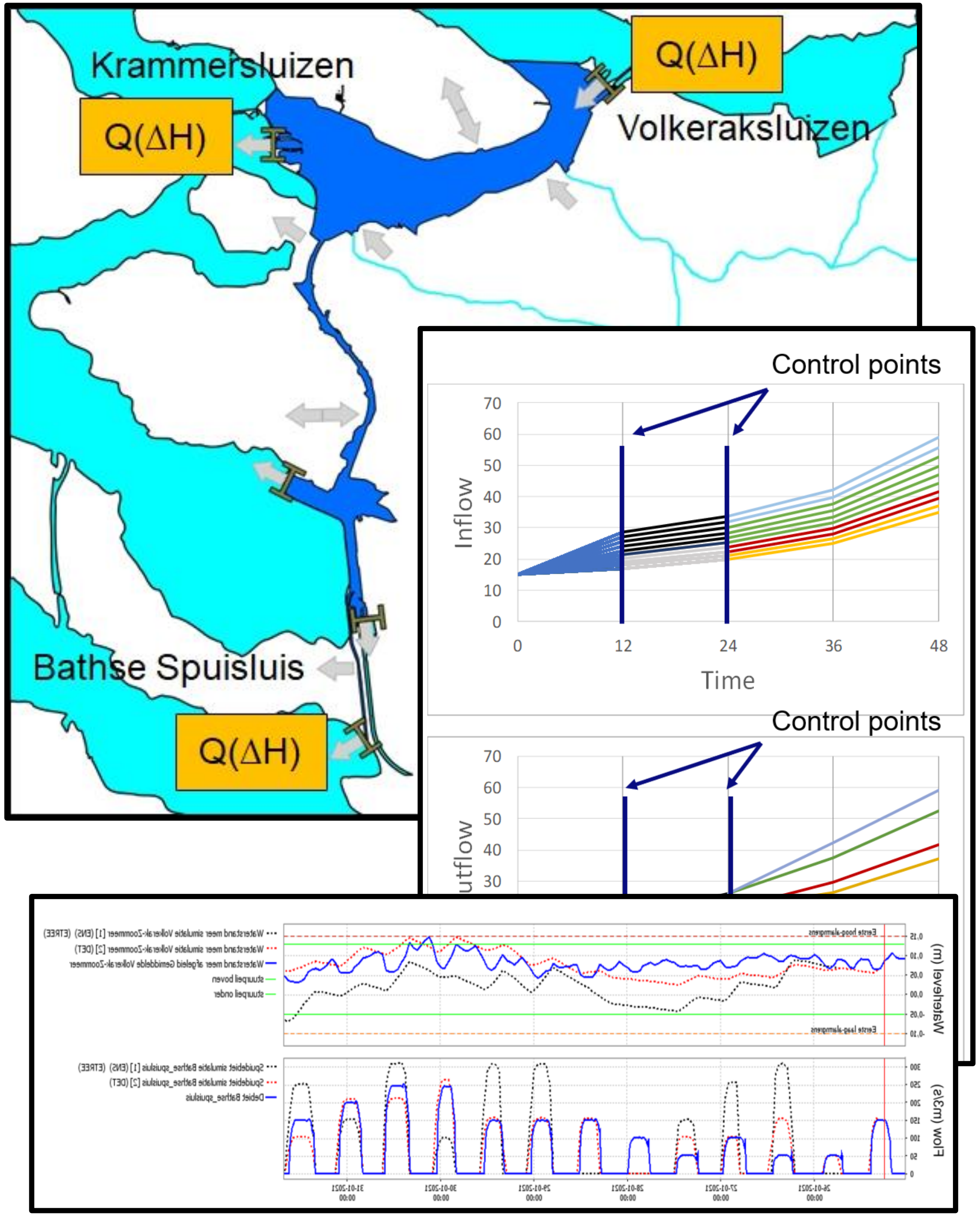

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Rijkswaterstaat
Ministry of Infrastructure and Water Management[2]

Computing the optimal response to an uncertain flood forecast

A case study with tree-based model predictive control for lake Volkerak-Zoommeer

Maarten Smoorenburg[1,2], Klaudia Horváth[1], Tjerk Vreeken[1], Teresa Piovesan,[1]

Wim Werkman[2], Stefan Nieuwenhuis[2], Rutger Blok[2]

3 November 2022, 5th Dutch-German workshop “From Flood Forecasts to Effective Emergency Response Measures, Zwolle (NL)

Table of contents

- Introduction (set the scene)
- Case study
- What is Tree-Based Model Predictive Control?
- Closed-loop analysis with real world event
- Practical problems
- Next steps
- Summary

Introduction - Deltares

- **National R&D-institution** for **water managemen** and **geotechnical engineering** (HQ in Delft)
- "Foundation under Dutch law" → **not for profit**
- Research, consultancy, physical modeling facilities, open software
- **"Bridges academia and practice"**

~800 employees,

~40 person team on operational water management

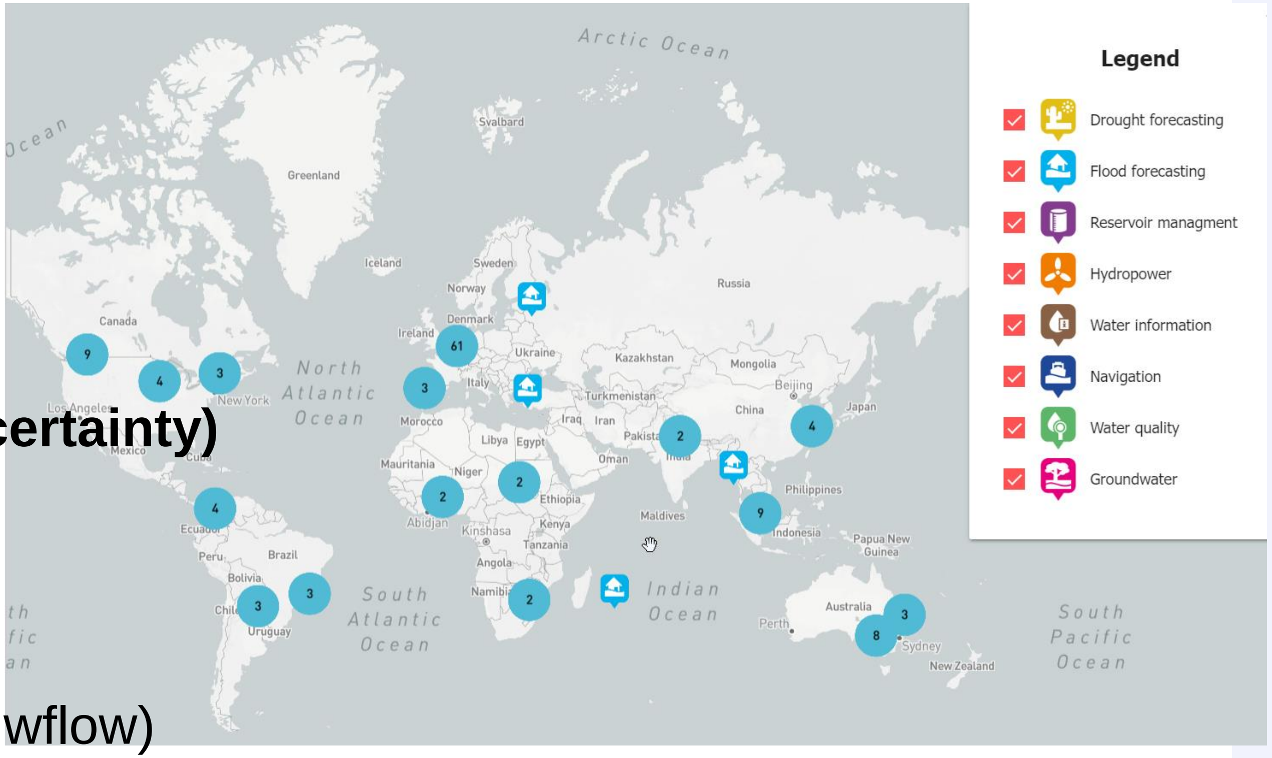
~many students

www.Deltares.nl

https://youtu.be/Nxb9SnBIxYY

Introduction - Deltares' Operational Watermanagement

- **Inland** and **coastal** systems (and **mix**!)
- Expertise:
  - Real-time data (in and out!)
  - **Forecasting** (with verification)
  - **Control / Decision making (under uncertainty)**
  - System engineering
- Software
  - **Delft-FEWS**
  - Simulation models (SOBEK, DHYDRO, wflow)
  - Control optimization **(RTC-Tools)**
- Close collaboration with Rijkswaterstaat (Dutch Ministry for Infrastructure an Water)
- Projects all over the world



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Introduction - Deltares' Operational Watermanagement

- **Inland** and **coastal** systems (and **mix**!)
- Expertise:
  - Real-time data (in and out!)
  - **Forecasting** (with verification)

"Enabling better forecasts, enabling better decisions"

  - Simulation models (SOBEK, DHYDRO, v
  - Control optimization **(RTC-Tools)**
- Close collaboration with Dutch Ministry of W
- Projects all over the world

