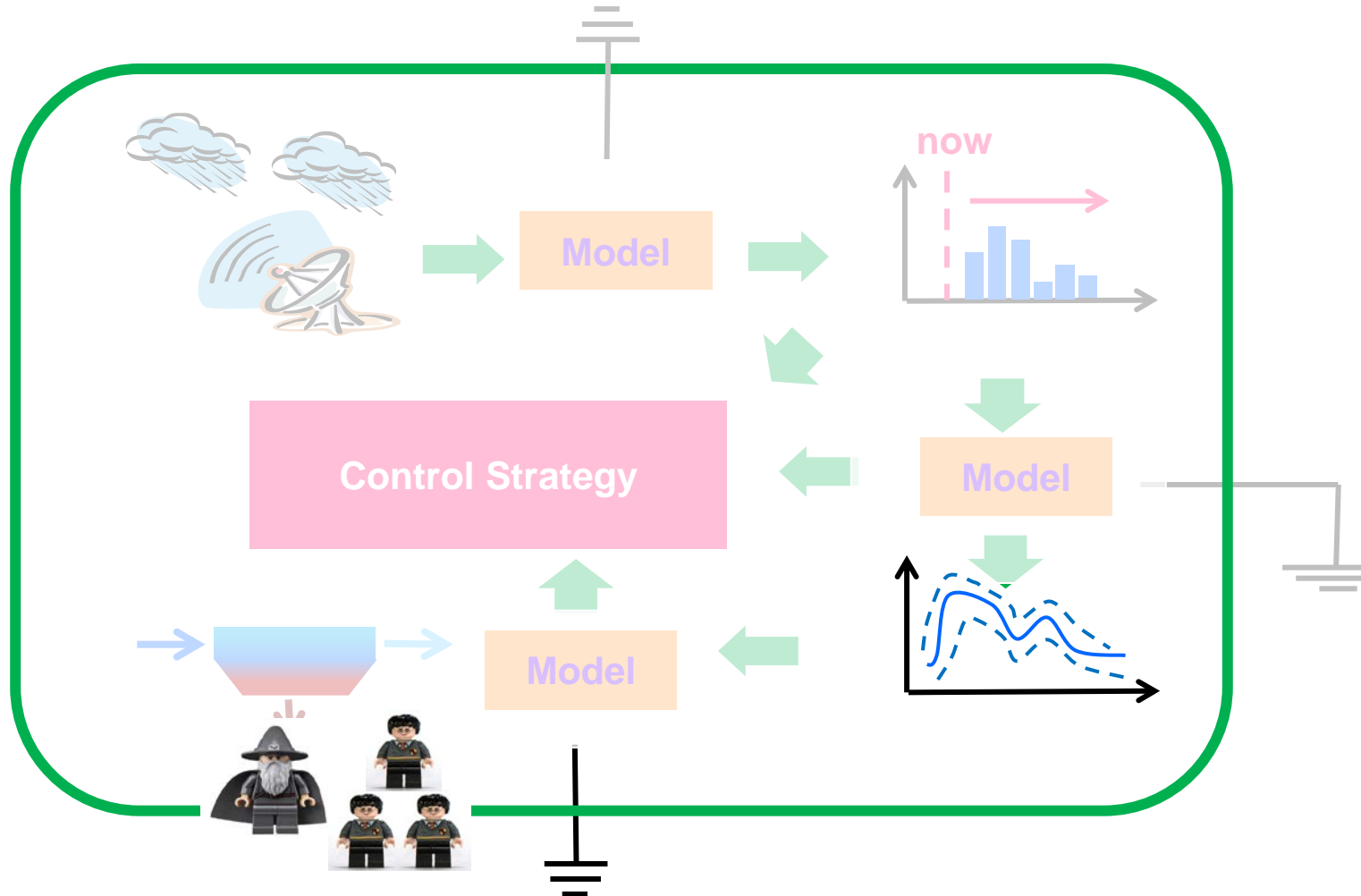
# Stochastic runoff forecasts



# The fellowship of SWI – the long journey



*The happy operator*

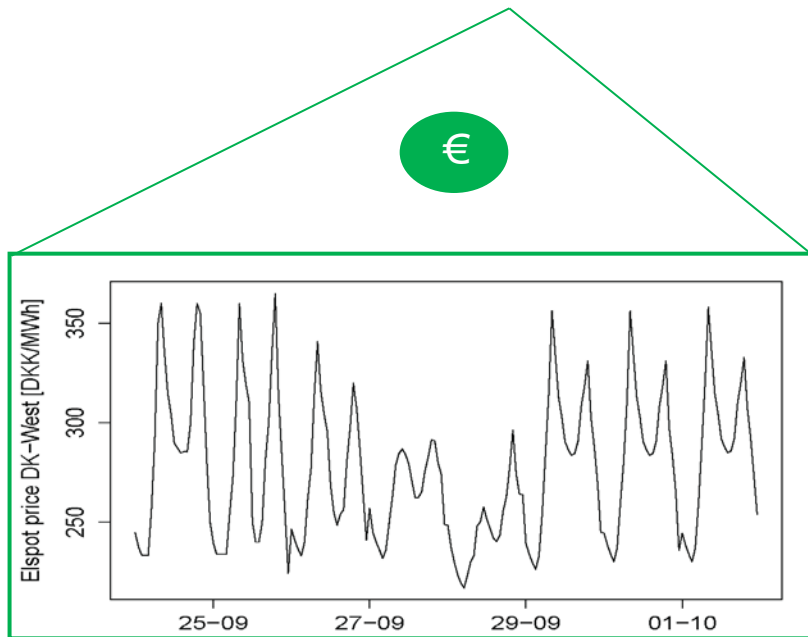
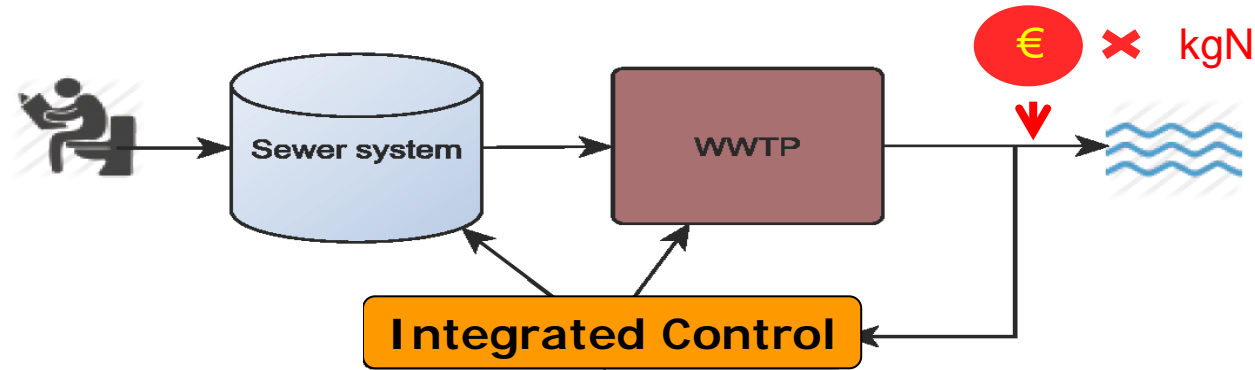


- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

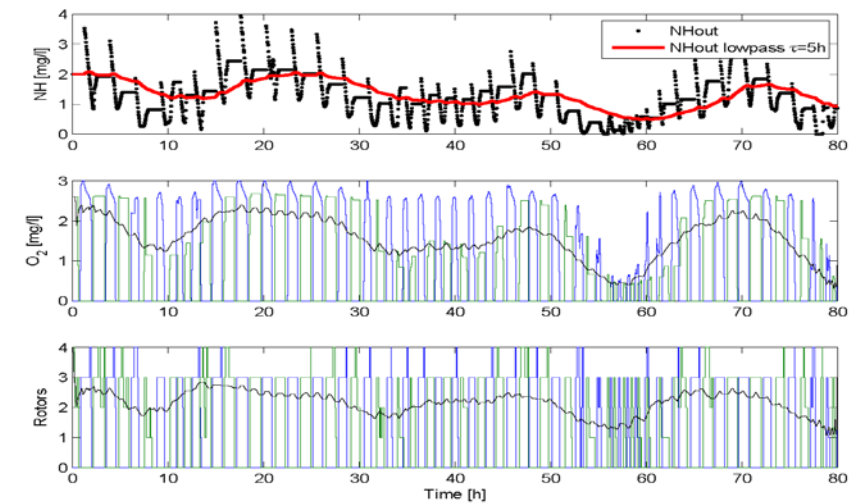
# Controlling the WWTP based on energy prices

