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Enabling Delta Life

Tree-Based Model Predictive Control for Optimizing Hydro Power under Uncertainty

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Outline

1. **Introduction**
2. Short-term forecasting and decision-making under uncertainty
3. Tree-Based Model Predictive Control (TB-MPC)
4. Use case: Short-term optimization of the Salto Grande Hydro Power Plant in Uruguay / Argentina (preliminary results)

Deltares

Stichting Deltares

- independent, non-profit institute for applied research and consultancy
- water, subsurface and infrastructure
- more than 800 people based in Delft and Utrecht in the Netherlands
- founded 2008 as a merger of Delft Hydraulics, GeoDelft, parts of TNO and governmental agencies.

Department of Operational Water Management (OWB)

- 35 researchers, software engineers and consultants
- design, development and implementation of state-of-the-art software products for operational water management
- open shell forecasting system Delft-FEWS
- many users worldwide including US-National Weather Service, UK-Environmental Agency and Bonneville Power Administration

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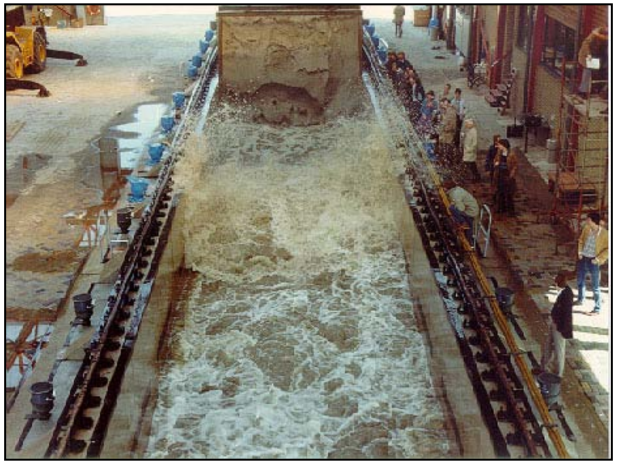
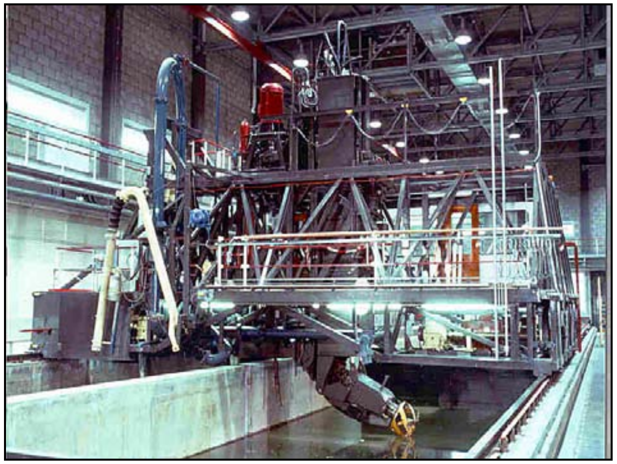
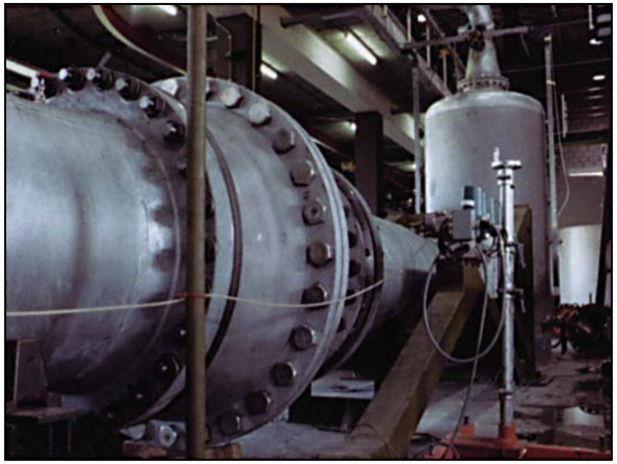
Test facilities





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Real-Time Control at Deltares

Motivation

Real-time control (RTC) has been an indispensable component for modeling man-made water systems in the Netherlands and elsewhere. Along with the rise of operational forecasting and management systems, new methodologies such as predictive control receive growing attention at Deltares.

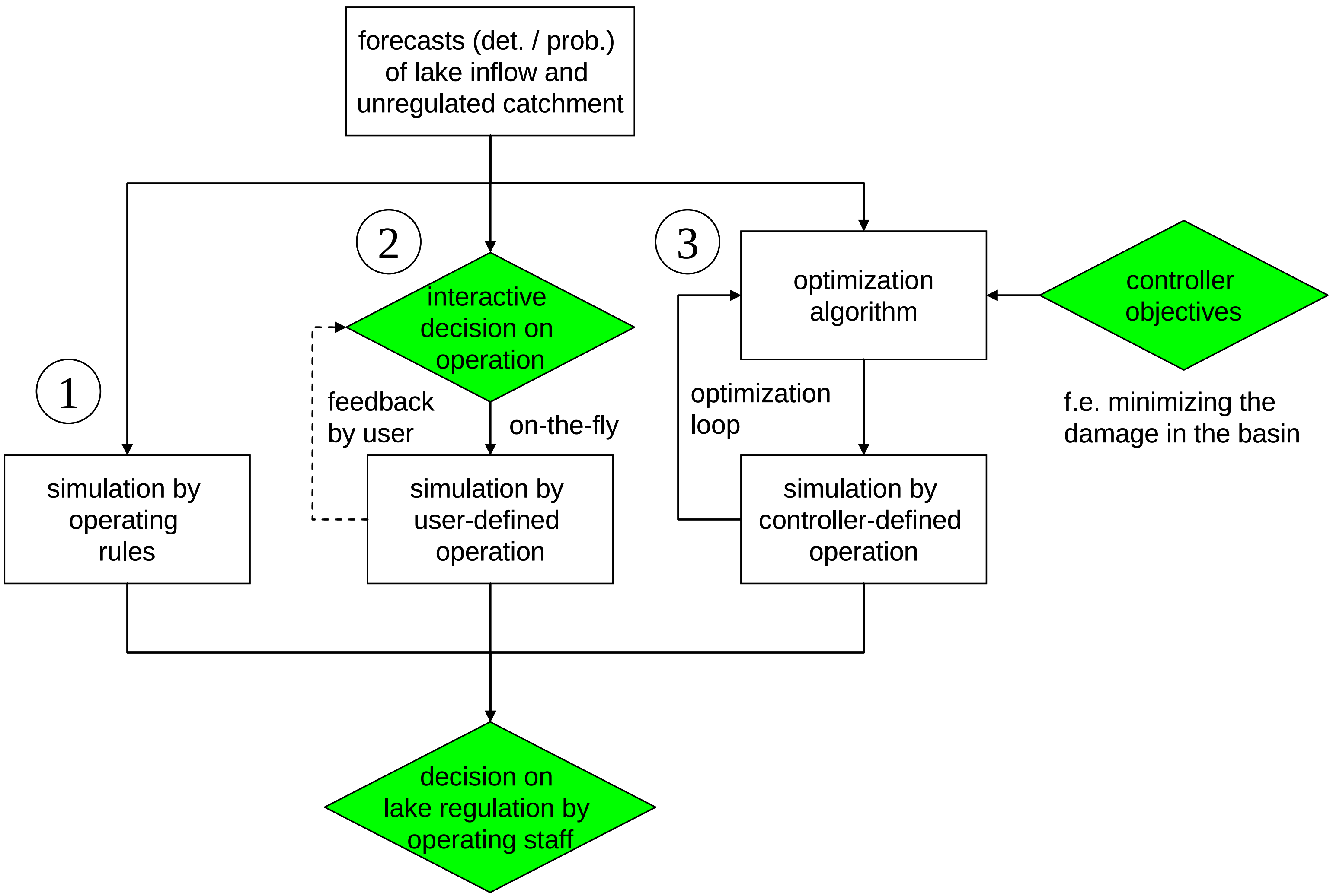
New platform RTC-Tools (since 2008):