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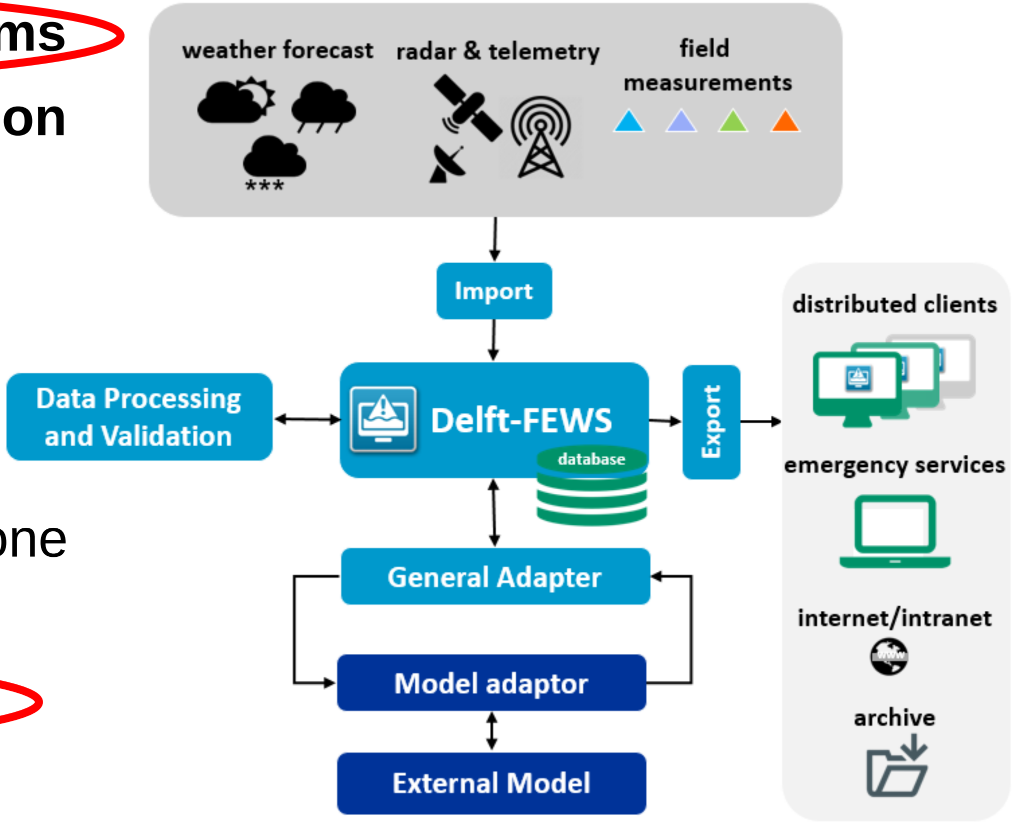
Introduction – Delft-FEWS

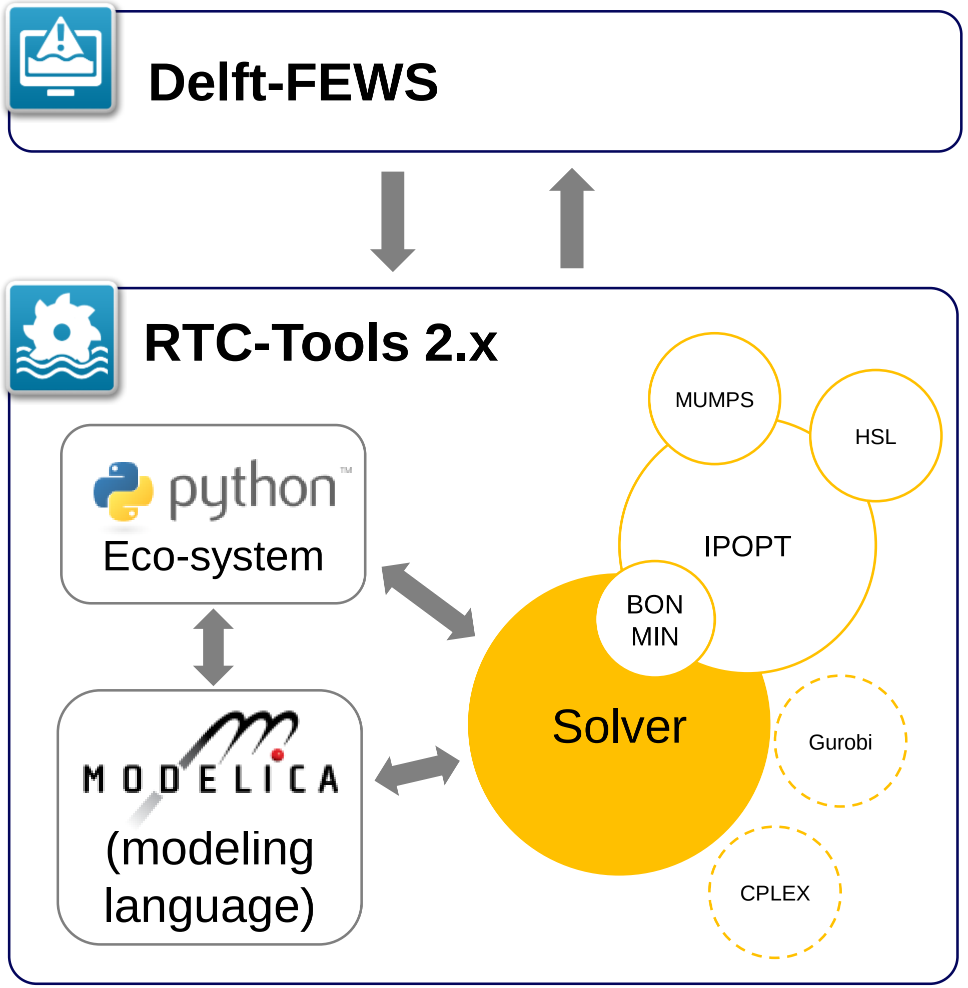
Delft-FEWS

Used world wide in various real-time applications

- **Platform** for **operational water resources systems**
- **Organising** from **input** to **forecast** to **dissimination**
- **Open** approach to **integrating models**
- Fully '**configurable**' by user
- **Real-Time**
- Rapid implementation, **scalable & flexible**
- Highly **resilient & automatic /** manual & stand alone
- **Large community involvement**
- **Open system – joint development approach**



Model Predictive Control with RTC-Tools + FEWS



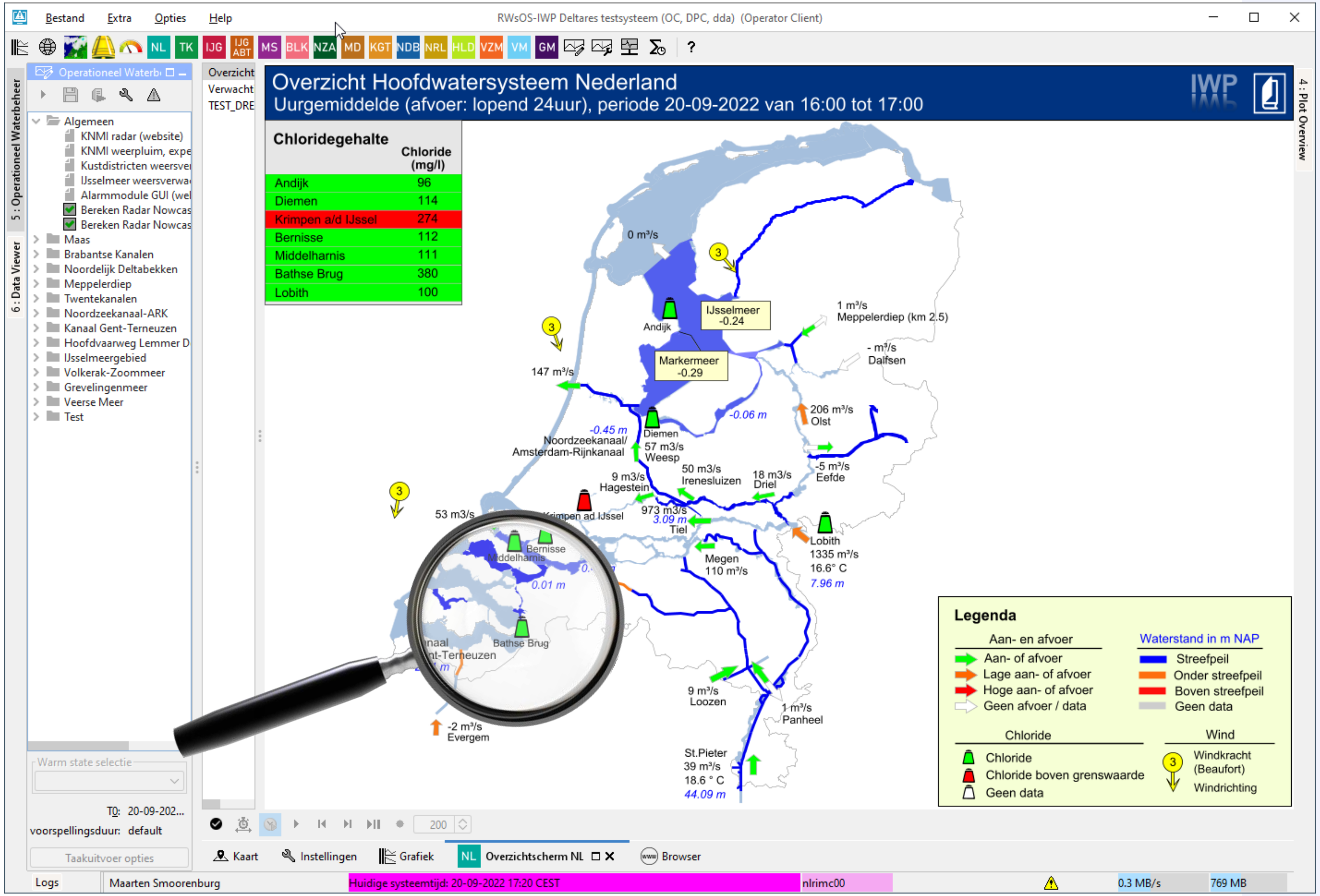
Open source toolbox for convex optimization in water systems

Simulation and Model Predictive Control (MPC), with multi-objective optimization for:

- **Maximization of production / profit (hydropower)**
- **Minimization of pumping costs**
- **Control of level, flow, salinity, heat, etc.**