## the Blue Kolding example

Slide courtesy of Rasmus Fogtmann Halvgaard

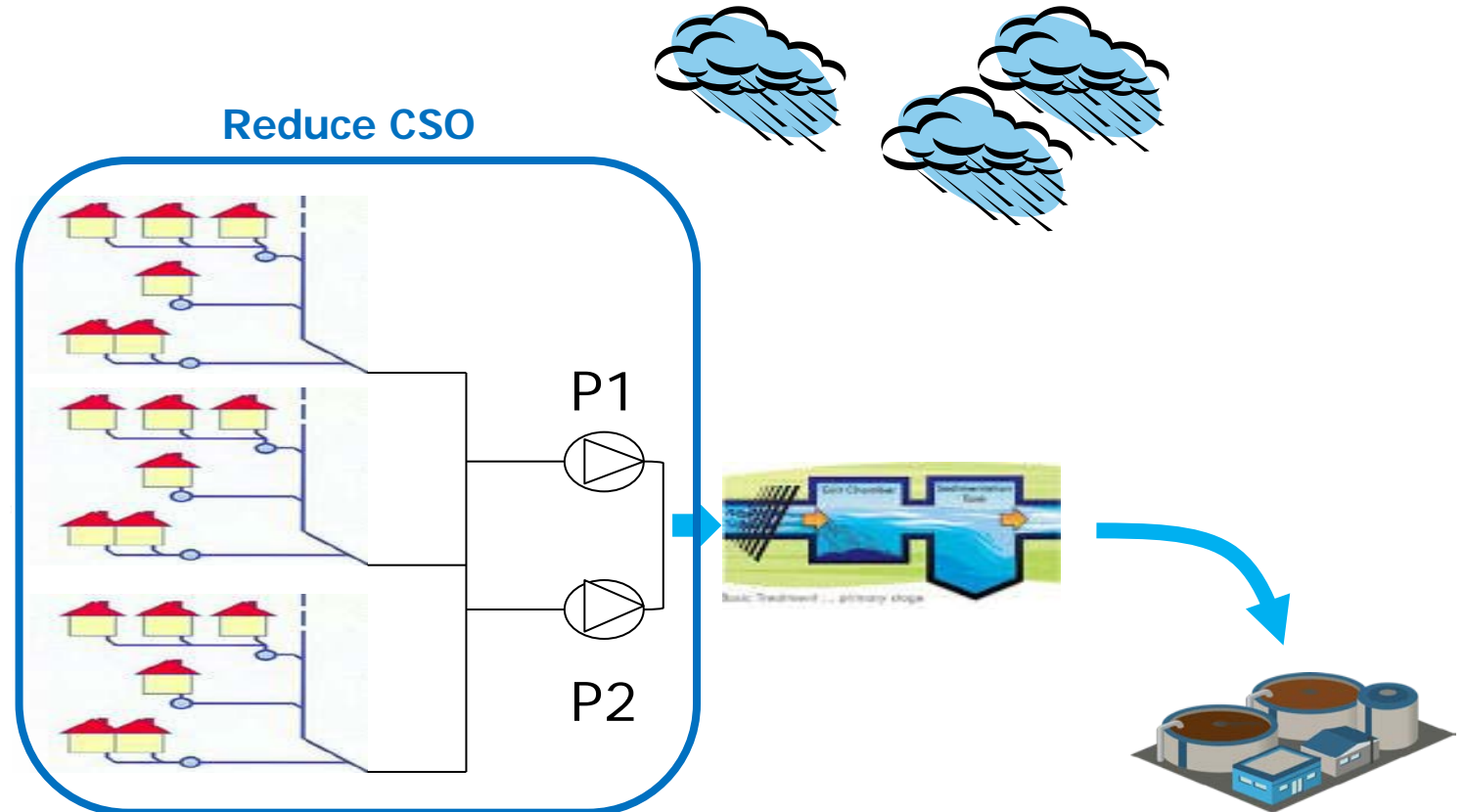
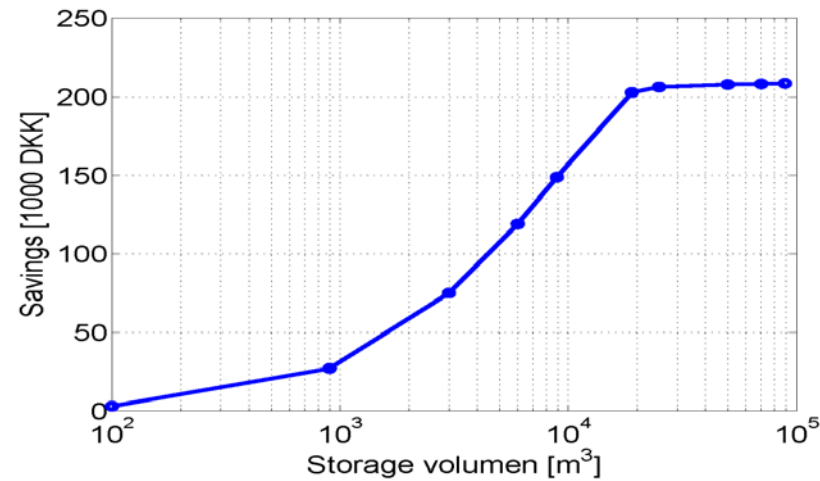


