Adjoint Modeling Framework for Real-Time Control of Water Systems

Reservoir System Modeling Technologies Conference

February 21-22, 2012 Portland, Oregon

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Outline

1. **<u>Introduction</u>**
2. Model Predictive Control (MPC)
3. Adjoint Modeling
4. Open Source Software at Deltares
5. Use Cases
    a) Upper Rhine along the German-French border
    b) Pump management in the polder Noorderzijlvest, NL
    c) National Hydrological Instrument (NHI) for operational water allocation in the Netherlands during draughts

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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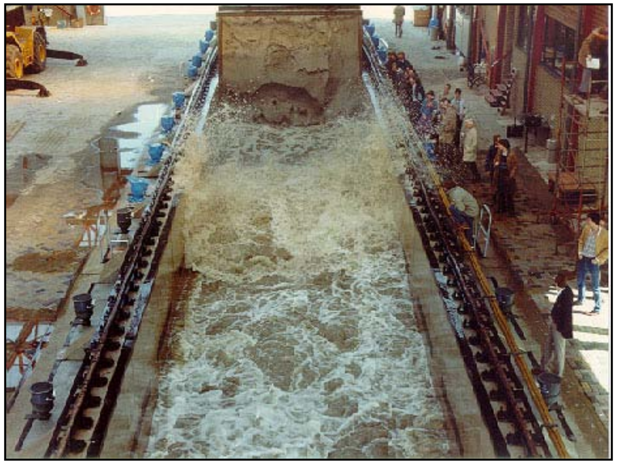
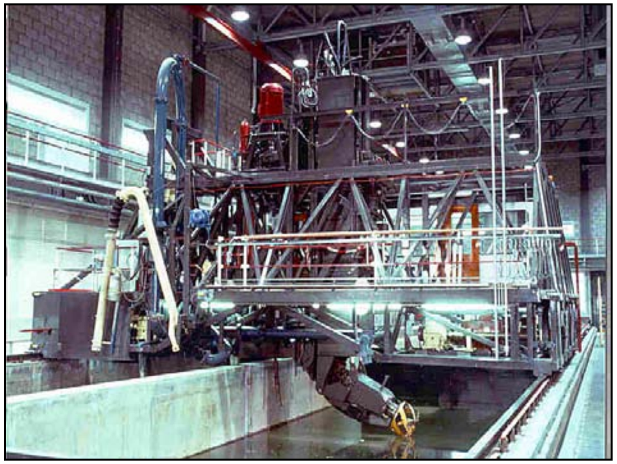
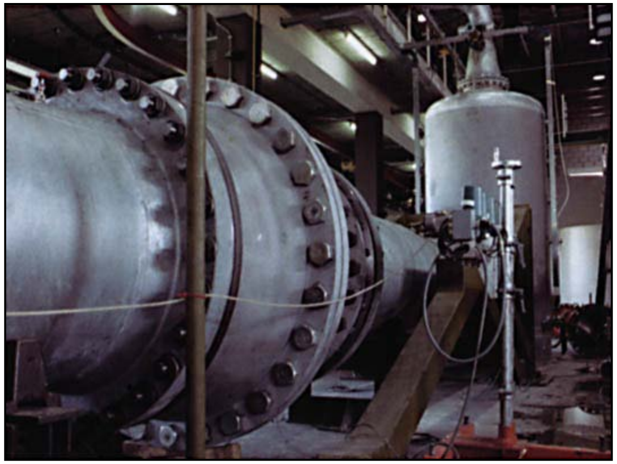
Test facilities









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.