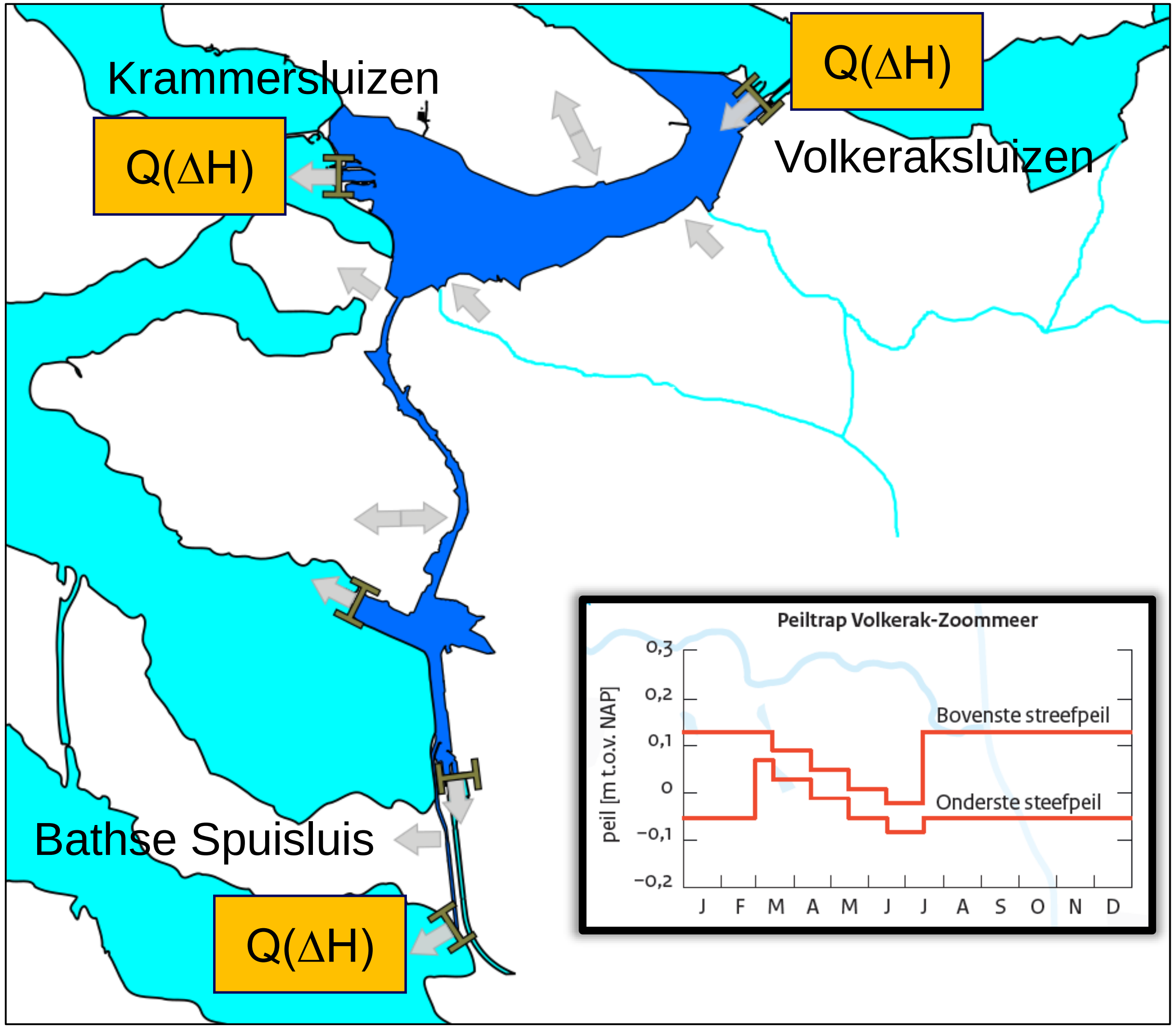
Case study – Volkerak-Zoommeer

- 3rd largest lake of Netherlands
- Decision support system of Rijkswaterstaat; FEWS-IWP
  - Control of lakes and canals
  - flow, waterlevel, salinity
  - 14 subregions
  - Interactive
- Forecast produced in other systems
- Simulation models
- Advice models (optimization)



Case study – Volkerak-Zoommeer

- Fresh water lake close to sea
  - Lake level control
  - Salinity control (by flushing the lake)
  - (minimizing energy costs of pump)
- Multiple natural inflows
- Large control knobs depend on outside waterlevels (***at low tide***)
  - 1 controlled inflow (to manage salinity) (Volkeraksluizen)
  - 1 emergency spill option (ship locks) (Krammersluizen)
  - 1 control outflow (6 spill gates) (Bathse Spuisluis)



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Case study – Volkerak-Zoommeer

Key challenge: compound floods

Example: Forecast for the coming days:

1) Storm at sea → surge on Westerschelde (up to ~2m!) → (much) less spill capacity
2) Substantial rainfall in Brabant → flood will fill up the lake (~100m3/s for 2-3 days)

Surface area lake :	80.74 km^2
1mm/h change in waterlevel:	22.4 m^3/s
Spillway through gate at low tide:	~50 m^3/s
Gate discharge average in 24h:	22.5 m^3/s*
Spill reduction at 0.5m surge:	22%
Spill reduction at 1.0m surge:	46%
Spill reduction at 2.0m surge:	93%

Westerschelde

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Case study – Volkerak-Zoommeer

Key challenge: compound floods

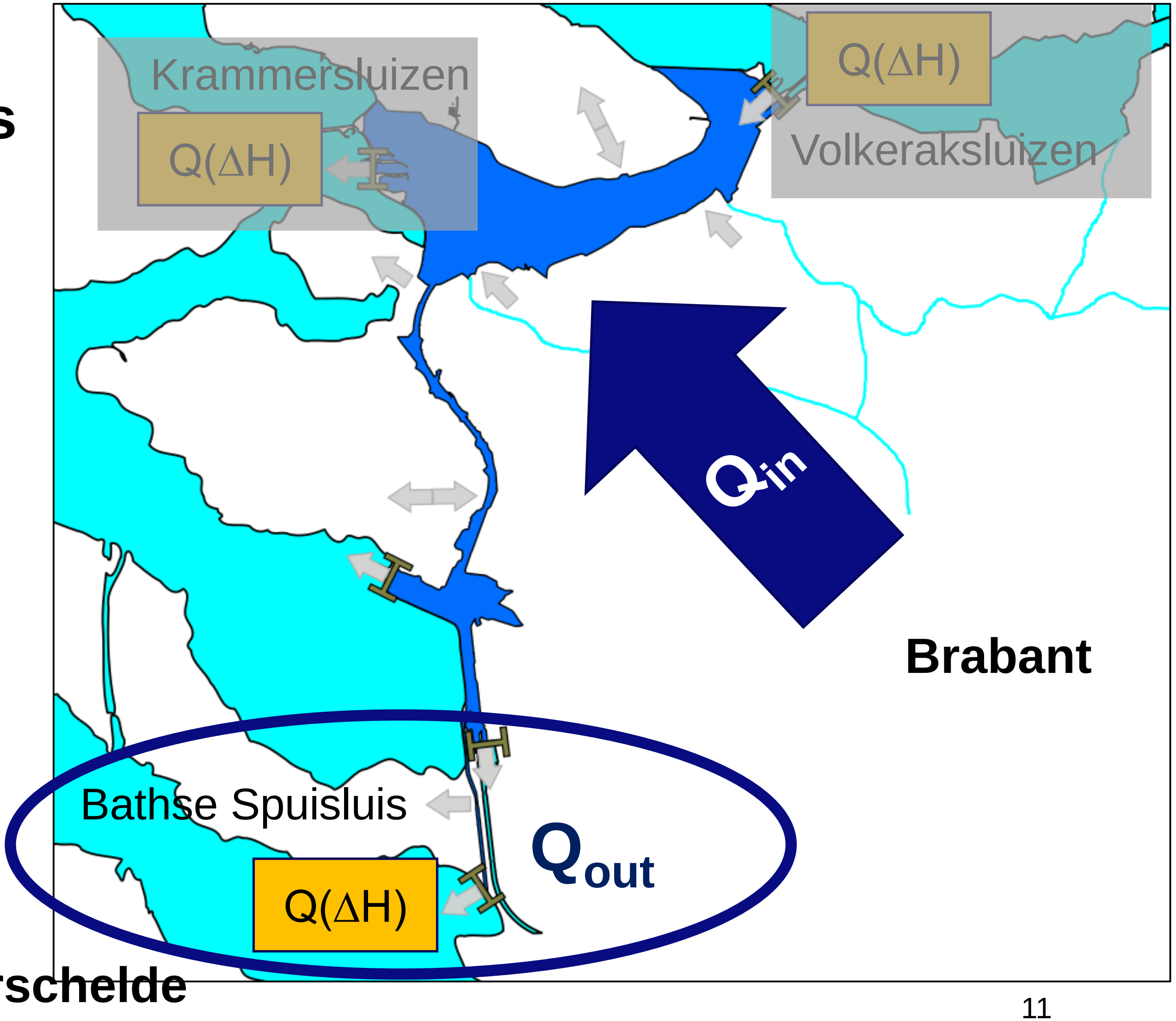
Critical decision:

1) High lake levels mean that upstream **polders cannot drain well anymore**
2) Krammersluizen locks will be closed for shipping if lake levels reach +0.5 m.s.l.
   → **spill through the locks!**

→ Operators need to lower the lake level in time by extra spill through Bathse Spuisluis

→ Action required 2-4 days in advance

→ Decision interval of ~12h



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Similar problem for many water systems

The future is uncertain, **show the ensembles**

…yet, decisions must be made

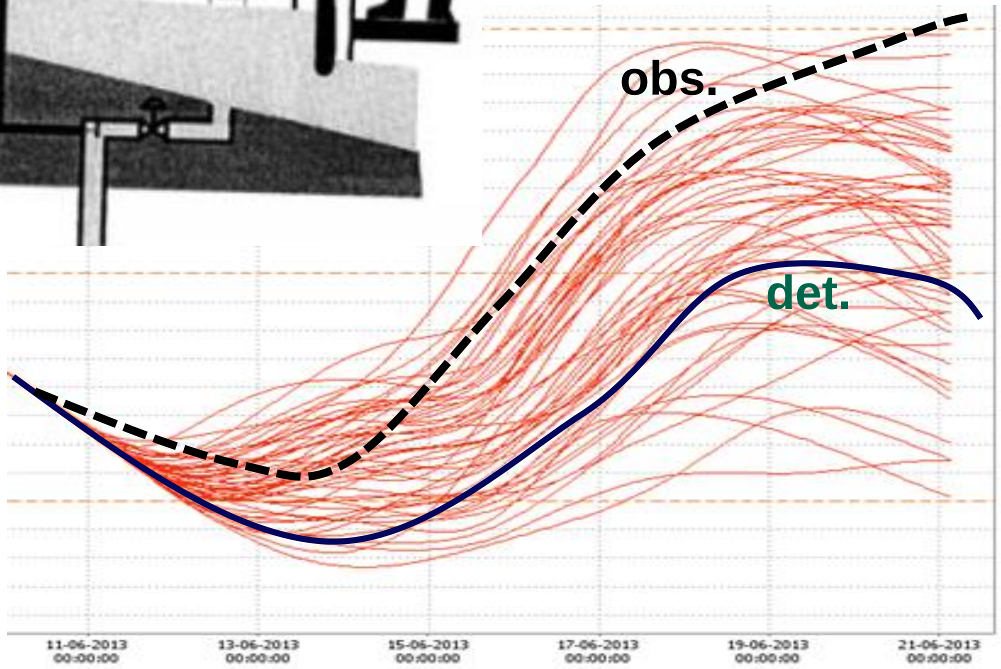
but how?