- integration and consolidation of formerly distributed RTC components
- R&D expansion from feedback components to the field of model predictive control

Integration of forecasting systems for hydropower utilities:

- Delft-FEWS applied at hydropower utilities with a total installed capacity of 36 GW worldwide
- Services include the set-up and maintenance of forecasting platforms (including wind power forecasts, etc.), the provision of hydrological and hydraulic models, and tools for optimization and decision-support.

Options for real-time control and decision support in forecasting systems



Real-Time Control at Deltares
Who's behind?

About 6-7 people of the OWB department work mainly on RTC-related research and development as well as consultancy projects.

Our open source software approach results in a number of strategic partner for research and development in the field of real-time control:

- Fraunhofer IOSB-AST (http://www.iosb.fraunhofer.de), Ilmenau, Germany (simulation of energy networks, energy trading, forecasting of electrical load)
- Polymath Insight Ltd. (http://polymathinsight.co.uk/), UK (piloting on mathematical techniques)
- Research collaborations with UNESCO IHE (http://www.unesco-ihe.org/), Delft, NL / Delft University of Technology (http://home.tudelft.nl/en/), Delft, NL / National University of Singapore (http://www.nus.edu.sg/) / University of Minho, Portugal (http://www.uminho.pt/en/)

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Model Predictive Control
Sequential MPC (SeMPC)

Check also the details on SeMPC in the presentation “Adjoint Modeling Framework for Real-Time Control of Water Systems” of this conference.

Basis for our further outline is the following deterministic SeMPC optimization problem according to:

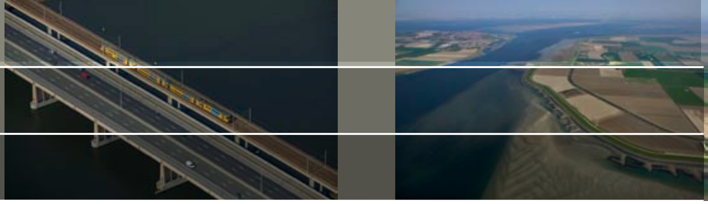
$$\min_{u} \sum_{k=1}^{T} J(\tilde{x}_k(u,d), u_k)$$

$$\text{subject to: } h(x_k, u_k) \le 0, \; k = 1, \cdots, T$$

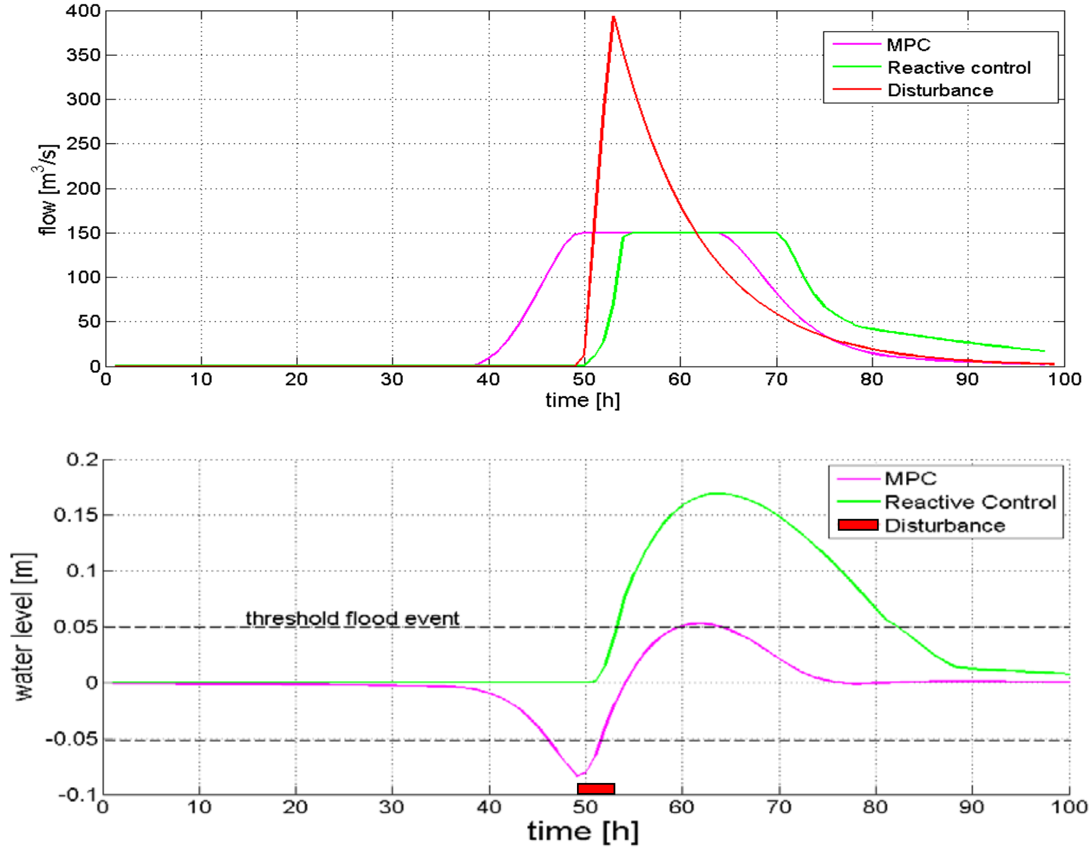
where $\tilde{x}_k(u,d)$ is a simulation result of the internal process model $x_k = f(x_k, x_{k-1}, u_k, d_k)$, u is a control input, d is a disturbance.