Aeration control



# Controlling the WWTP based on energy prices – moving upstream

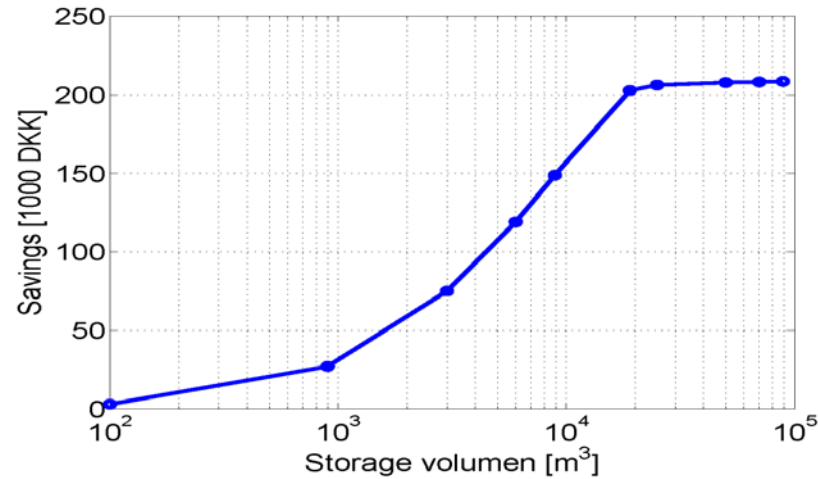
Sewer system annual Elspot savings



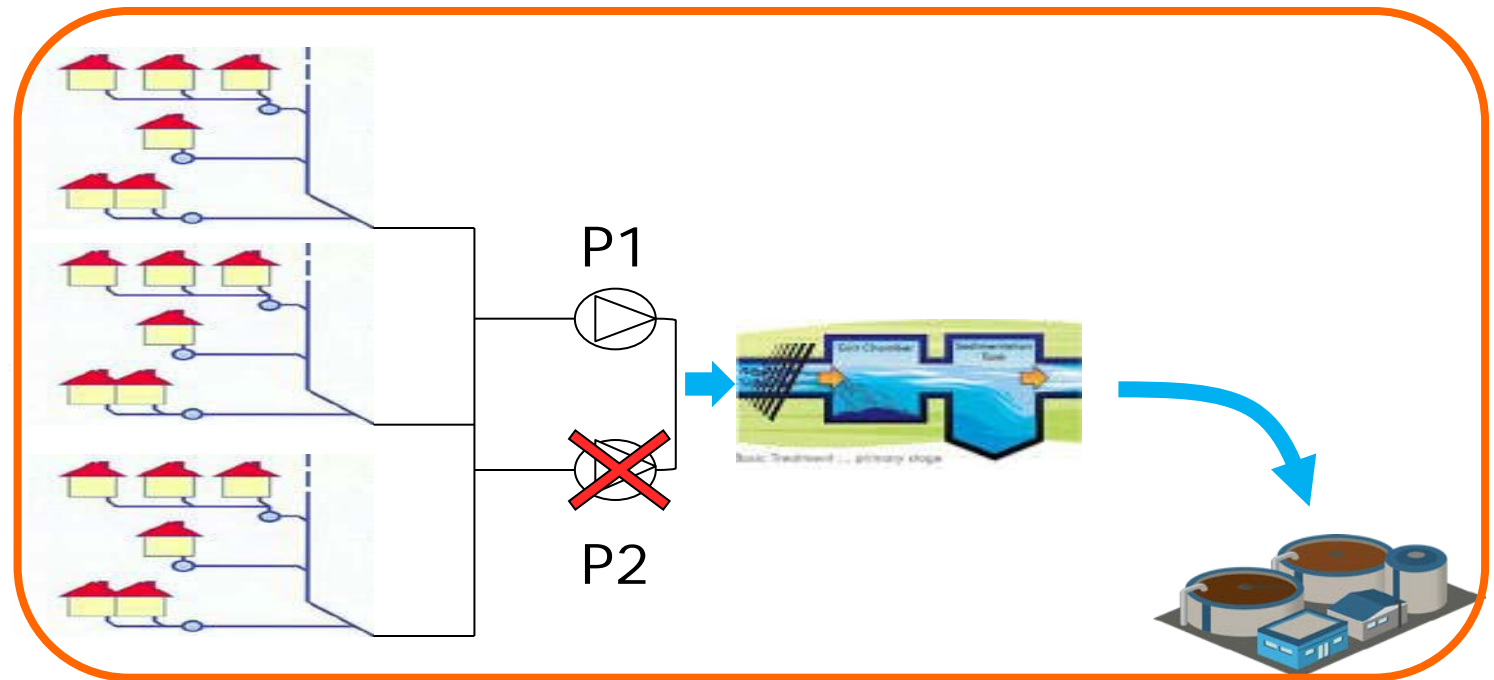


# Controlling the WWTP based on energy prices – moving upstream

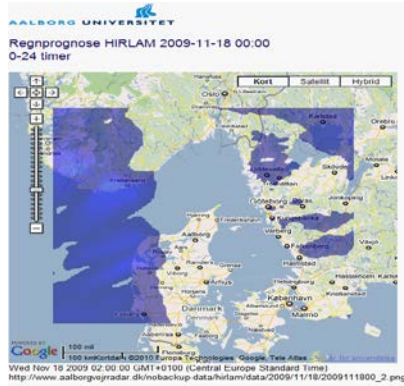
Sewer system annual Elspot savings



## Optimize WWTP Operations

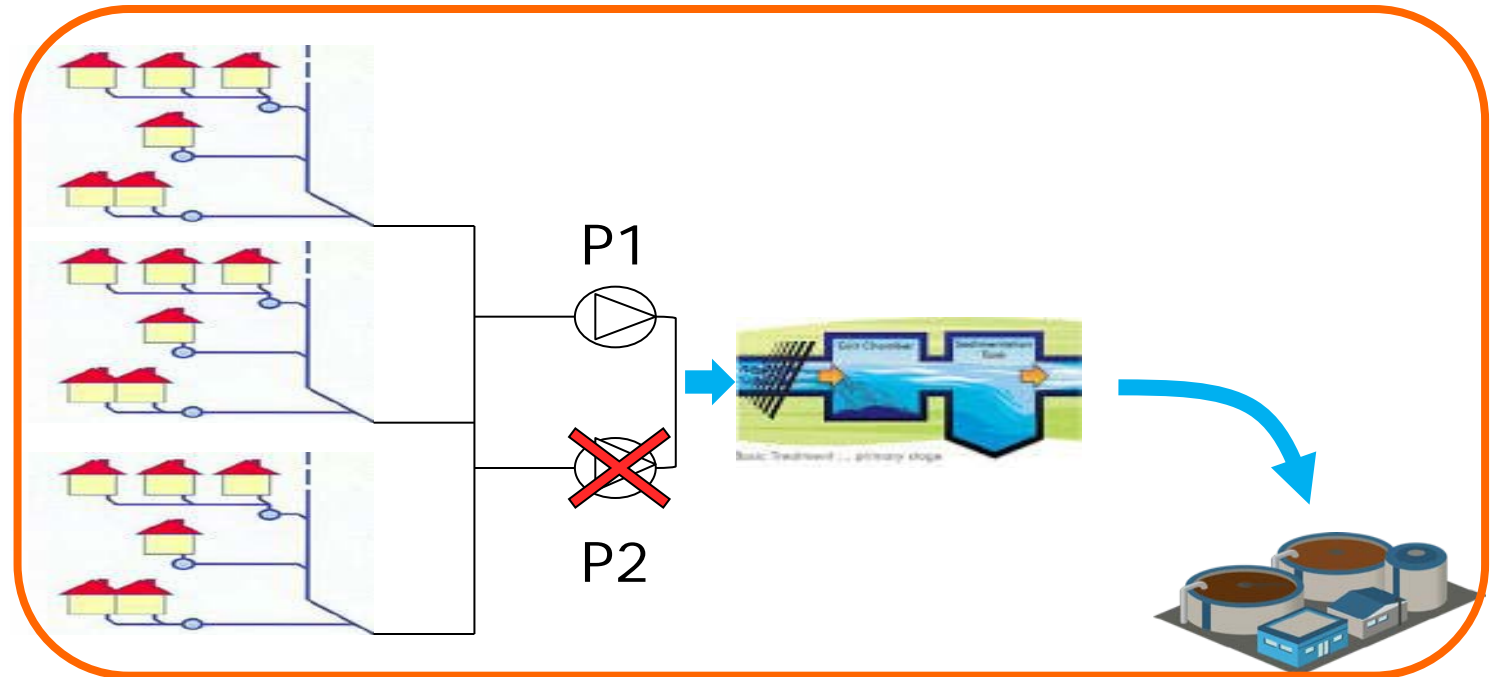