What is needed?

1) Anticipatory control

2) Taking into account forecast uncertainty



Problem Volkerak-Zoommeer: compound floods

Desire of operators:

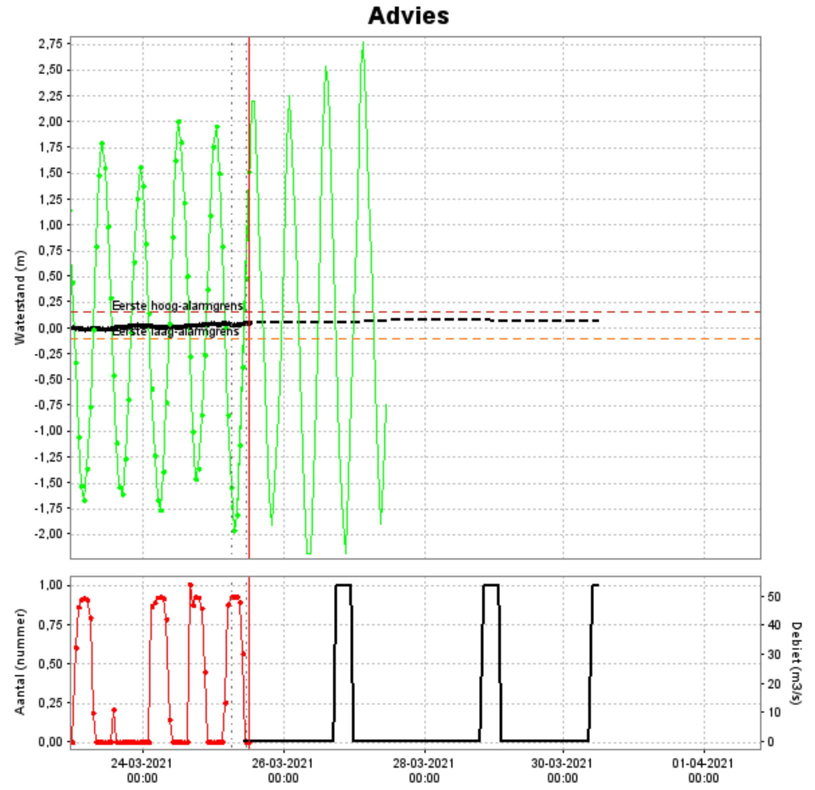
1. Quality forecasts of surge and inflow (!)
2. Advice on the control of the lake

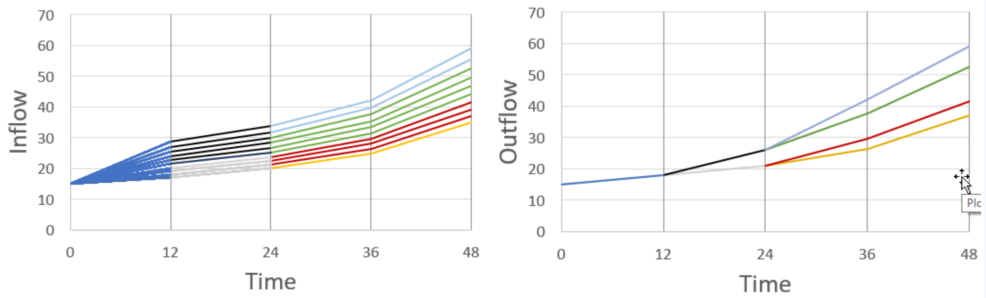
Current situation:

1. Implicit knowledge of uncertainties
2. Iterative control selection (looking up to 48h ahead)
3. (advised control through deterministic MPC)

Future:

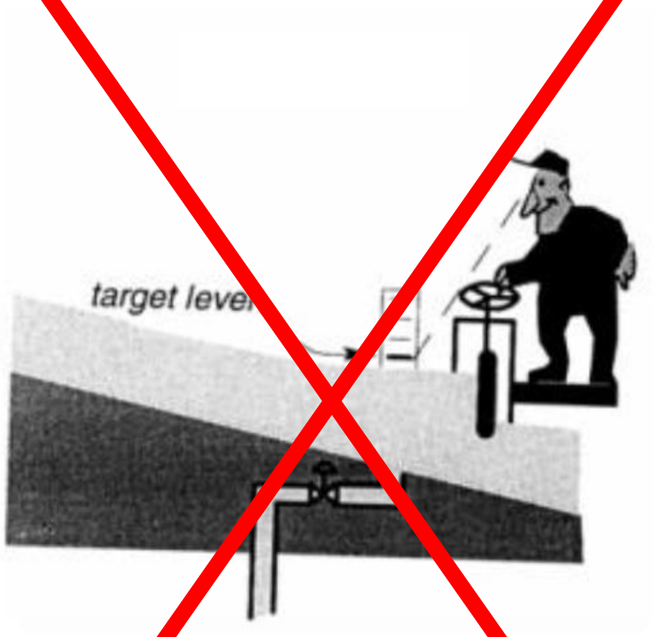
1. Ensemble forecasts of relevant processes
2. Tree-Based MPC producing advised control





Anticipatory control

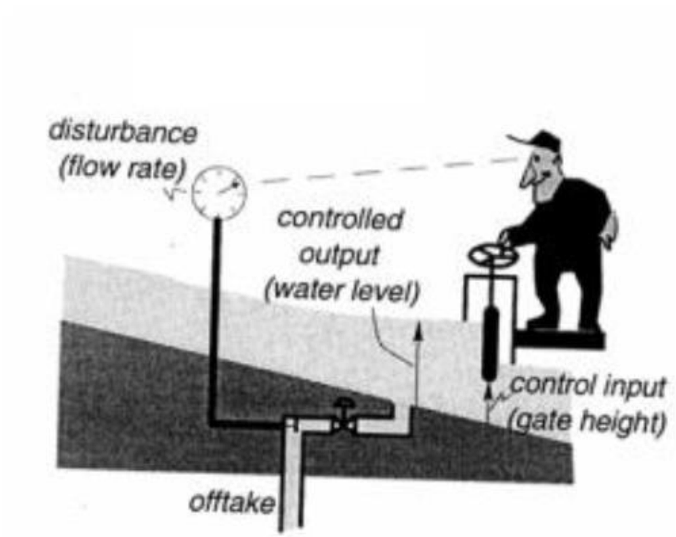
feedback control



Rule-based (if-then)

SOBEK or RTC-Tools

feedforward control



Rule-based (if-then)

SOBEK or RTC-Tools

model predictive control

optimization for objectives

RTC-Tools

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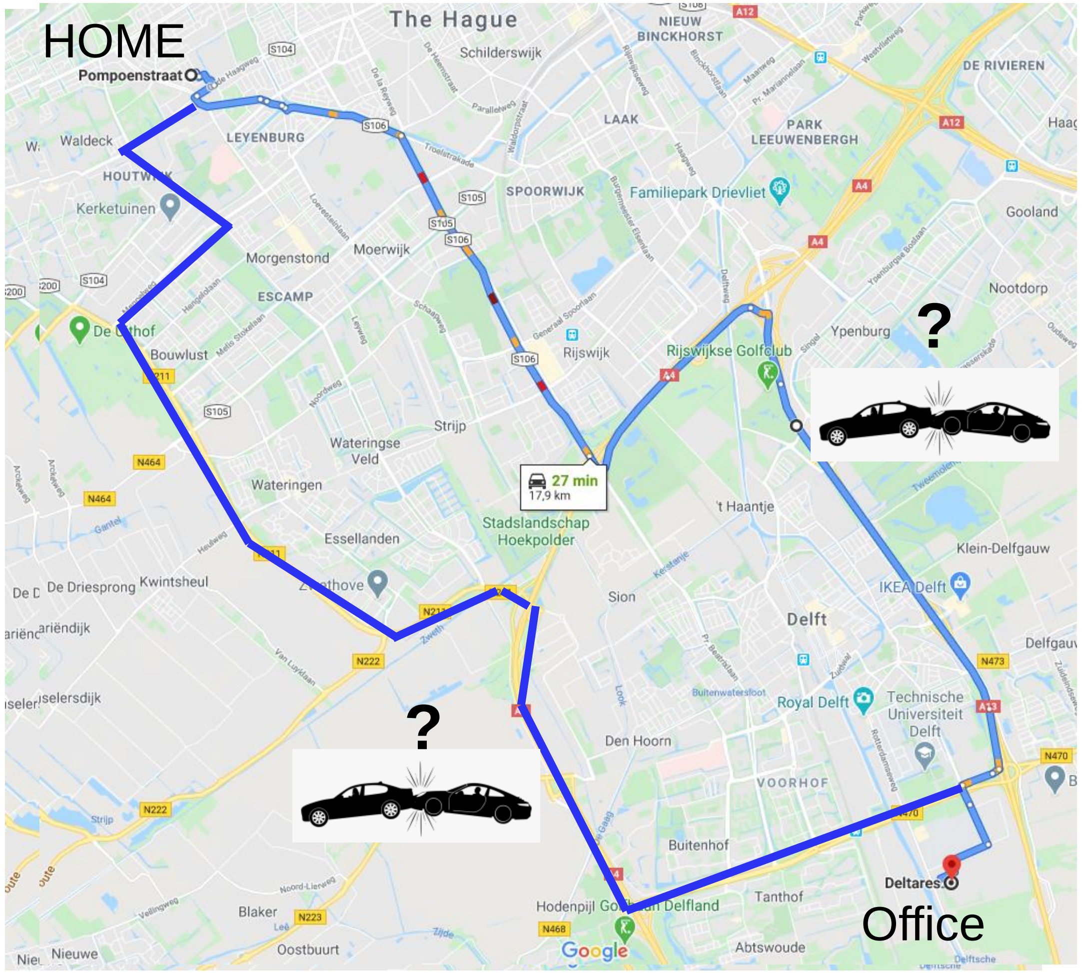
What is Tree-Based MPC?