Model Predictive Control (2)

Sequential MPC (SeMPC)



Comparing reactive control and MPC for a disturbance event



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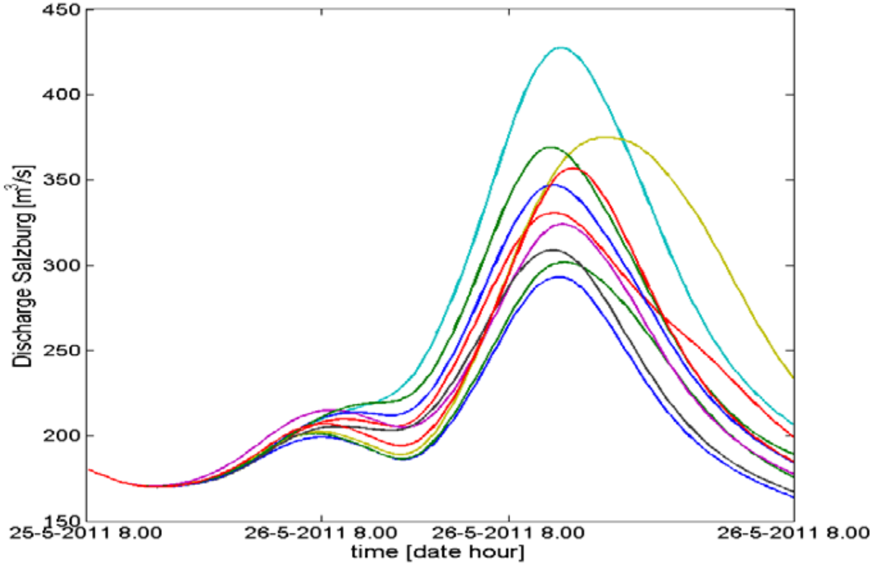
Ensemble forecasts and decision-making?

The use of meteorological / hydrological forecasts makes the water management pro-active (or anticipatory).

But:
Forecasts are uncertain.
What if the forecast is wrong?

Common practice:
Use of ensemble forecasts as a set of representative future trajectories

<u>Key question:</u>
<u>How to process this information in supervisory control and decision-making?</u>



Ensemble forecasts and decision-making?

Properties of short-term ensemble forecasts

- typical lead time of about 5-20 days
- aim at representative sample of the future states
- account for two main sources of uncertainty in weather models:
  - chaotic behavior of the weather system
  - imperfections of the model due to resolution, parameterization, etc.
- generated by small perturbations of initial conditions

Conclusions:

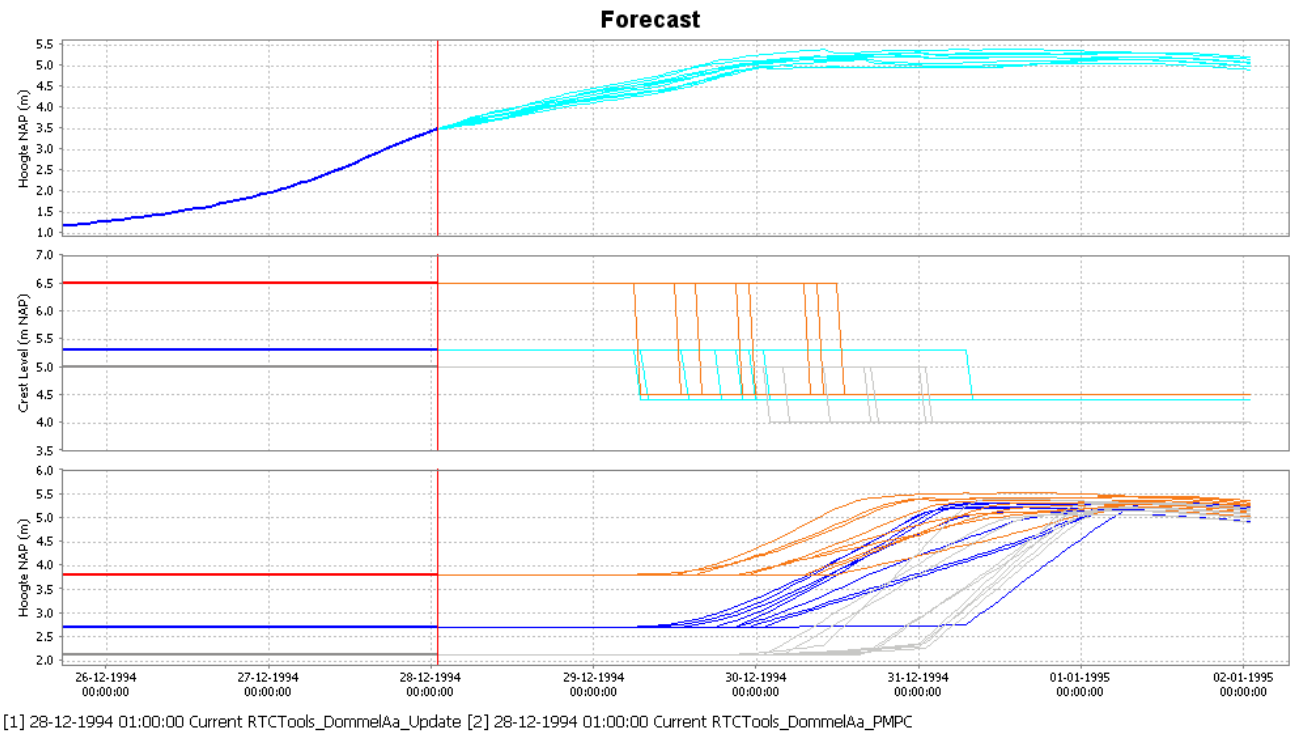
- Methods including probability density functions or other statistical assumptions are NOT suited for processing short-term ensembles !!!
- The problem set-up is different to the one in long-term water management, e.g. of reservoir systems, where variables such as the monthly climate conditions or inflows can be better represented by statistics.
- Members of the ensemble forecast are physically valid trajectories and should be used in the way they become available.