# Controlling the WWTP based on energy prices – moving upstream

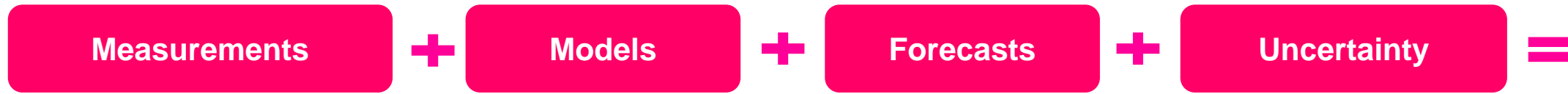


Numerical Weather Prediction models are used to switch between the two controls

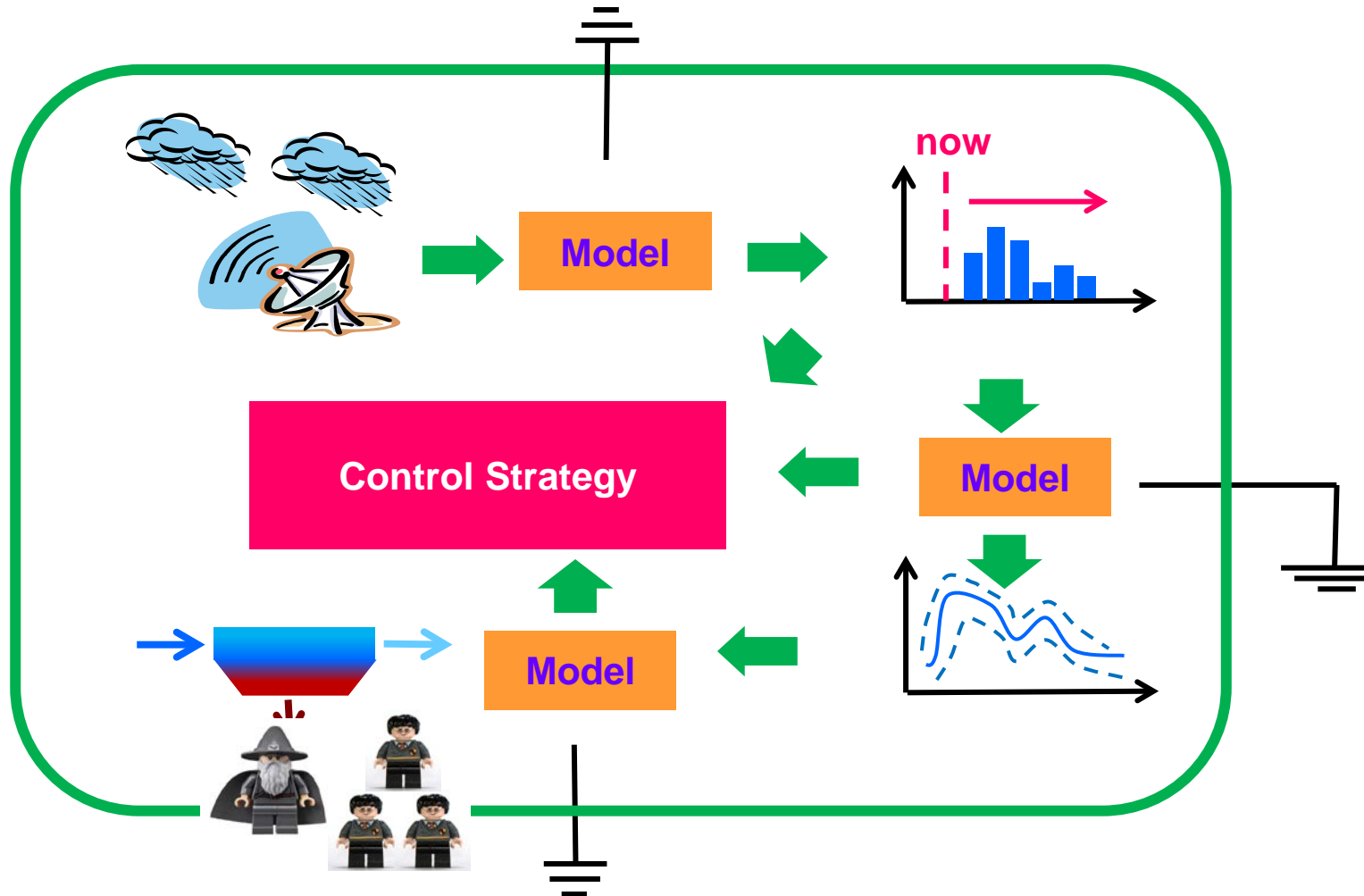
## Optimize WWTP Operations



# The fellowship of SWI – the long journey



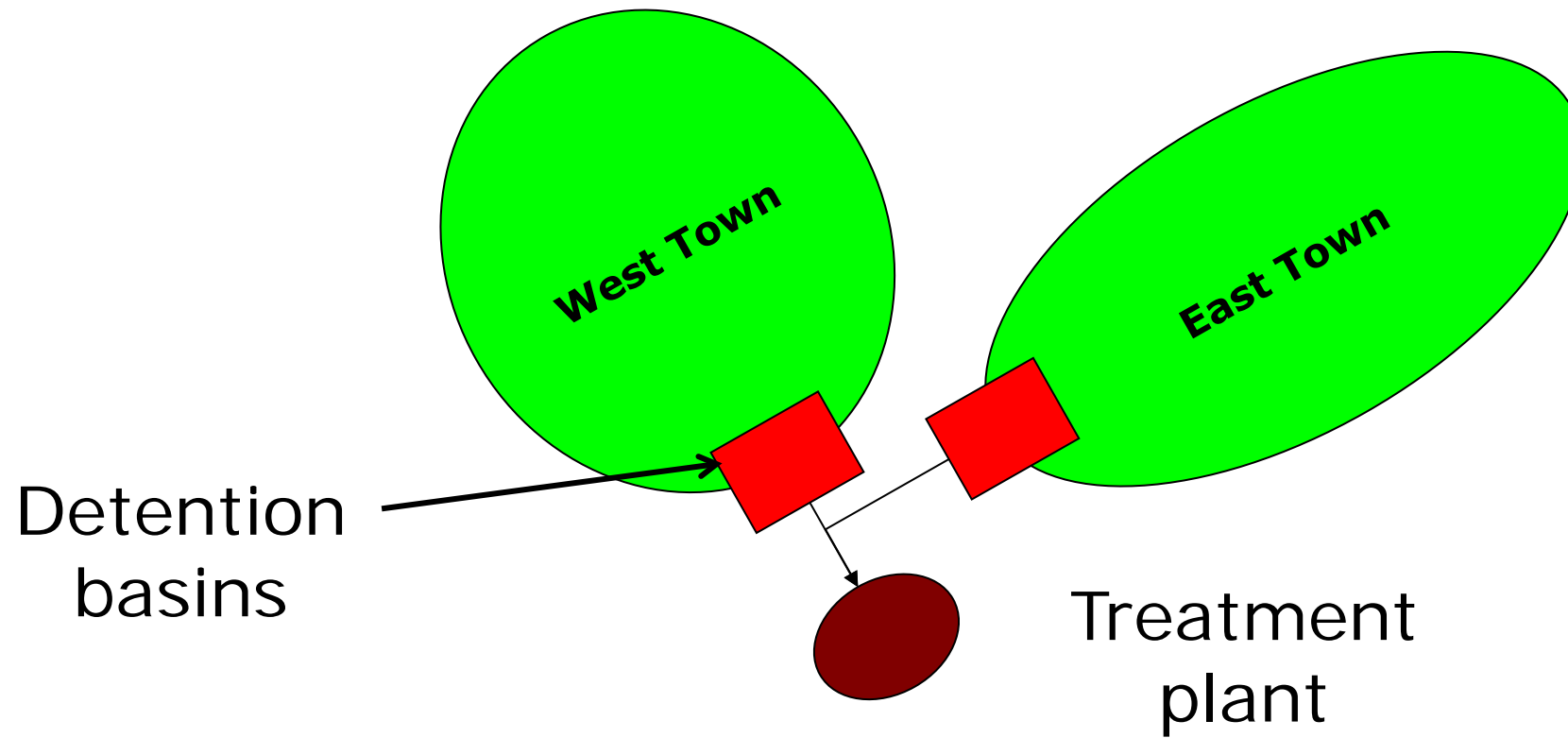
*The happy operator*



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

# Why uncertainty matters

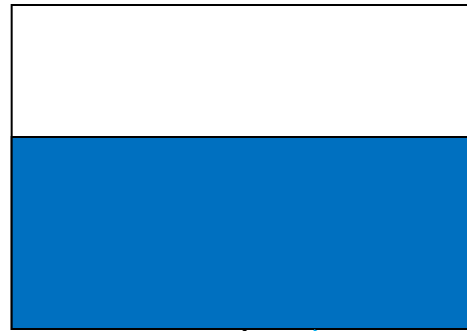