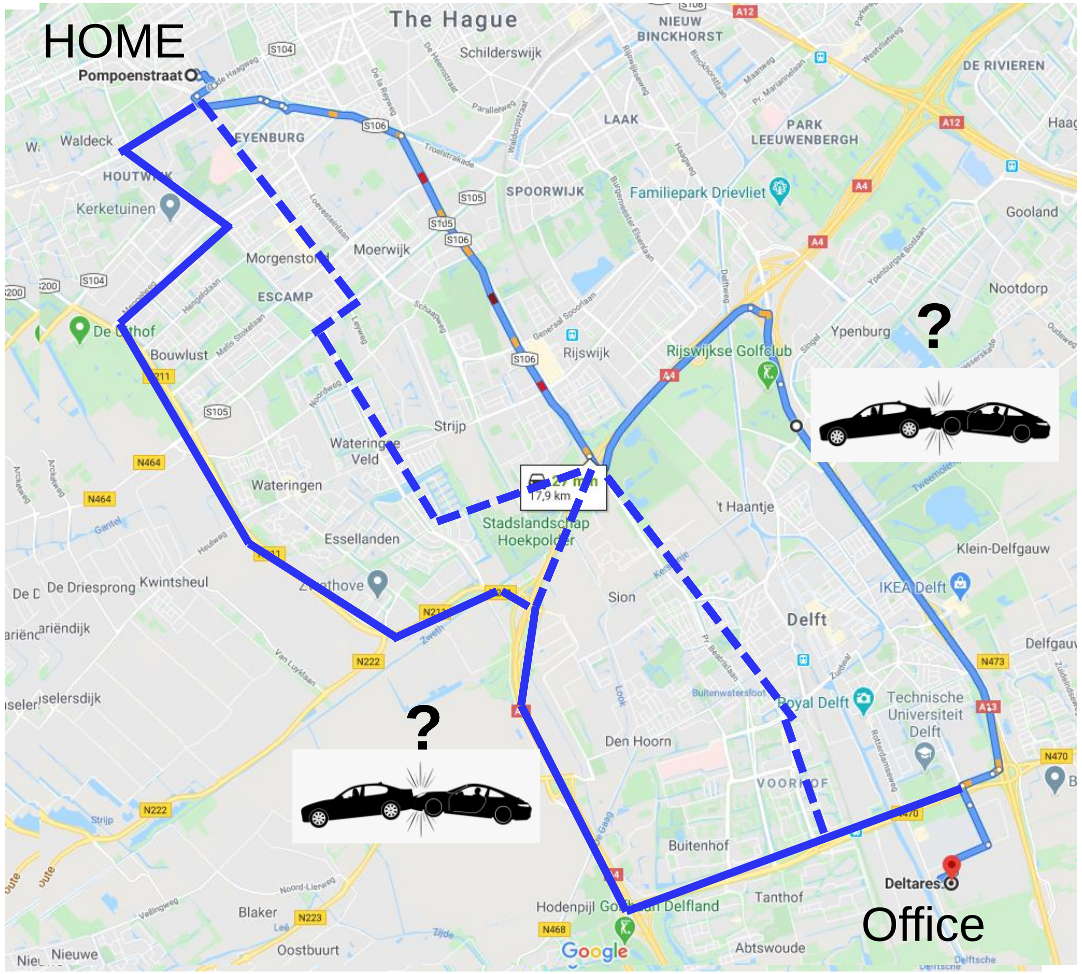


Decision problem:

goal is clear,

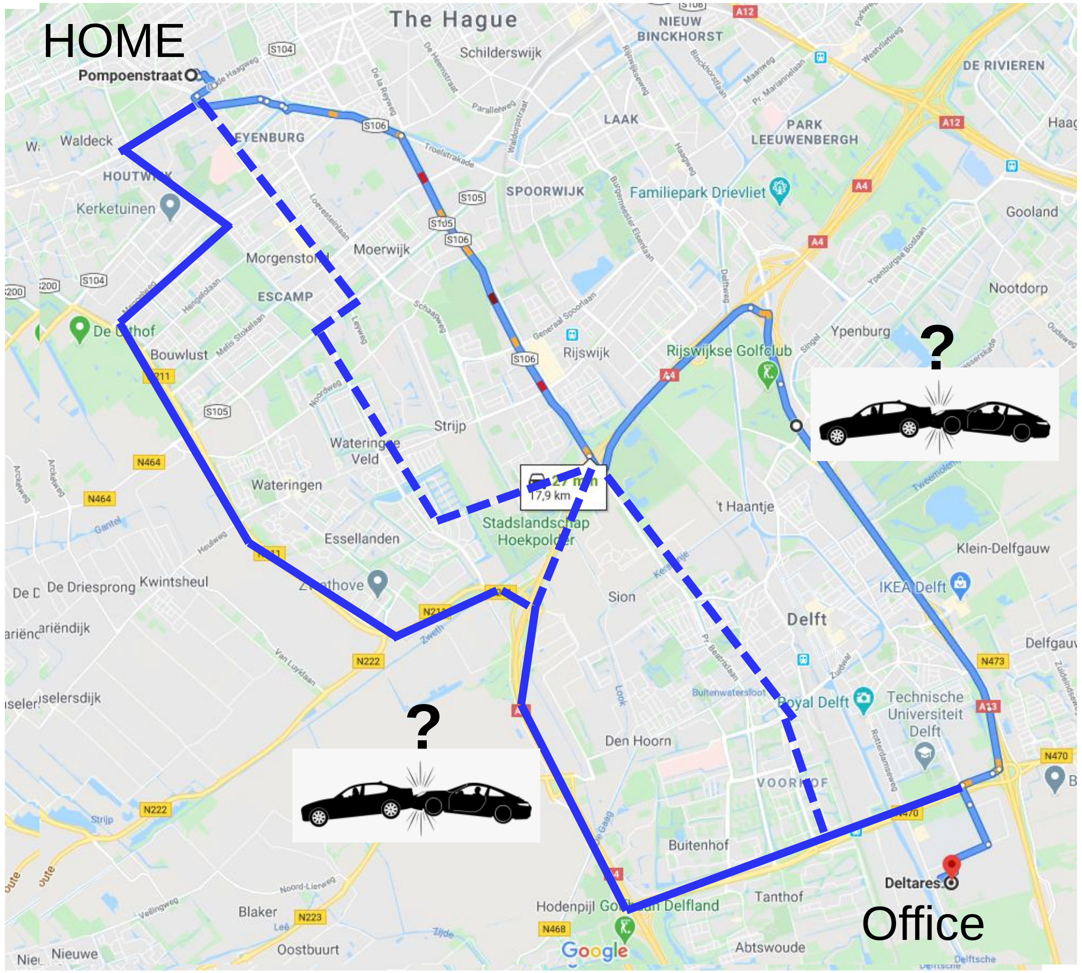
future is uncertain

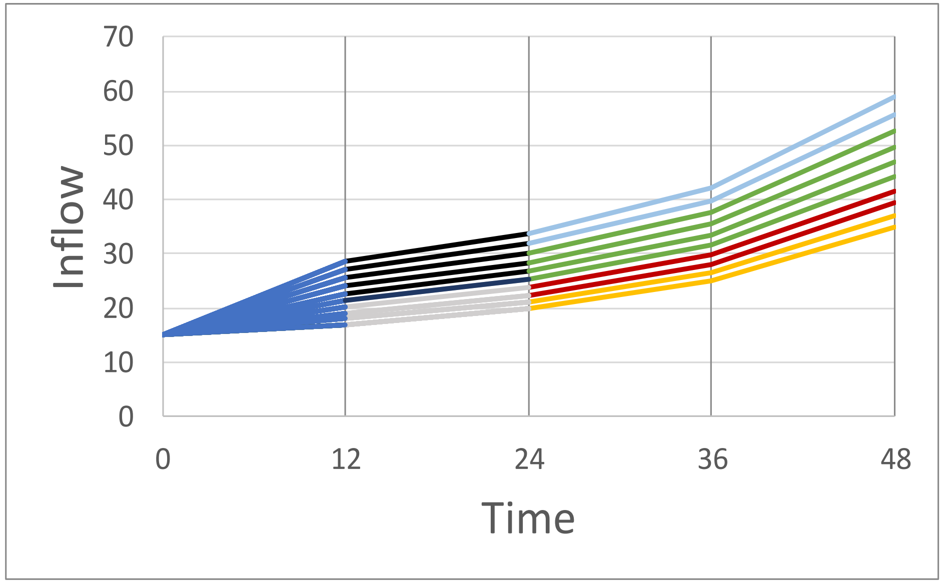
What is Tree-Based MPC?

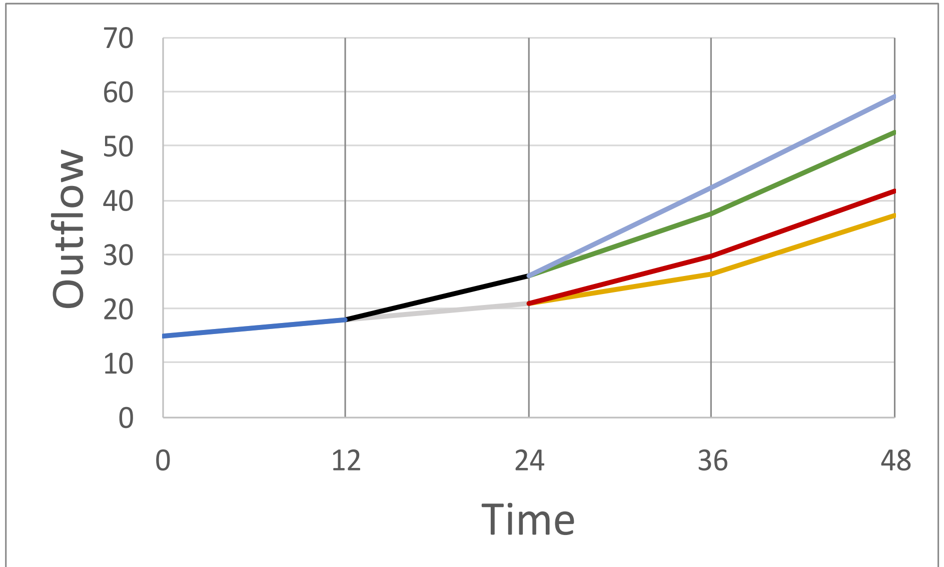


Original idea by:
Raso, L., D. Schwanenberg, N. C. van de Giesen, and P. J. van Overloop. 2014. “Short-Term Optimal Operation of Water Systems Using Ensemble Forecasts.” Advances in Water Resources 71 *https://doi.org/10.1016/j.advwatres.2014.06.009*

What is Tree-Based MPC?