Model Predictive Control and Ensembles
Option 1: The dummy approach

Option 1:

Apply the deterministic MPC on every ensemble member to get a set of control trajectories

Example from DSS Dommel en Aa (water boards De Dommel & Aa en Maas, NL)



reference flood water level

weir level at flood detention inlets

filling level of flood detention basins

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Model Predictive Control and Ensembles

Option 1: The dummy approach (2)

Discussion:

- wrong problem set-up if predictive control is included, since the control in each ensemble assumes perfect deterministic knowledge of the system
- user gets an ensemble of control trajectories, there is no theory of what needs to be implemented in the future
- easy implementation from a technical point of view
- sufficient if the controlled system components have a minor impact on the overall result, but in this case MPC is maybe not required at all

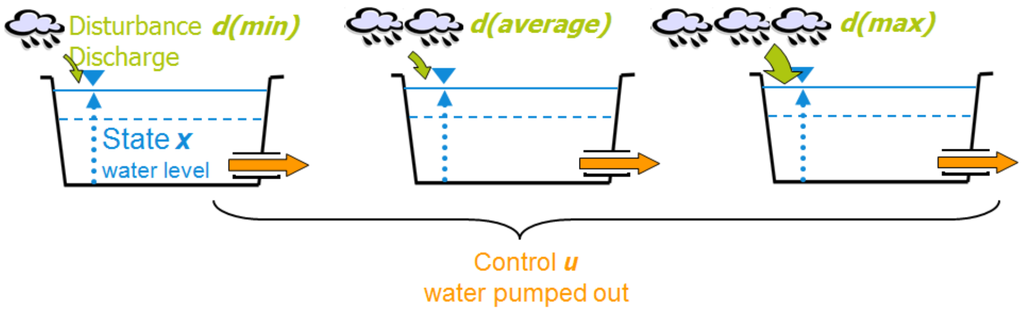
From deterministic to stochastic optimal control

Option 2:

Stochastic optimization techniques

Deterministic problem -> Find the control trajectory which is optimal for the deterministic forecast

Probabilistic problem -> Find the control trajectory which is optimal for the entire ensemble (on average, worst case, chance constrained, etc.)



Stochastic Optimal Control
Non-adaptive techniques

Stochastic Optimal Control:

$$\min_u \sum_{k=1}^{T} E\{J(\tilde{x}_k(u,d),u_k)\}$$

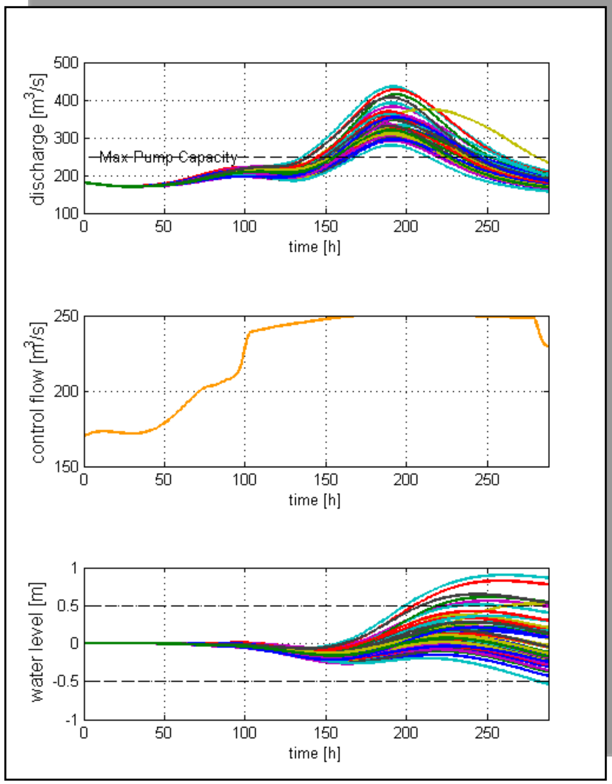
$$\text{subject to}: \ h(x_k,u_k) \le 0, \ k = 1,\cdots,T, \ x_k \forall d$$

Sample Average Approximation (SAA):

$$\min_u \sum_{j=1}^{N}\sum_{k=1}^{T} J(\tilde{x}_{j,k}(u,d_j),u_k)$$

$$\text{subject to}: \ h(x_{j,k},u_k) \le 0,$$

$$j = 1,\cdots,N, \ k = 1,\cdots,T$$



References:

- van Overloop, P. J., Weijs, S., and Dijkstra, S.: Multiple model predictive control on a drainage canal system, Control Engineering Practice, 16, 531-540, 2008
- Zavala, V. M., Constantinescu, E. M., Krause, T., and Anitescu, M.: On-line economic optimization of energy systems using weather forecast information, Journal of Process Control, 19, 1725-1736, 2009

Stochastic Optimal Control

Non-adaptive techniques (2)

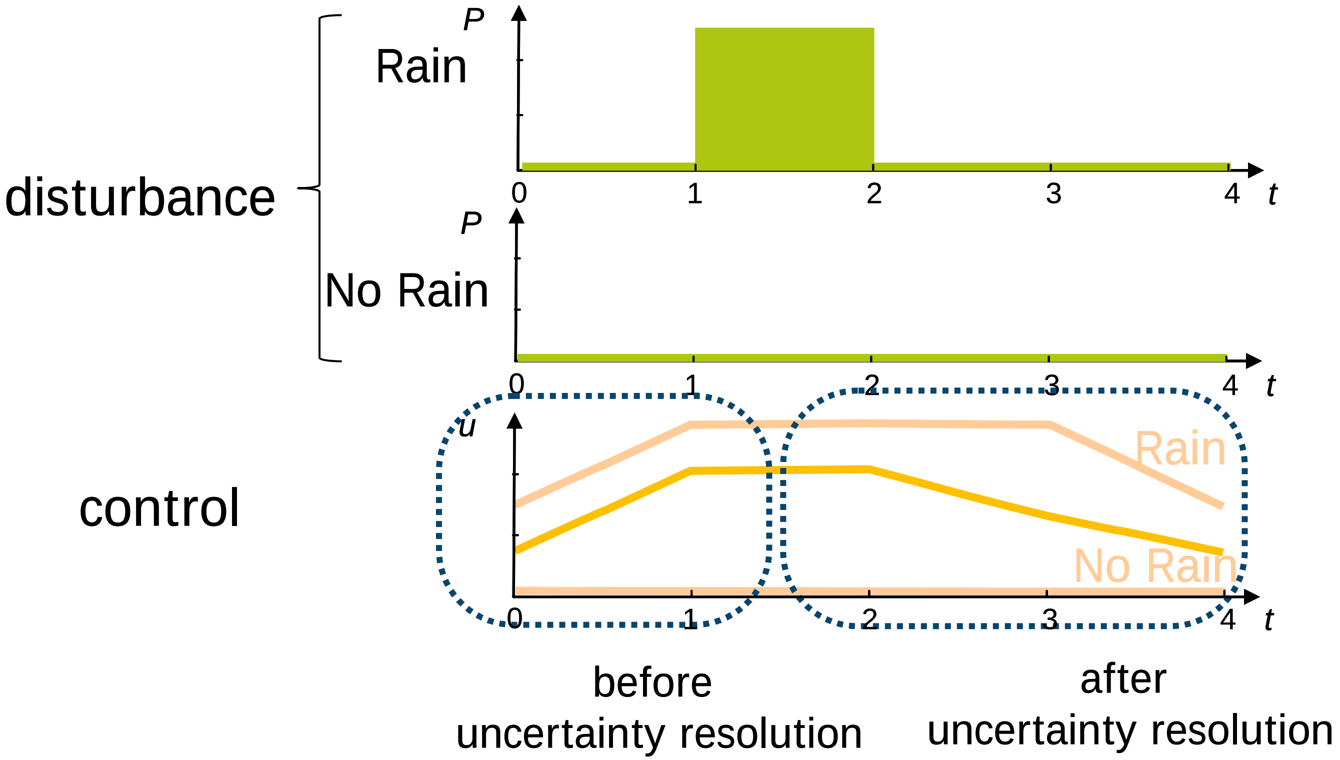
Conclusions:

- method is non-adaptive, control trajectory does not take into account that the uncertainty will get resolved in time along the forecast horizon
- if the operation of the water system is highly constrained, the solution of the optimization can get dominated by these constraints or becomes infeasible to solve (in case of hard constraints in particular)
- technical implementation in Sequential MPC:
  - number of dimensions of the optimization problem stays the same
  - number of executions of the process model is increasing with the number of ensemble members, but it can be parallelized easily
  - hard constraints on states result in a significant computational effort, i.e. nBranches x nTimeSteps for a single hard constraint
- suggested only for problems with small ensemble variations

Stochastic Multistage Optimal Control

Introduction by example

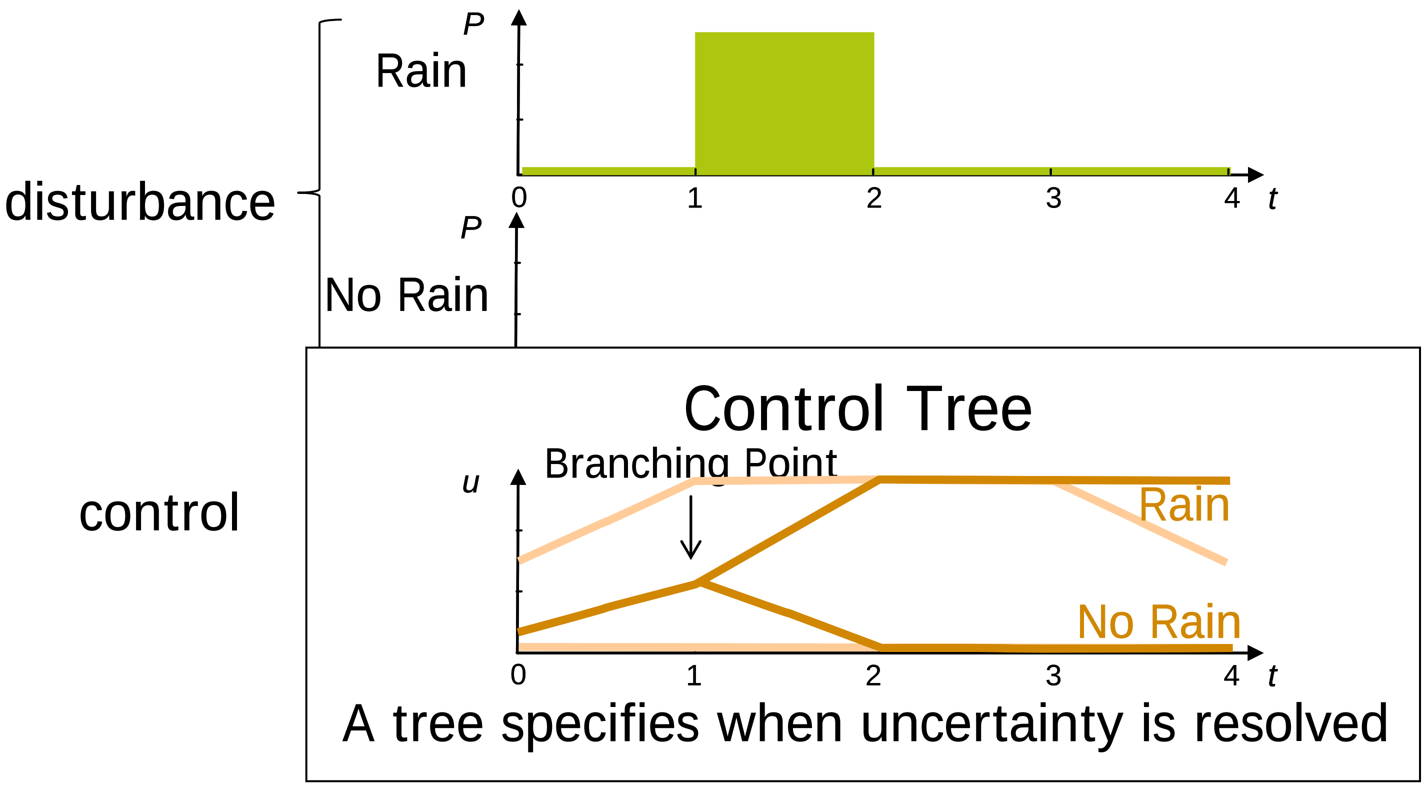
Decision   Uncertainty Resolution   Decision



Once uncertainty is resolved, it is possible to adopt the control strategy optimal to the remaining scenario !!!

Stochastic Multistage Optimal Control
Introduction by example (2)

Decision   Uncertainty Resolution   Decision



Once uncertainty is solved, it is possible to adopt the control strategy optimal to the remaining scenario !!!