## Didactical example



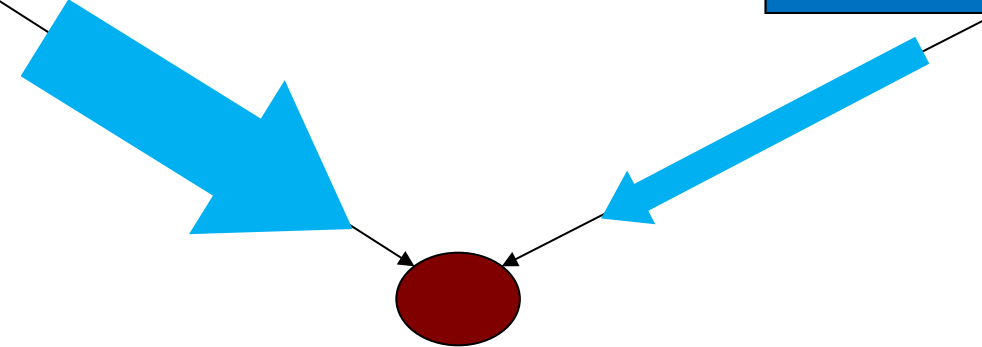
# Real Time Control

Objective:  
Maximize storage

West Town

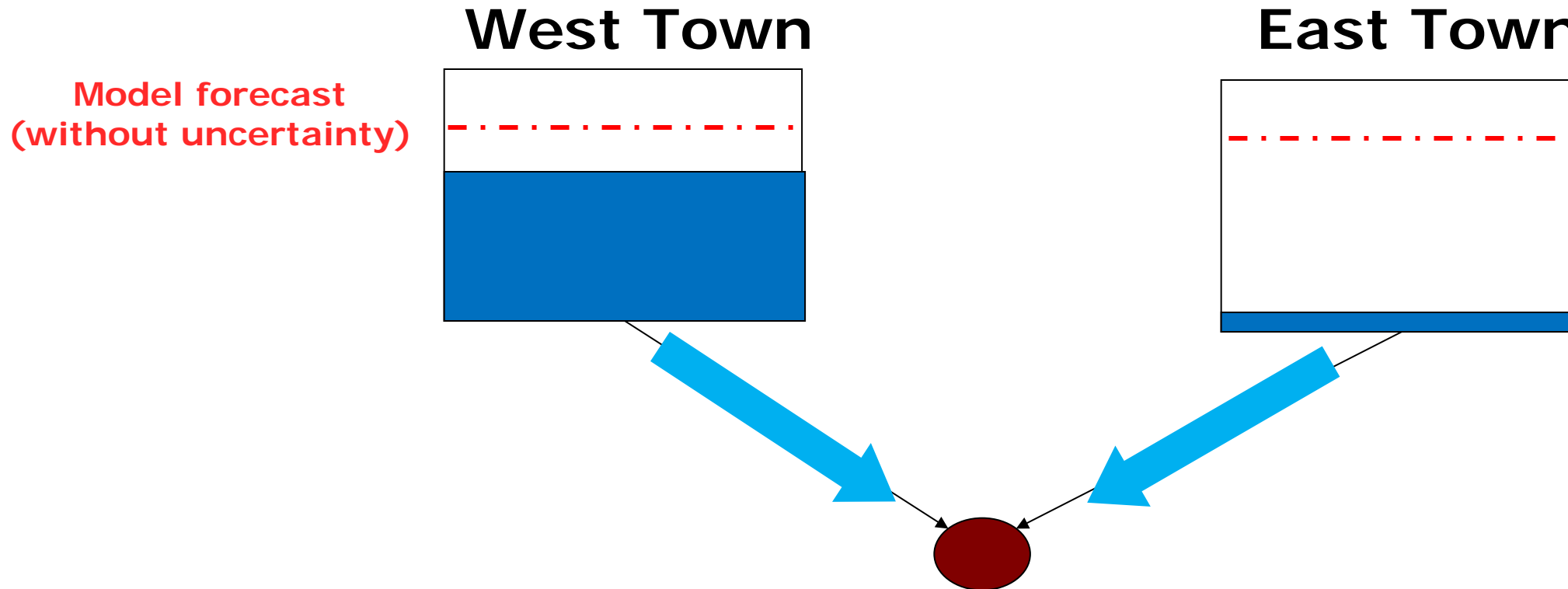


East Town



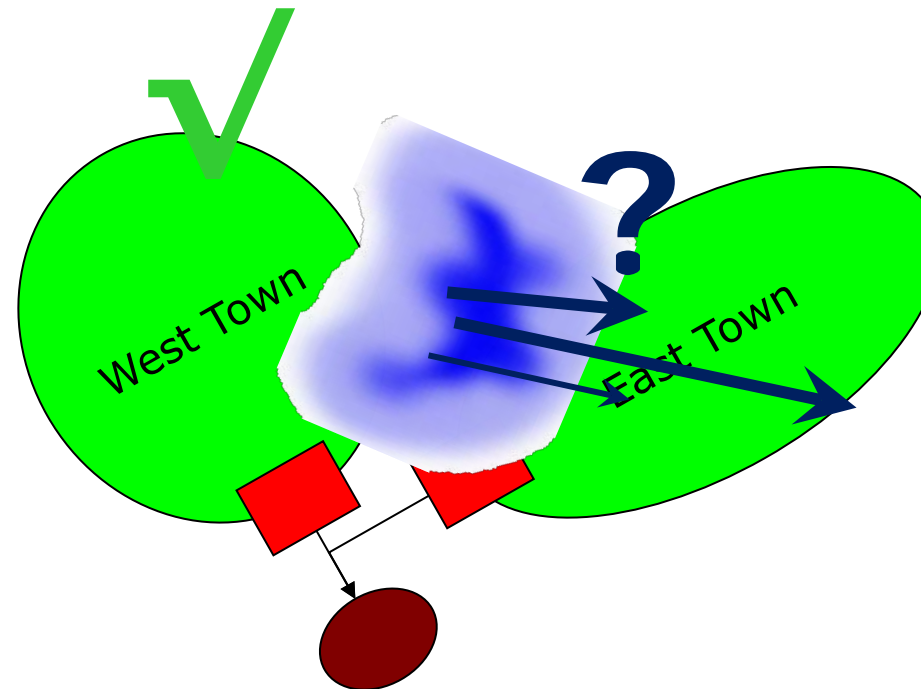
# "Traditional" MPC

Objective:  
Maximize future storage



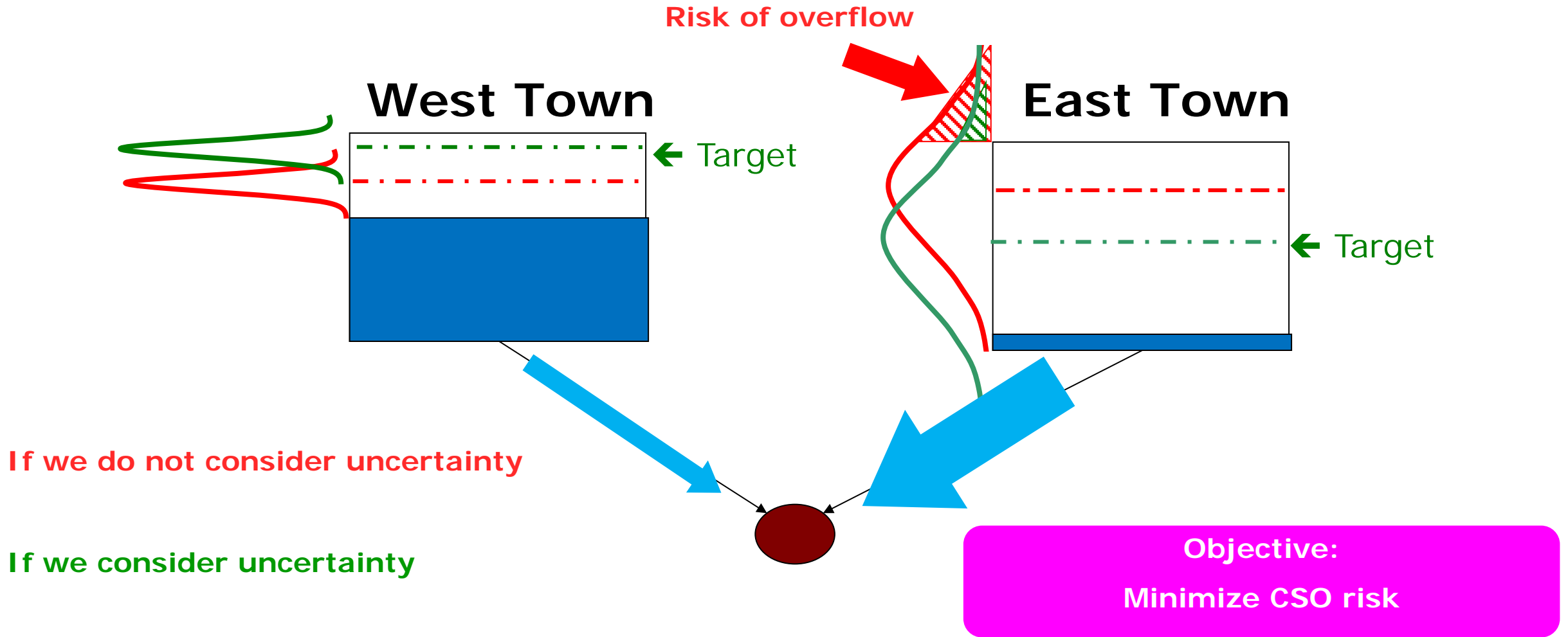


# Risk-based Model Predictive Control

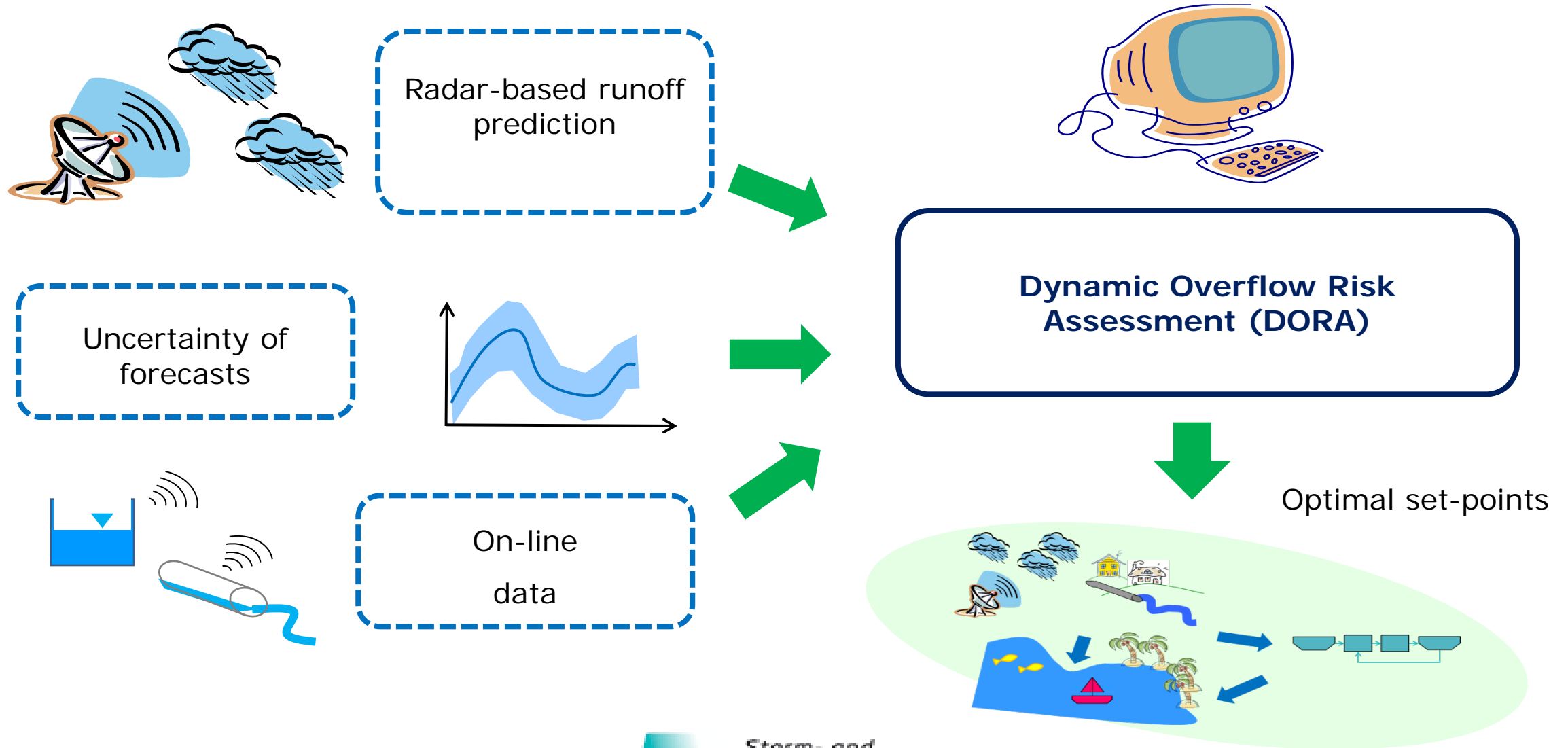


Rainfall evolution is uncertain