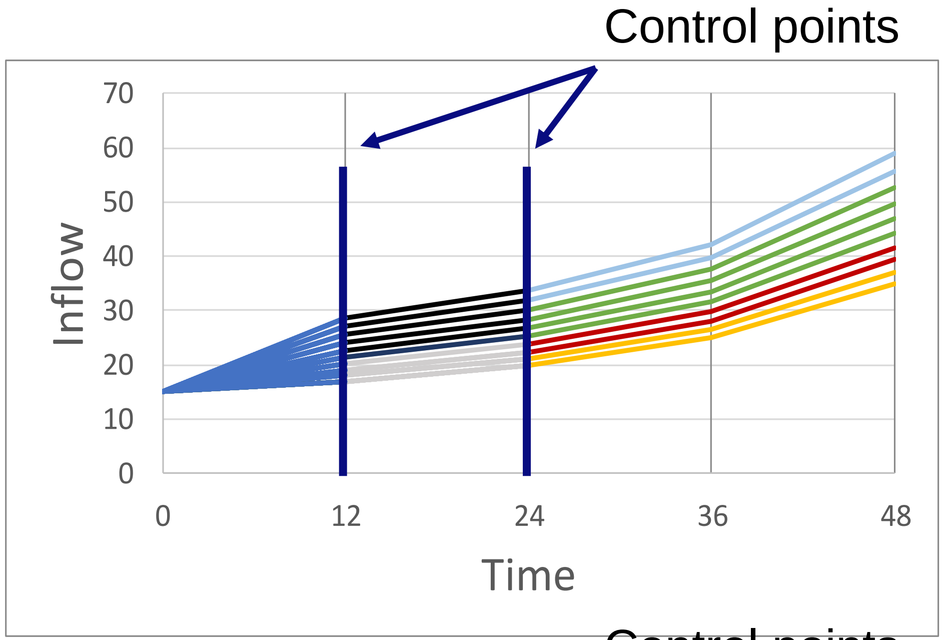


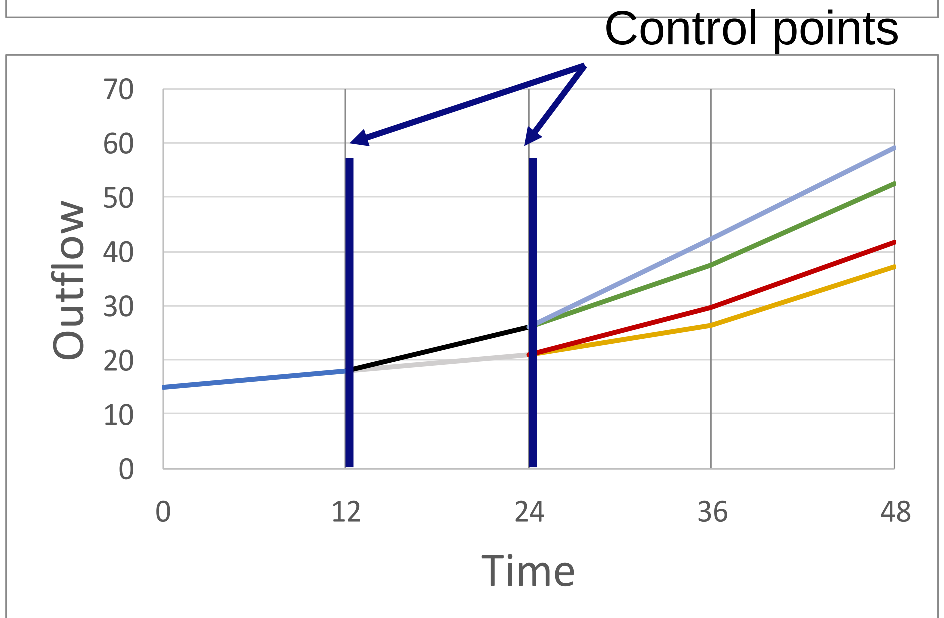
What is Tree-Based MPC?

- At control point:
  - Split ensemble in groups
  - Compute optimal control per group

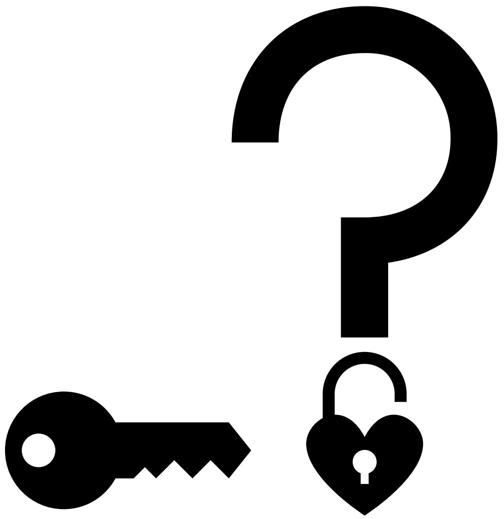
- Output:
  - Tree of advices
  - Projection of single ensemble members trajectory if advice is followed

→ At control points, different members have different states because they were subject to different forecasts!



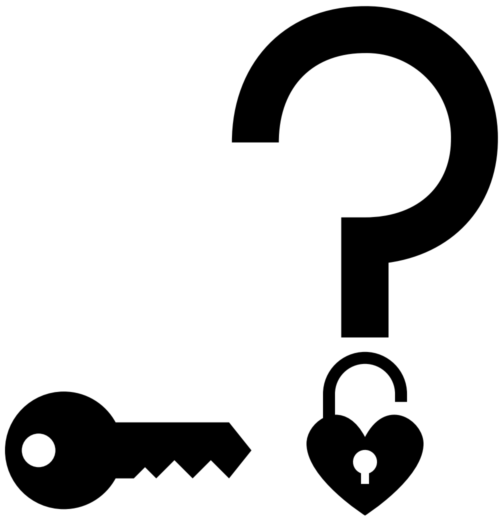


Key question



How useful is this solution for the user?

Key question



How useful is this solution for the user?

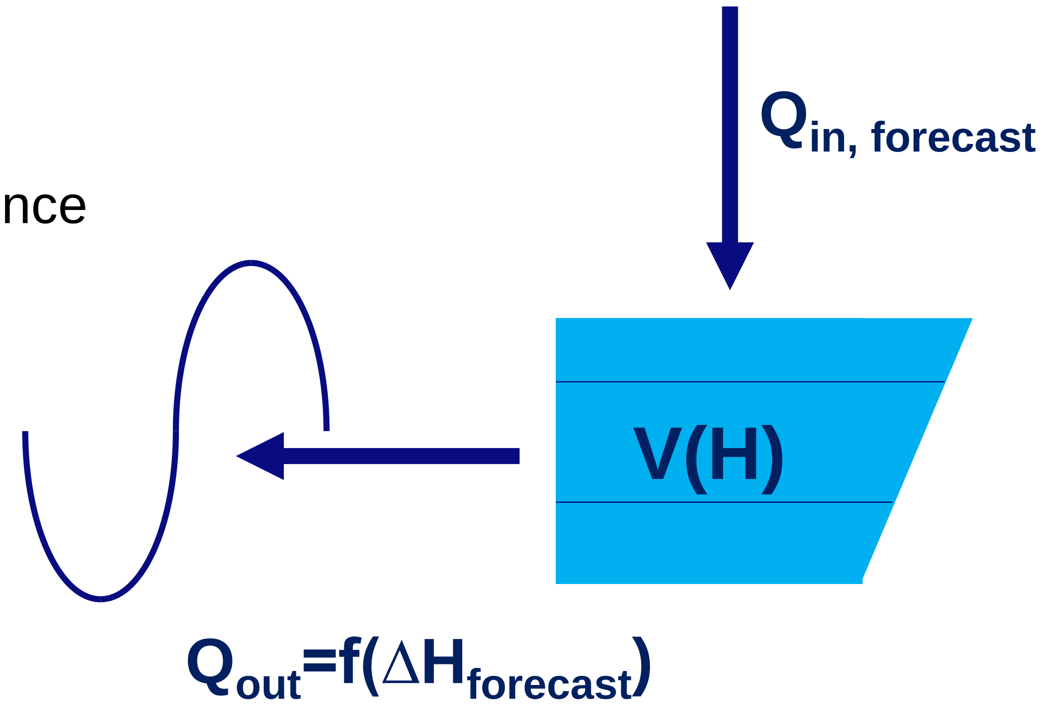
Technical answer: evaluate objectives with closed-loop analyses

‘Soft’ answer: evaluate ‘everything’ with end users (real-life; open-loop)

RTC-Tools model Volkerak-Zoommeer

Mixed Integer Linear Programming:

- Piece-wise linear relation volume – lake level
- Piece-wise linear relation discharge - head difference
- Discrete decision variables for flow direction



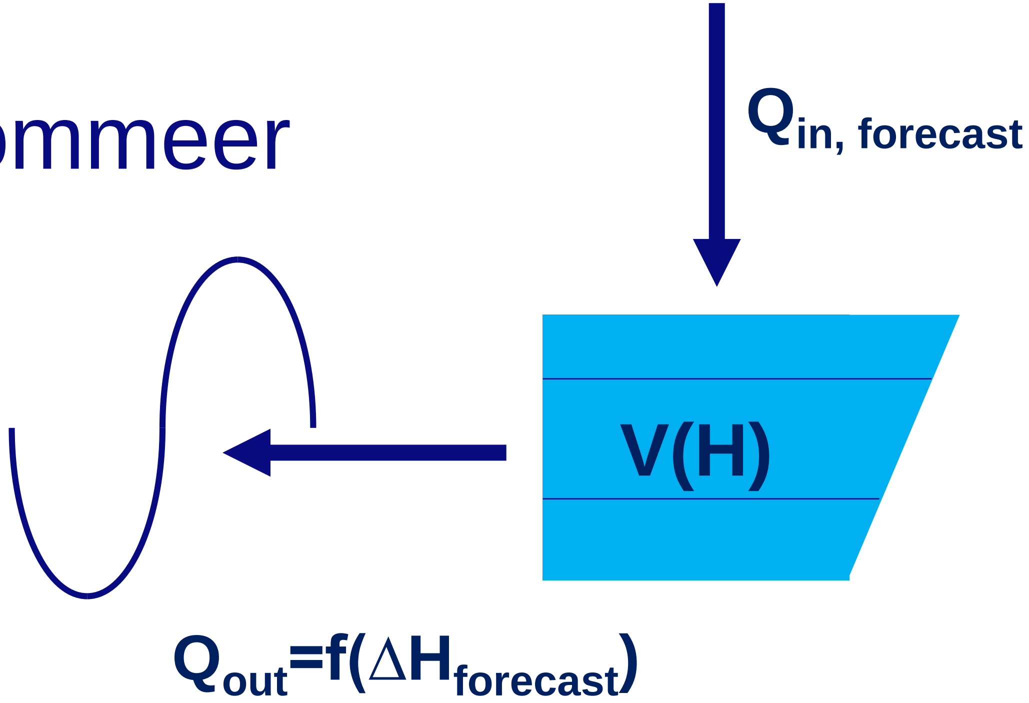
Main goal:

- Maintain lake level between target levels
- Quadratic penalty on target exceedance

Ensemble forecast for dominant processes:

- inflow from the “Brabant Rivers” and direct precipitation *(minus deterministic evaporation)*
- ‘outside’ waterlevel Westerschelde (spillway “Bathse Spuisluis”)

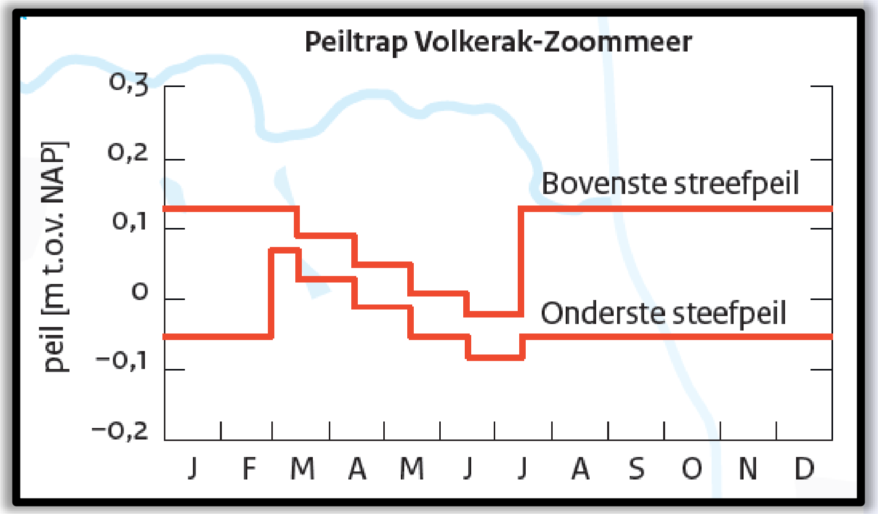
RTC-Tools model Volkerak-Zoommeer



4-stage 'rocket':

1. Pre-processing: situation-checker to define goals
2. Optimization (linear): compute optimal '*continuous*' spill flows through
3. Post-processing: compute '*discrete*' gate settings
4. Post-simulation (nonlinear): forecast flow and waterlevel with advised gate settings

RTC-Tools model Volkerak-Zoommeer



Goal programming (targets in order of priority)

Prio 1: Keep lake level between NAP -0.10m and +0.15m.

Prio 2: Keep lake level between softer targets

Prio 3: Minimize inflow through Volkeraksluizen

Prio 4: For t_{end} : try to get lake level centered between prio 2 targets

Ensemble load formulation needed:

$$\text{load} = \text{Inflow} + \text{Precipitation} - Q_{\text{bath, potential}}$$

$$Q_{\text{bath, potential}} = f(H_{\text{bath}} - H_{\text{target, mean}})$$

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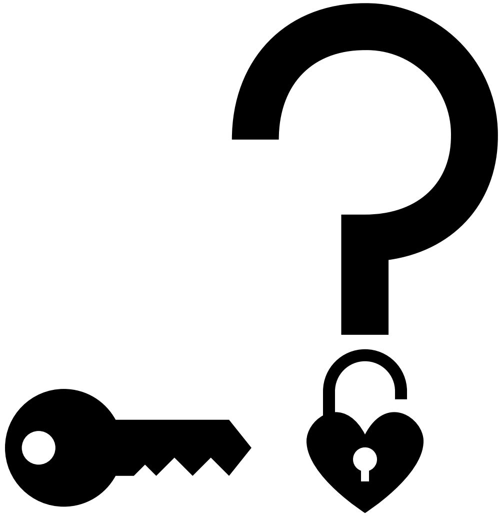
Voettekst van de presentatie

Key question



How useful is this solution for the user?

Technical answer: evaluate objectives with closed-loop analyses

‘Soft’ answer: evaluate ‘everything’ with end users (real-life; open-loop)

Closed-loop setup

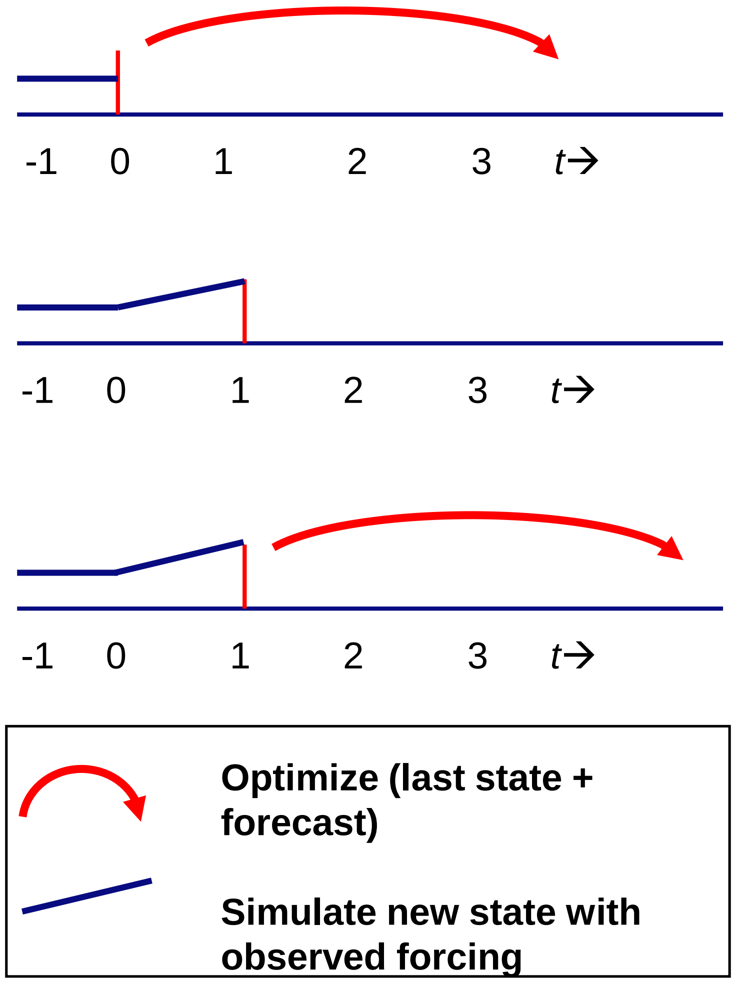
→ Mimick operations assuming advice is followed

Setup

- each 12h a new T0 with new forecasts,
- max. lead time of 5 days
- TB-MPC with control points at 12h, 24h and 48h

Procedure

1. Advice optimal control for measured initial conditions (=state) and forecast forcings
2. At next T0, simulate the effect of following the advice until present with measured forcings
3. Compute new optimal control advice with latest simulated system state and new forecasts
4. Etc. etc.



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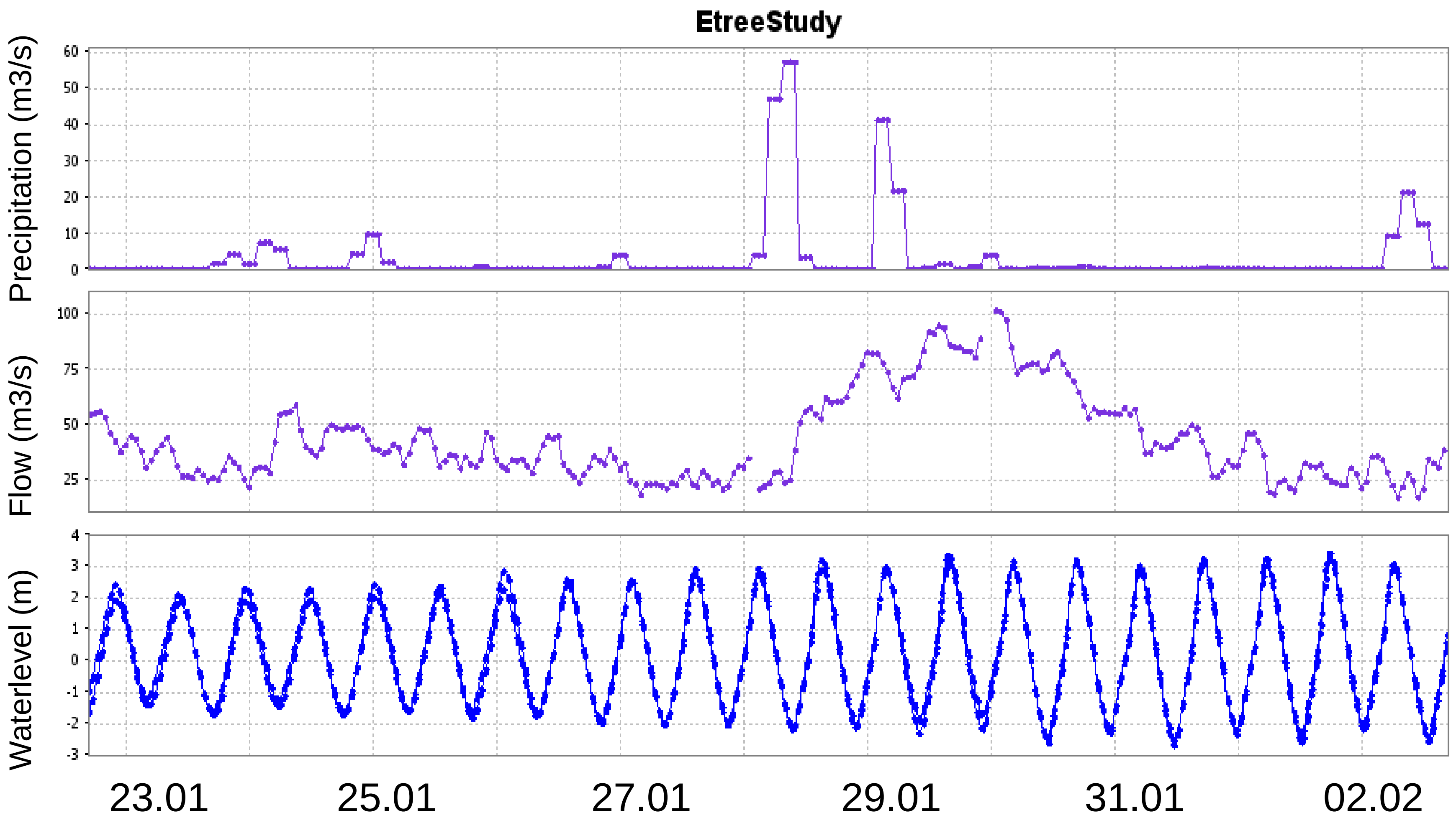
Voettekst van de presentatie