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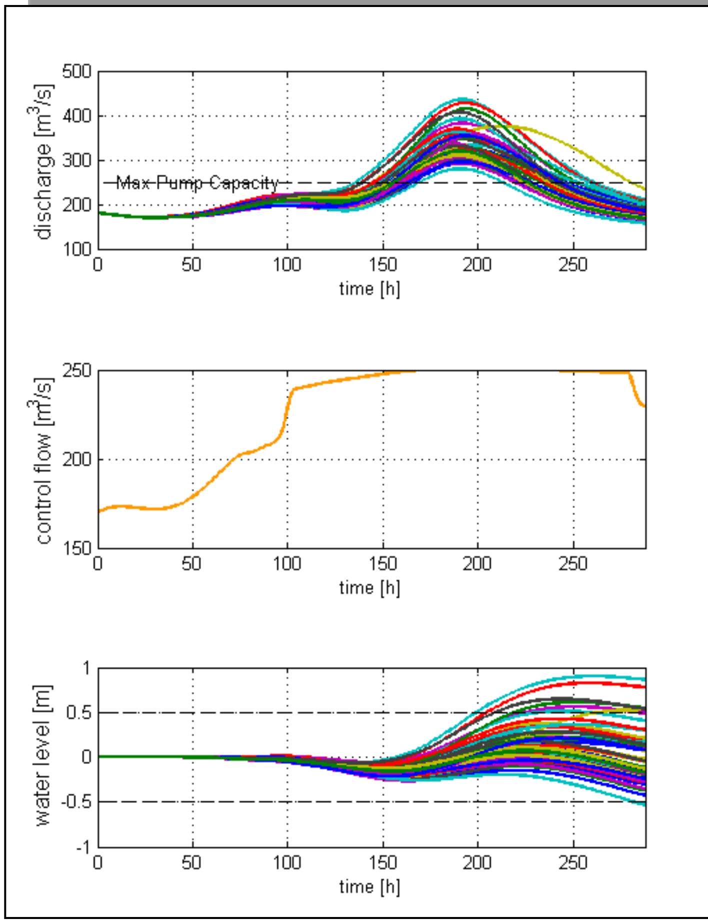
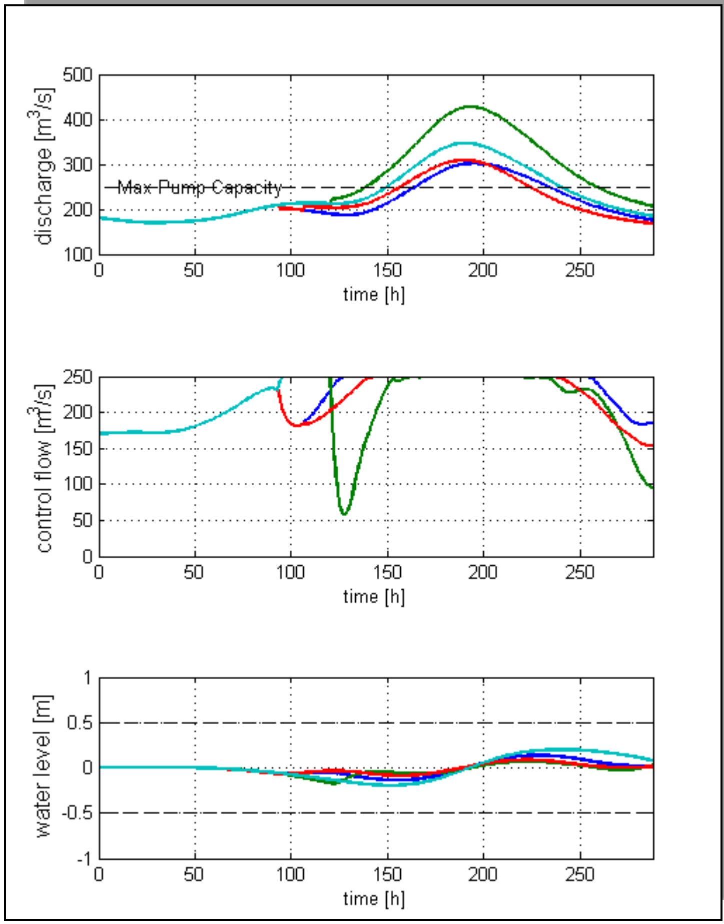
Comparison of adaptive and non-adaptive control



non-adaptive



adaptive

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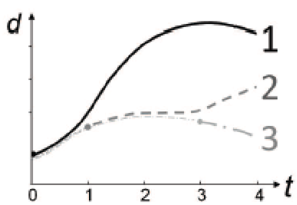
Tree-Based MPC
Mathematical background

The extension of the SAA approach by a scenario tree makes the control adaptive. We refer to it as Tree-Based MPC.

$$\min_{u} \sum_{j=1}^{N} \sum_{k=1}^{T} p_j J(\tilde{x}_{j,k}, u_{\mathbf{M}(j,k)})$$

$$\text{subject to: } h(x_{j,k}, u_{\mathbf{M}(j,k)}) \leq 0,$$

$$j = 1, \cdots, N, \;\; k = 1, \cdots, T, \;\; \mathbf{M} \in \mathbb{N}^{N} \times \mathbb{N}^{T}$$



$$\mathrm{M} = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ 1 & 2 & 6 & 7 & 8 \\ 1 & 2 & 6 & 7 & 9 \end{bmatrix}$$

The TB-MPC covers also the deterministic case as well as the classical SAA formulation.

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Tree-Based MPC
Scenario tree generation

The key issue of Tree-Based MPC is the proper definition of the scenario tree, see the upcoming paper of Raso et al. (“Tree Topology Generation from Ensemble Forecasts for Real Time Control”, submitted to Journal of Hydrological Processes).

Other references:

- Heitsch, H. and Römisch, W.: Scenario tree reduction for multistage stochastic programs, Computational Management Science, 6, 117-133, 2009
- Latorre, J., Cerisola, S., and Ramos, A.: Clustering algorithms for scenario tree generation: Application to natural hydro inflows, European Journal of Operational Research, 181, 1339-1353, 2007
- Sutiene, K., Makackas, D., and Pranevicius, H.: Multistage K-means clustering for scenario tree construction, Informatica, 21, 123-138, 2010

Tree-Based MPC
Technical details of the implementation in RTC-Tools

Background on the technical implementation of Tree-Based MPC in RTC-Tools in combination with the Sequential MPC mode:

- Process model execution in simulation mode and adjoint mode can be parallelized easily -> no significant higher execution time on suited multi-core CPUs if nCores > nBranches
- The dimensions of the optimization problem are increasing by about 60-80% times the number of branches, thus, a tree with 10 final branches results in a factor between 6-8 -> requires efficient optimizers