# Risk-based Model Predictive Control

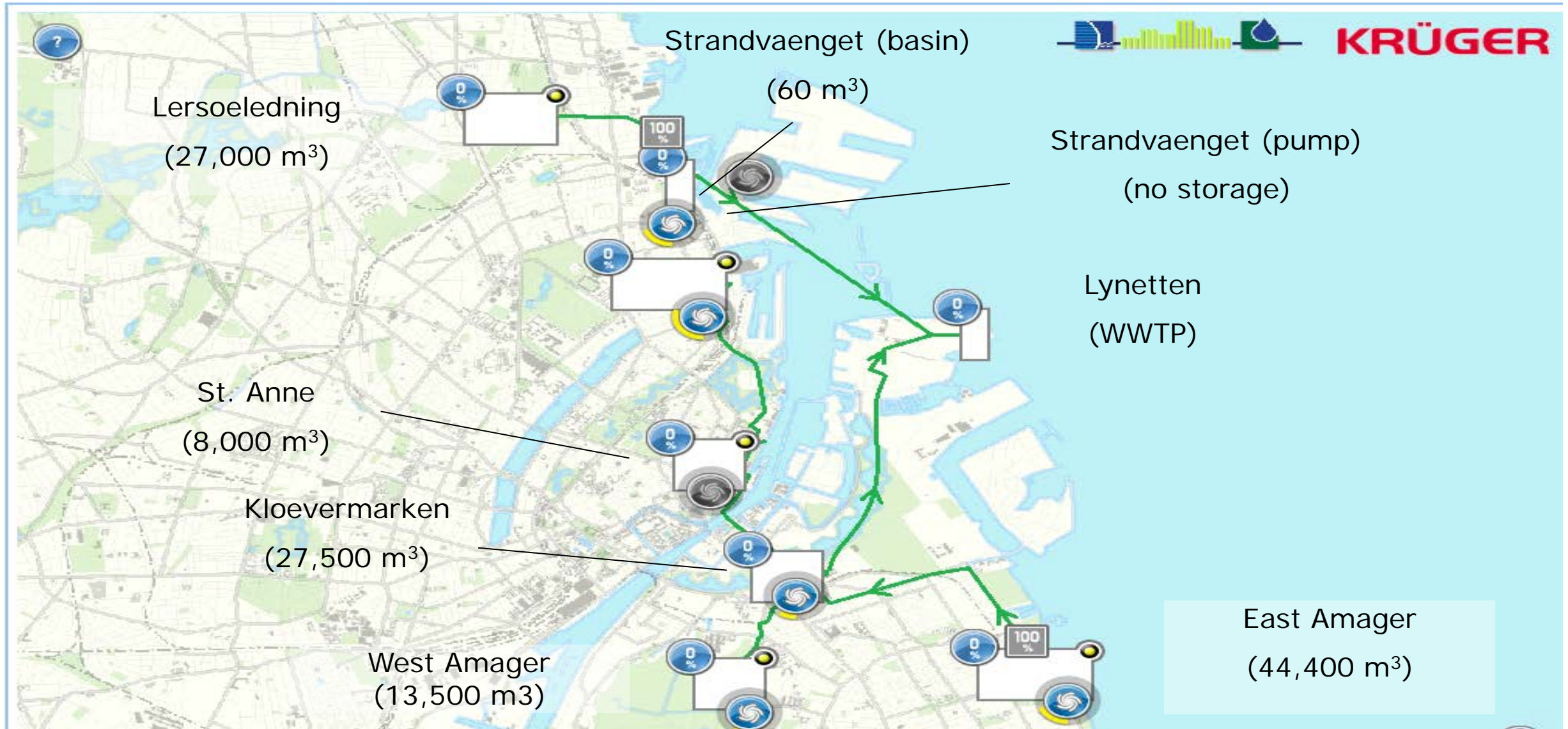


# The Dynamic Overflow Risk Analysis (DORA)



# The Lynetten catchment

## Central Copenhagen, Denmark







# The fellowship of SWI – the long journey

Measurements

+

Models

+

Forecasts

+

Uncertainty

=

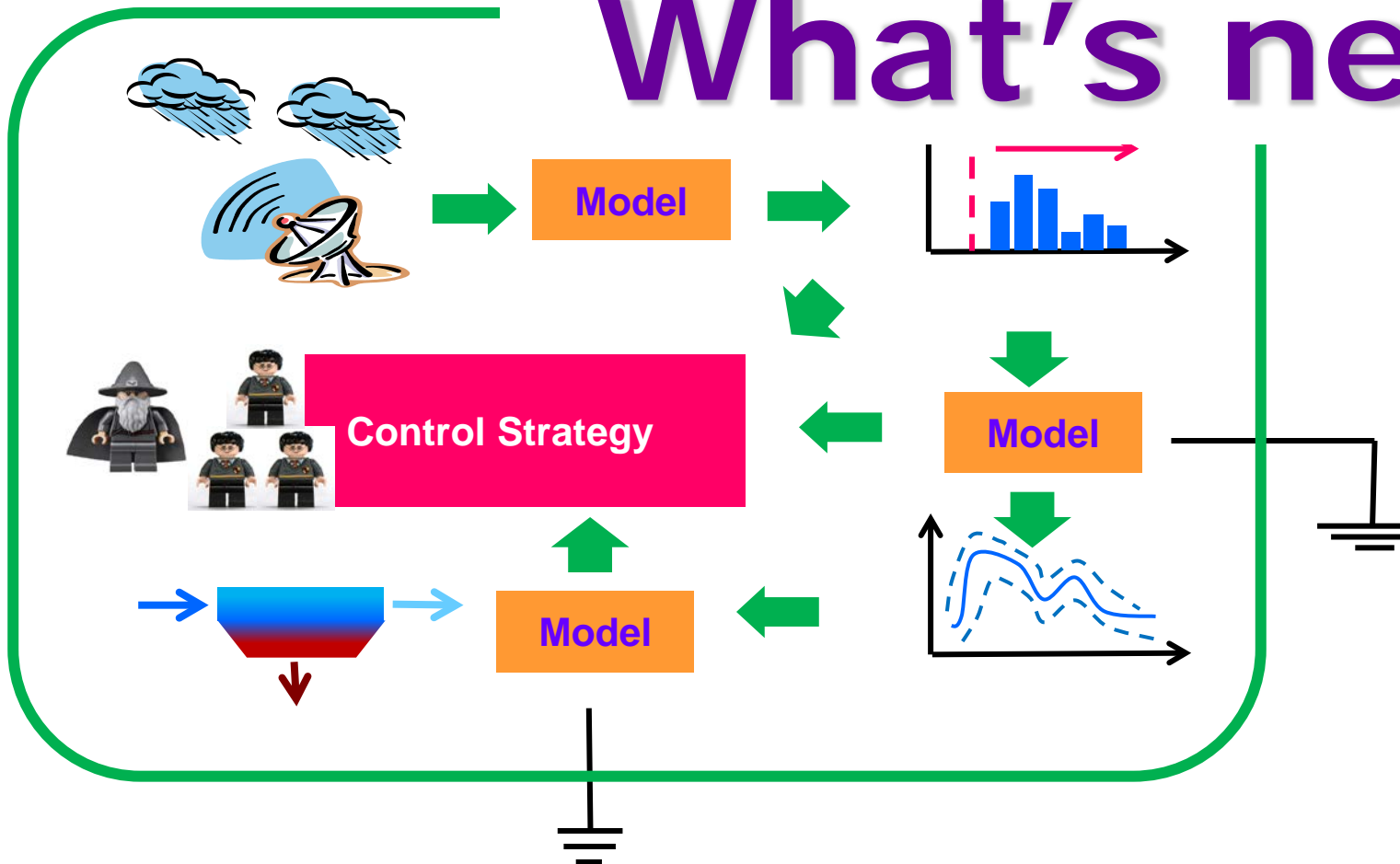


*The happy operator*

## What's next?

measurements  
in rainfall forecasts

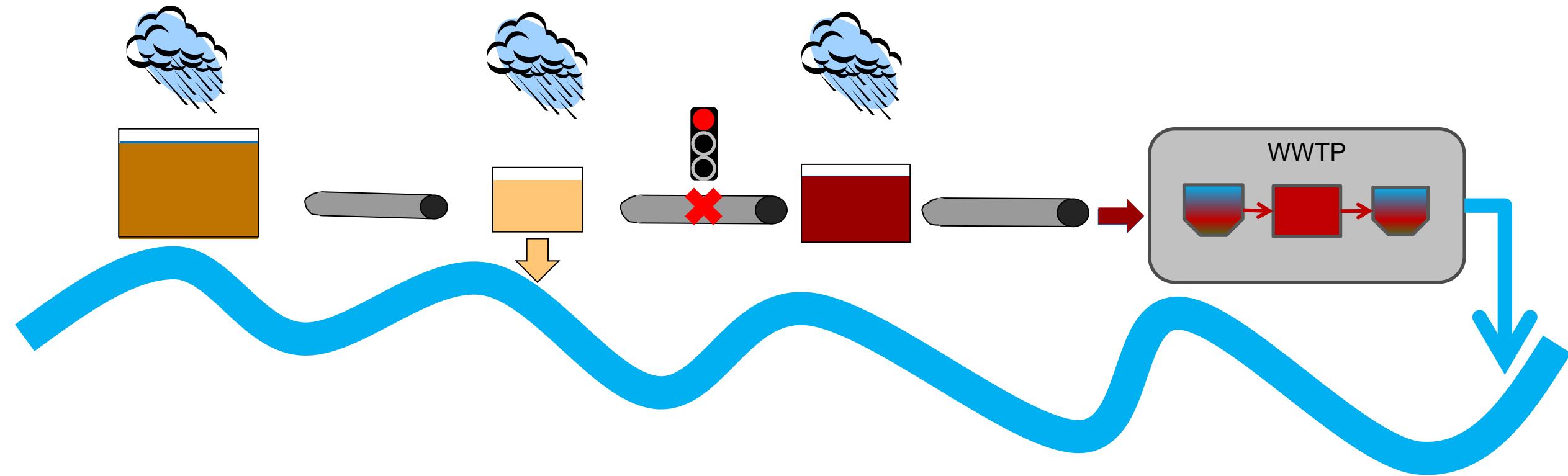
- Continuously updated hydrodynamic models