Closed-loop analysis with real world event (Jan 2021)



Forecast rainfall peak 1:
DET: structurally underestimated
ENS: in sight from 26 Jan 18h

Forecast rainfall peak 2:
DET: underpredicted until 28th
ENS: in sight with peak 1

Forecast inflow
Peak too low and too late
DET was high in the ensemble

Wind surge
Obs: 40 - 45 cm on 29 Jan,
→ Spill reduction ~ 10-20%, forecast alright-ish

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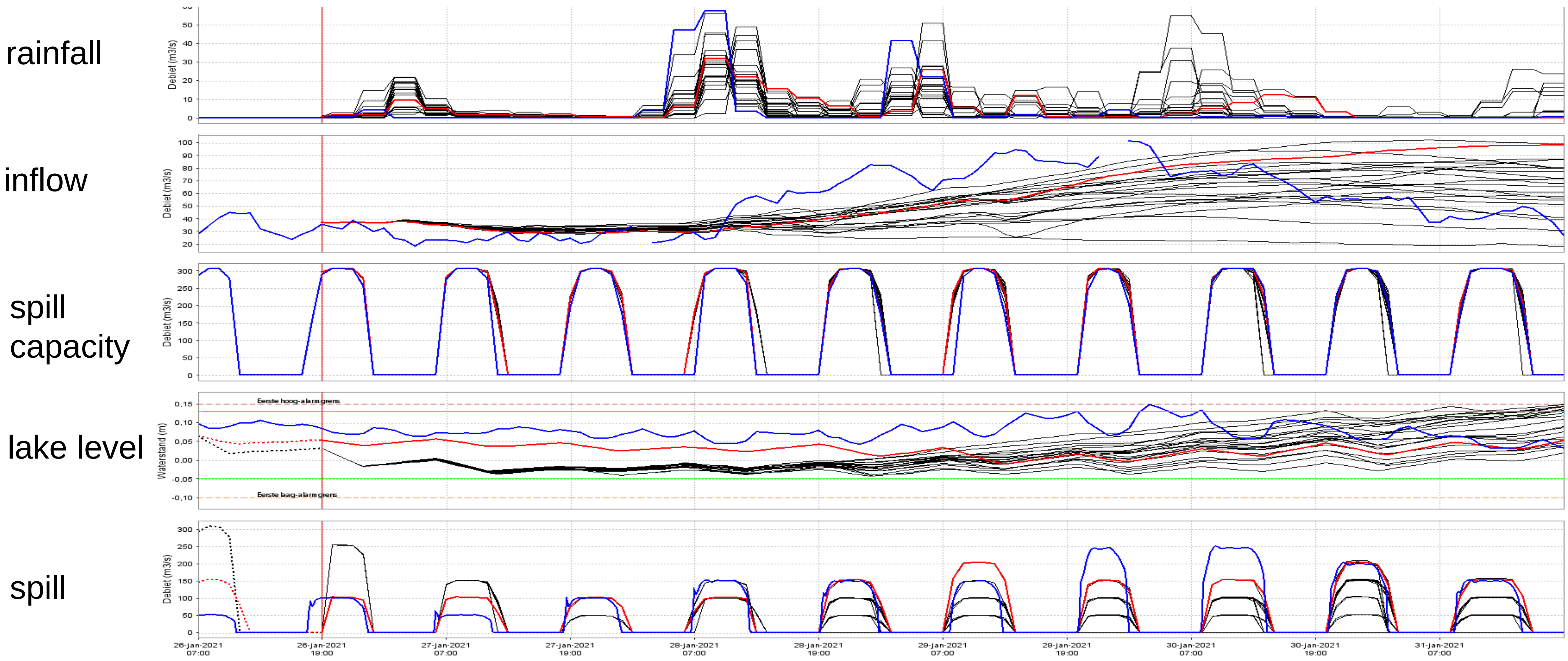
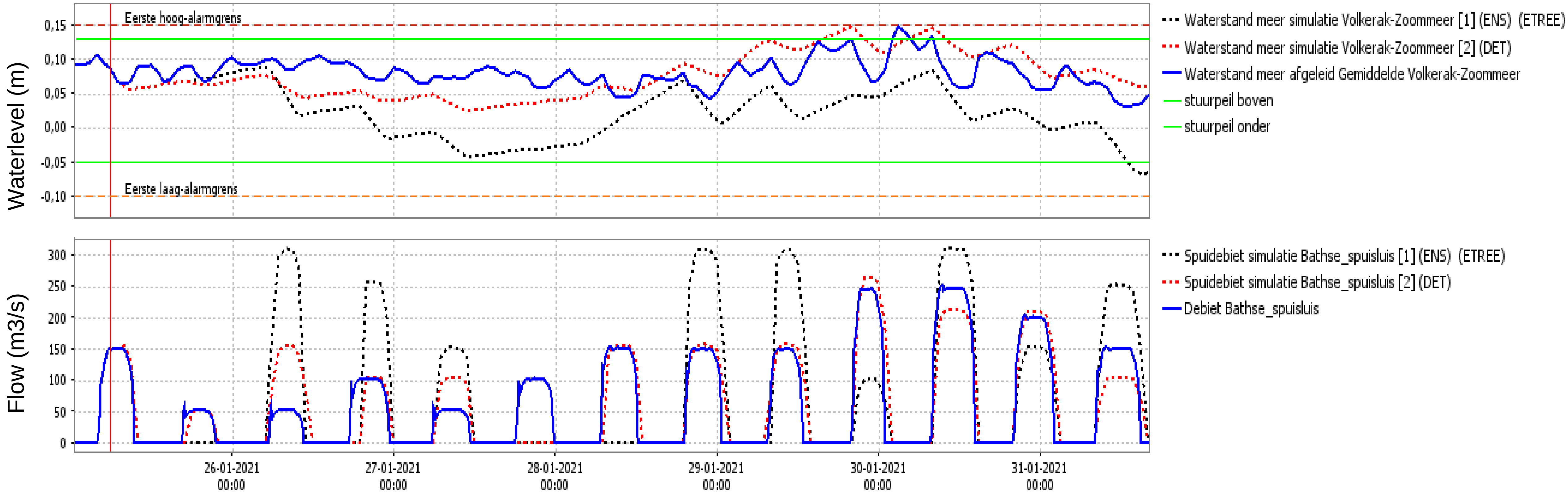
Example results
(control points at 12, 24 and 48h)

- advice (TB-MPC)
- advice (Det. MPC)
- simulation (TB-MPC)
- simulation (Det-MPC)
- Observations
- Target levels



Results of closed-loop analysis

- TB-MPC advice would have led to larger buffer capacity
- With lake level peak about 8cm below max. target
- Actual control and deterministic advice **both** led to lake levels around max target.



Some practical problems… that in theory don't exist

1. ECMWF-ENS surge forecast only has 20 members
2. No ARMA correction on inflow forecasts (yet?)
3. Visualization is complex, interaction desirable?
4. Aligning of ensemble T0 times is sometimes difficult
5. Relax integers at longer lead times to speed up enough for open source solver (CBC)
6. MILP and ensemble: multiple global optima

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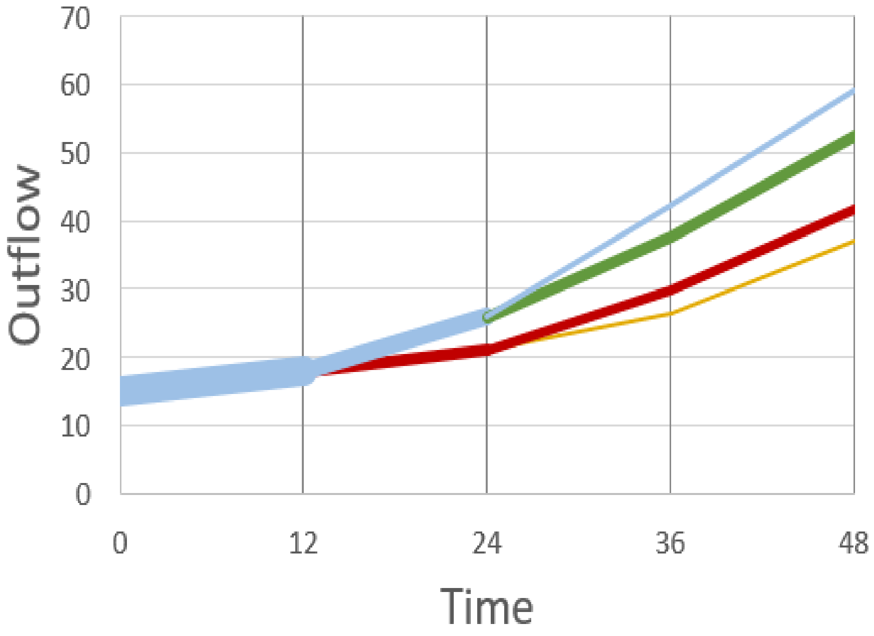
Next steps



1. Integrate the model into operational system

2. Improve visualization

3. Continuous evaluation (incl. closed-loop analyses)

4. Training and periodic evaluation with end-users
    1. Fine-tuning decision tree
    2. Fine tuning (extra) goals

5. Expand efforts to other regions and problems

Summary

1. **Ensemble forecasts are the future, (and so is MPC?)**

2. **Closed-loop analysis of 2021 event *illustrated* the value that was already demonstrated with the study with synthetic tests in 2019**
   → Saver flood control of Volkerak-Zoommeer

3. **Ready to use and test in operations**

4. **Bringing advice models to operational practice is not trivial**
   → technically, organizationally, acceptance

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