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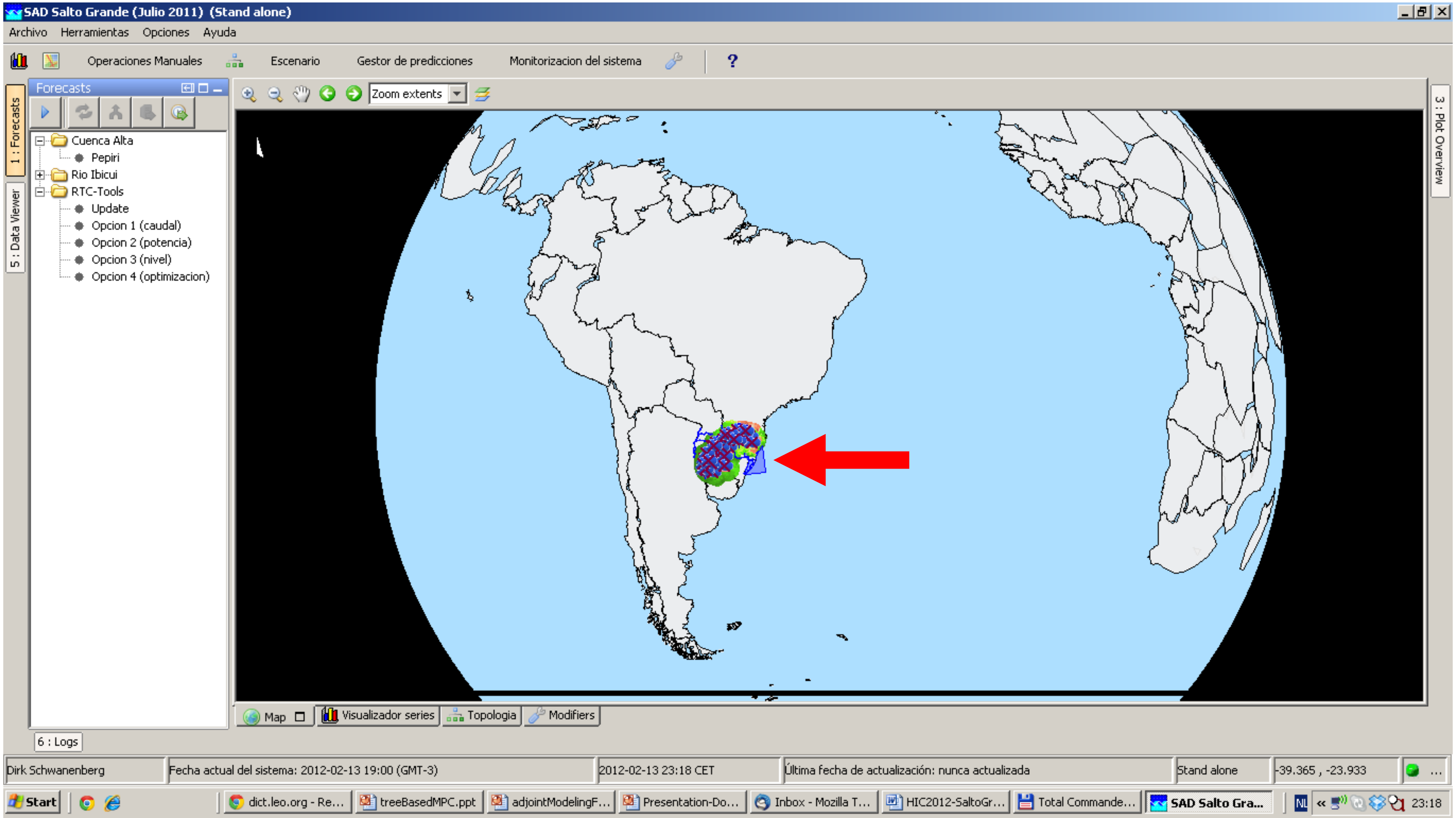
Salto-Grande Hydro Plant in Uruguay / Argentina

Where?



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Salto-Grande Hydro Plant in Uruguay / Argentina

Introduction to the hydro power plant

- dam and hydro power plant on the Uruguay River
- owned by the governments of Uruguay and Argentina
- associated reservoir extends for 783 km^2
- storage volume is about 5000 hm^3
- watershed area is approximately 224,000 km^2 and covers parts of Argentina, Brazil and Uruguay
- average flow is about 4620 m^3/s between the extremes of 109 m^3/s and 37,714 m^3/s
- hybrid between run-of-river and storage hydro power plant
- installed capacity is 1890 MW

Salto-Grande Hydro Plant in Uruguay / Argentina

Need for forecasts

- The main objectives load balancing, maximization of hydro power production and flood mitigation require a proper tactical reservoir management
- A team of hydrologists issues a daily deterministic forecast of a lead time of 14 days ahead
- Ongoing work of Deltares focuses on the set-up of a
  - state-of-the-art forecasting platform,
  - support on setting-up new hydrological models,
  - ensemble forecasting and
  - a decision-making component for the hydro power plant

Salto-Grande Hydro Plant in Uruguay / Argentina
Lead time requirements

- assessment of the required lead time of a forecast based on a closed-loop experiment
- assumption of a perfect inflow forecast in combination with deterministic MPC
- simulation period September 2008 – August 2010
- relevant performance indicators are
  - energy production
  - spillage / maximum total release

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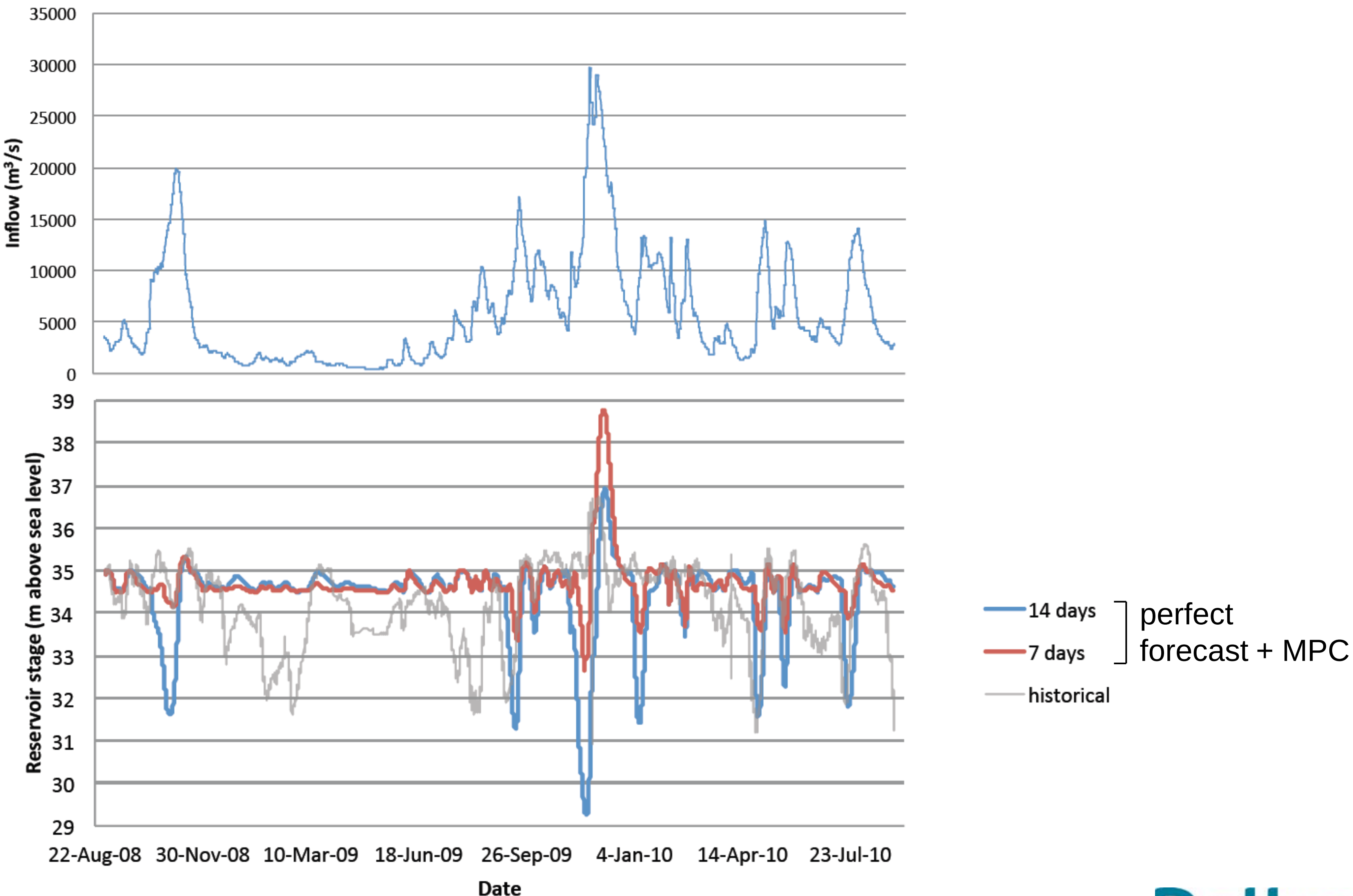
Salto-Grande Hydro Plant in Uruguay / Argentina