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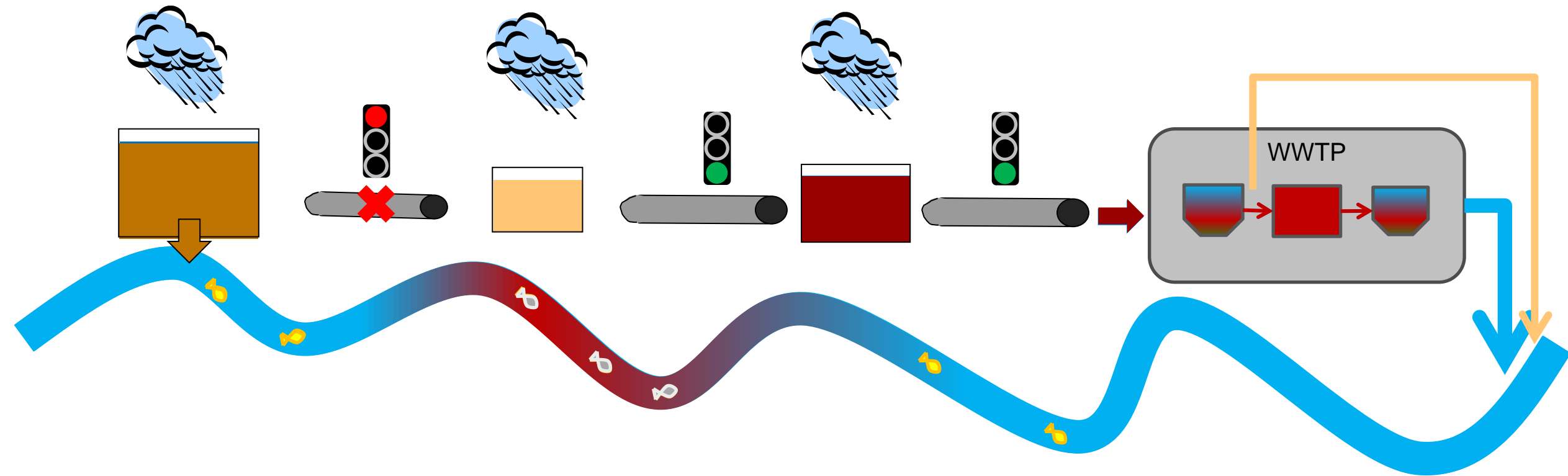
# Water Quality-based control

- Pollutant concentrations are not uniform →



# Water Quality-based control

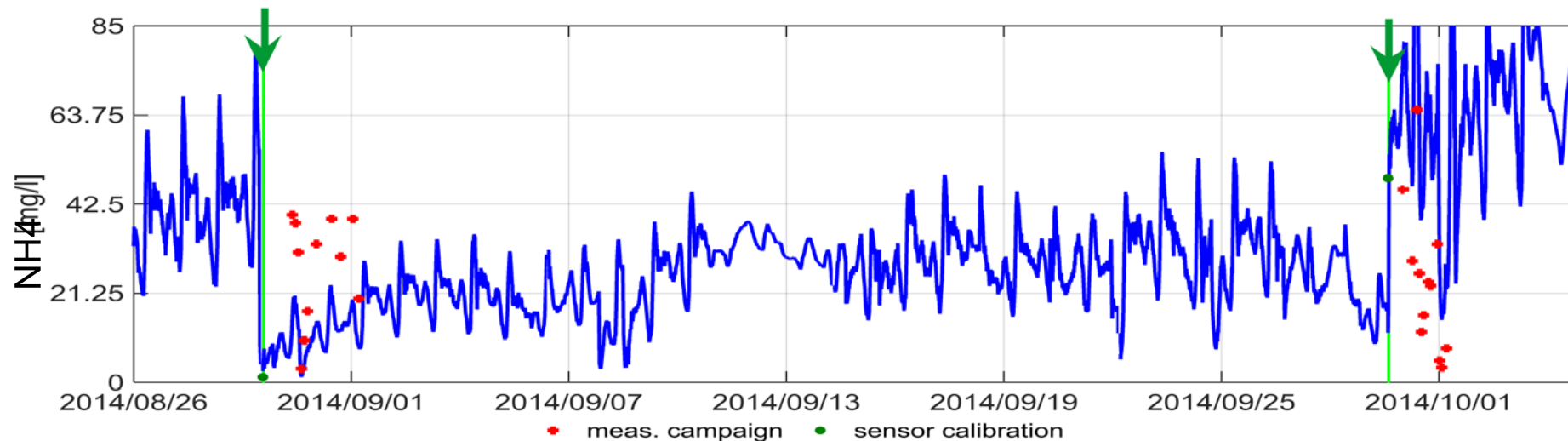
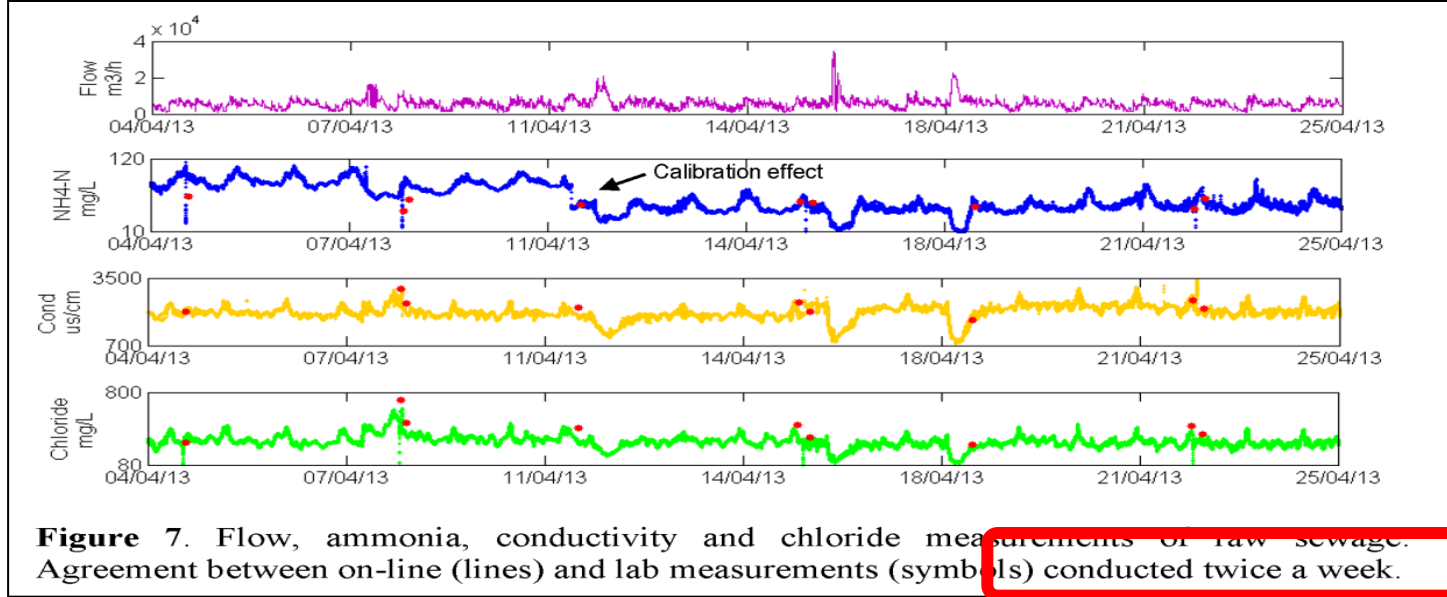
- Pollutant concentrations are not uniform → we can control the system based on Water Quality (instead of water quantity)
- The natural waters have not all the same status →