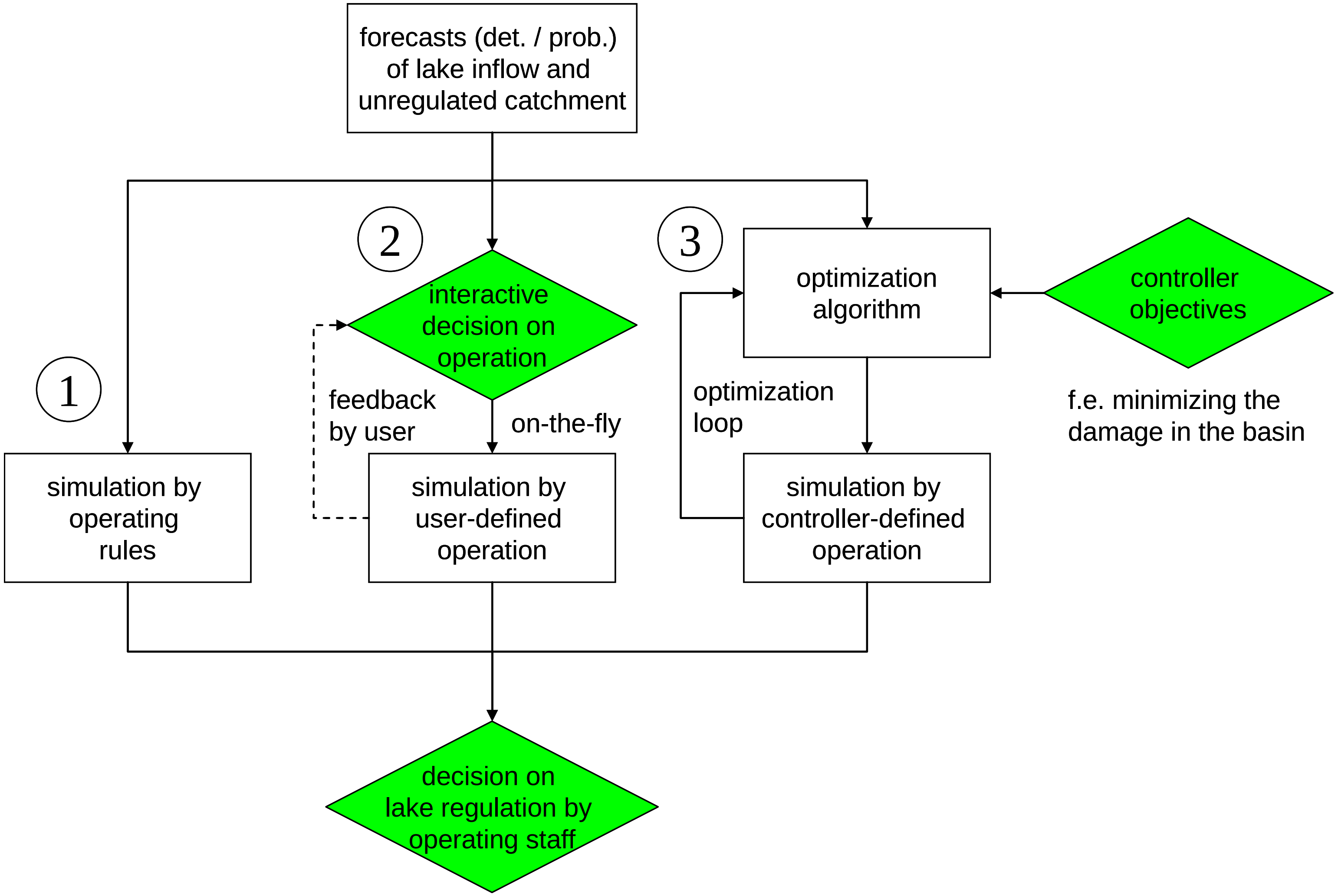
New platform RTC-Tools (since 2008):

- 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



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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

Model Predictive Control (MPC) aims at finding optimal control trajectories for actuators such as hydraulic structures. It combines the prediction of future systems states x over a forecast horizon by an internal model with optimization algorithms for finding the optimal control trajectory u under the disturbance d.