Lead time requirements (2)



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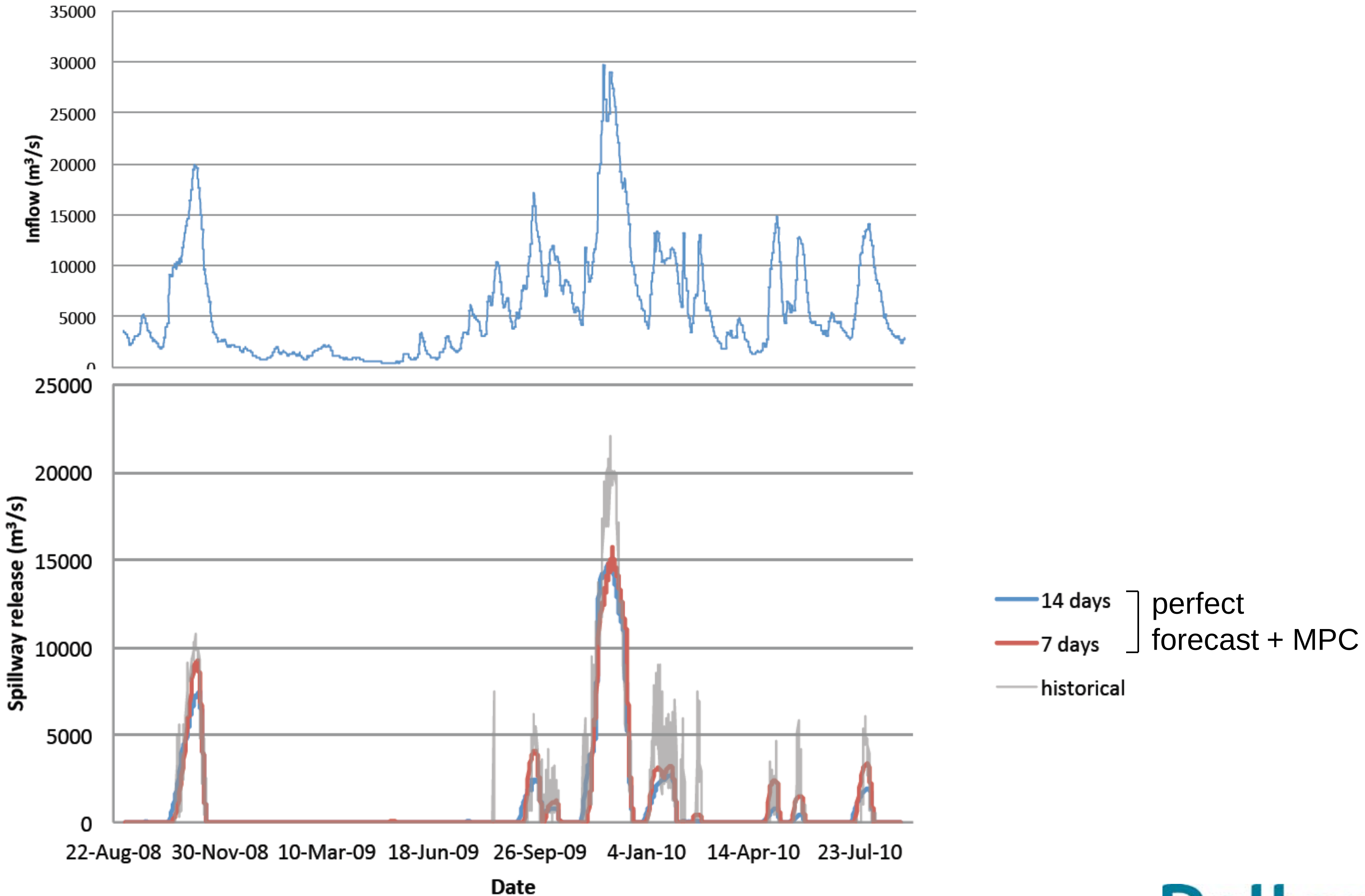
Salto-Grande Hydro Plant in Uruguay / Argentina
Lead time requirements (3)



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Salto-Grande Hydro Plant in Uruguay / Argentina

Lead time requirements and available ensemble forecasts

- lead time requirement of 14 days (confirmation of current practice)
- maximum added value of a perfect inflow forecast of 14 days in combination with predictive control in the period of 2 years is about 800 GWh extra energy and a maximum total release reduction of about 5000 m^3/s
- available ensemble forecasts of CPTEC (Brazilian met office) and GEFS (NOAA, US) are available for the required lead time
- wave propagation time from upstream to downstream catchment is more than one week in average, i.e. for different hydrological conditions

Salto-Grande Hydro Plant in Uruguay / Argentina
Ongoing implementation of the Tree-Based MPC

- Deterministic MPC and Tree-Based MPC (including the scenario tree reduction) have been set-up and embedded into the test bed
- ongoing work focuses on the integration of historical ensemble forecasts (CPTEC, GEFS, ECMWF) into the test database
- semi-lumped hydrological forecasting model will be finalized till April 2012
- bias correction of the ensemble forecasts will be conducted in April 2012
- final results will be presented on Hydroinformatics Conference 2012, 14-18 July, Hamburg, Germany by Raso et al.


Conclusions

- Short-term control of water systems, e.g. reservoirs and hydro power systems, require dedicated techniques for processing uncertainty information from ensemble forecasts
- The control needs to be adaptive, in particular if the variation of the ensemble members is large and the optimization problem is highly constrained
- Tree-Based MPC is a promising candidate for short-term adaptive control, an implementation is available in the open source RTC-Tools package
- The set-up of a proper scenario tree reduction is a crucial aspect of the TB-MPC application and topic of ongoing research

Further Information and Contacts

Operational warning and management systems at Deltares:
http://www.deltares.nl/en/expertise/101137/operational-warning-and-management-systems

RTC-Tools:
website (under construction): http://oss.deltares.nl/web/rtc-tools/
Email: rtc-tools@deltares.nl
LinkedIn group: http://www.linkedin.com/groups/RTCTools-4239308

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