# 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?



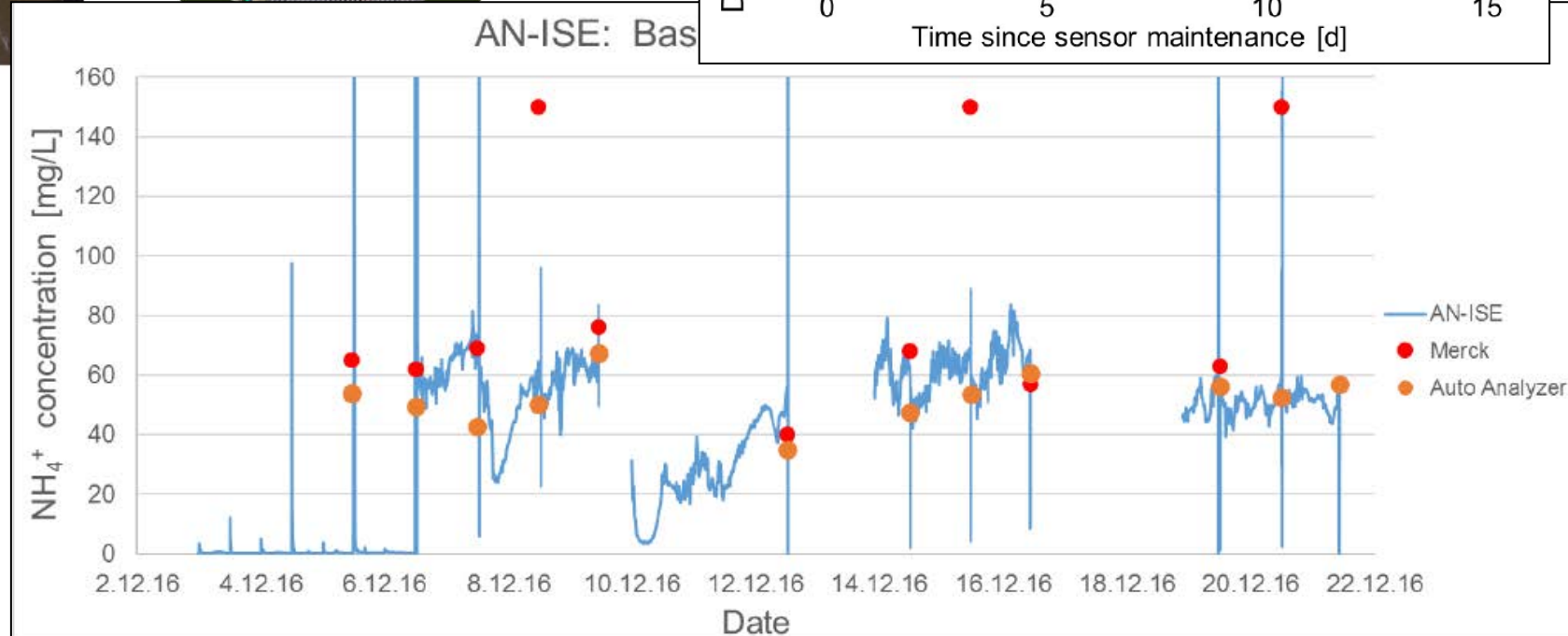
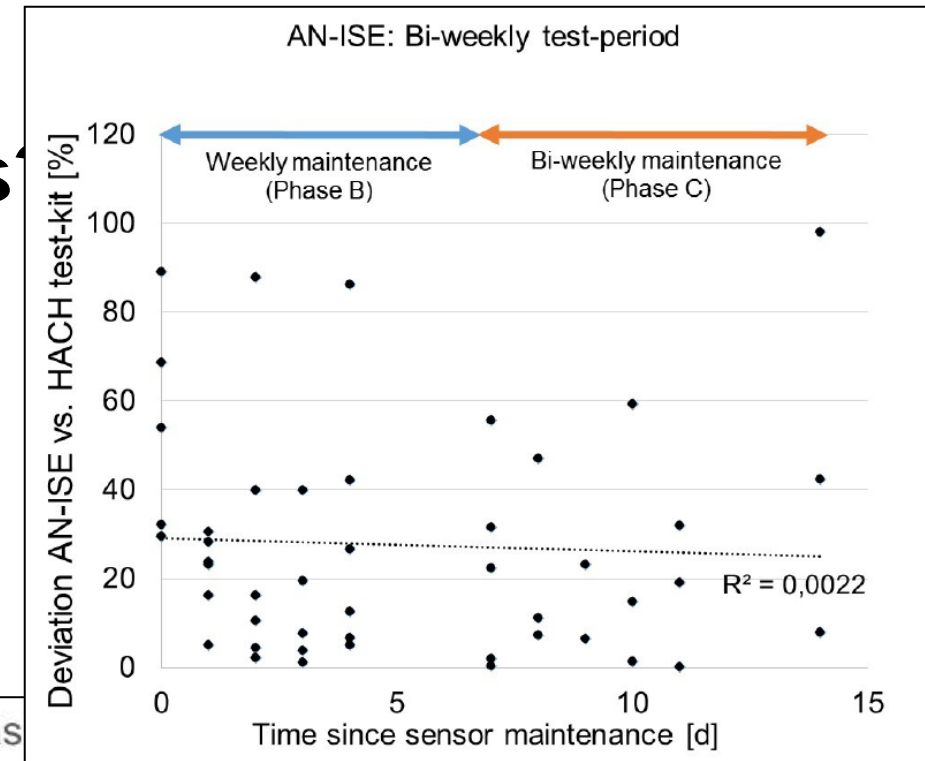


# The Ålebækken "playground"



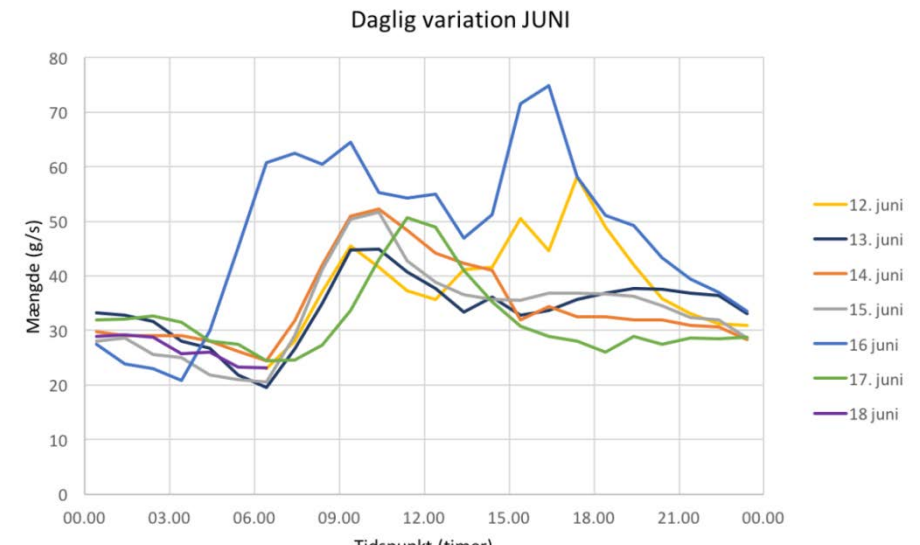
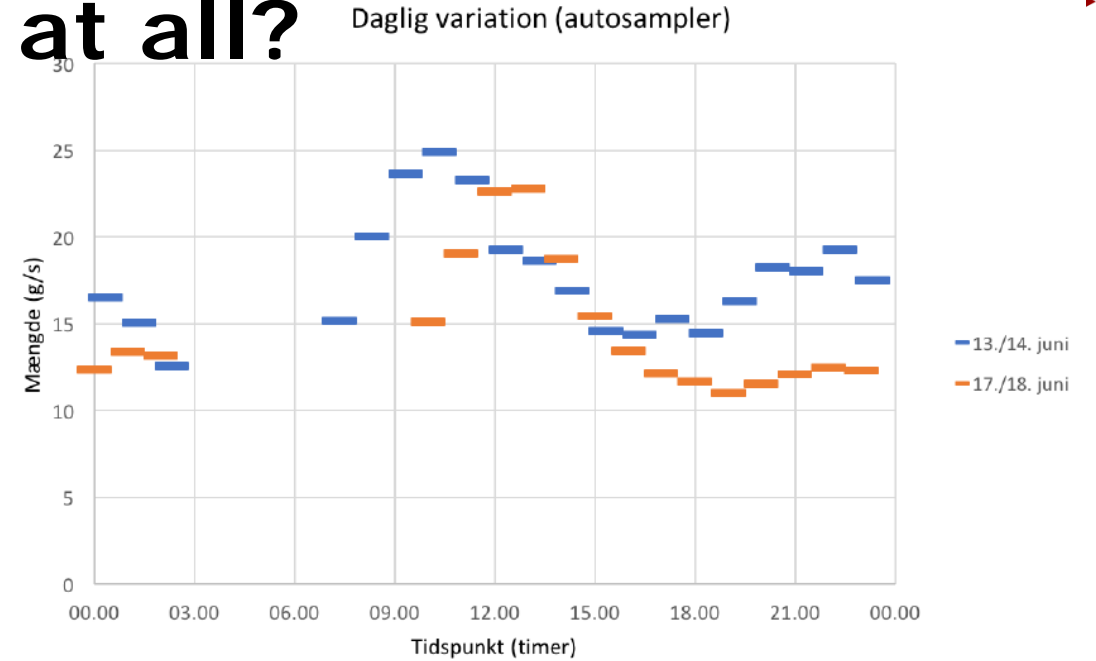


# How much can we trust sensors





# Do we need fancy sensors at all?



# The importance of involving the final users



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

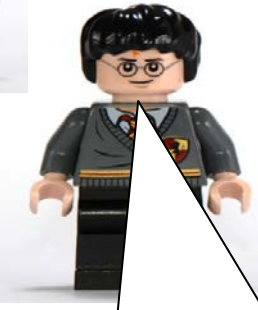


??????

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

Thanks, but my system  
works fine as it is

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



If you use a stochastic  
differential equation...

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

# The importance of involving the final users

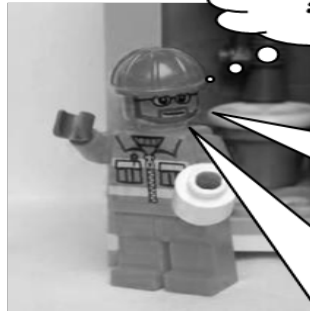


Dear smart people from university, what wonderful tool did you prepare for me?



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?

Thanks, but my system works fine as it is



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

# 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