Internal process model: $x_k = f(x_k, x_{k-1}, u_k, d_k)$

Simultaneous MPC:

$$\min_{x,u} \sum_{k=1}^{n} J\left(x_k, u_k\right)$$

$$\text{subject to: } g\left(x_k, u_k\right) = 0,\ k = 1, \cdots, n$$

$$h(x_k, u_k) \leq 0,\ k = 1, \cdots, n$$

equality constraint

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Model Predictive Control

Simultaneous MPC (SiMPC)

Some characteristics:

- Standard procedure used in most publications
- The optimization problem and the process simulation are solved simultaneously by the optimizer
- No additional integration scheme is required for the process model, however, it can not executed in simulation mode only, e.g. for interactive forecasting
- The dimension of the optimization problem is equal to (nControl + nStates) * nTimeSteps. This results in large optimization problem, in particular if a system representation requires many states.
- The definition of hard constraints is straightforward.
- Intermediate model trajectories within the optimization or not always on a valid state trajectory, thus, physics are violated in this case

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Model Predictive Control

Sequential MPC (SeMPC)

In the sequential approach, the process model is solved in every iteration step of the optimizer by an appropriate simulation scheme. Thus, optimization and simulation are more decoupled. The optimization problem reads:

Sequential MPC:

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

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

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


Model Predictive Control

Sequential MPC (SeMPC) (2)

Some characteristics:

- The optimization problem and the process simulation are solved sequentially
- A separate integration scheme is required for the process model. It can be used also for conducting simulations and forecasts
- The dimension of the optimization problem is equal to nControl * nTimeSteps compared to (nControl + nStates) * nTimeSteps for the SiMPC. However, the optimization problem gets “more nonlinear” according to some authors.
- Control and simulation time steps can be easily decoupled, e.g. for fading from a control step of 1h at forecast time to 6h at the end of the forecast horizon in combination with a simulation step of 15min
- All intermediate results of the optimizer are on a valid state trajectory
- Hard constraints on states are more difficult to implement

Model Predictive Control

Simultaneous versus Sequential MPC

Xu & Schwanenberg (HIC2012, Hamburg, Germany, 14-18 July) present a performance comparison of SiMPC and SeMPC in application to a generic reservoir system. SeMPC beats SiMPC by a factor of 3-5 in computational efficiency. Furthermore, it shows better scaling.

A key ingredient of SeMPC is the efficient computation of the gradient

$$\mathrm{d}J(\tilde{x}_k(u,d),u_k)\,/\,\mathrm{d}u_k$$

enabling the use of state-of-the-art Nonlinear Programming such as the open sourve optimizer IPOPT (Wächter & Biegler, Mathematical Programming 106(1), 2006), or commercial solvers such as SNOPT, etc.

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Algorithmic Differentiation (AD) in reverse mode

Let's assume a process model and an objective function according to

$$x_k = f(x_{k-1}, u_k, d_k), \; J(\tilde{x}_k(u,d), u_k)$$

The total derivative $\mathrm{d}J(\tilde{x}_k(u,d),u_k)/\mathrm{d}u_k$ can be computed by initializing the adjoint states $\hat{x}_k, \hat{u}_k$ with the partial derivatives of the objective function and applying the chain rule to every step of the process model in reverse order:

1)

$$\hat{x}_k = \partial J(\tilde{x}_k(u,d),u_k)/\partial x_k$$
$$\hat{u}_k = \partial J(\tilde{x}_k(u,d),u_k)/\partial u_k$$

2)

$$\hat{x}_{k-1} += \hat{x}_k \partial f(x_{k-1},u_k,d_k)/\partial x_{k-1}$$
$$\hat{u}_k += \hat{x}_k \partial f(x_{k-1},u_k,d_k)/\partial u_k$$
$$\hat{d}_k += \hat{x}_k \partial f(x_{k-1},u_k,d_k)/\partial d_k$$

Handling models with implicit time stepping

Let's assume a model with an implicit time stepping according to

$$x_k = f(\underline{x_{k-1}}, x_k, u_k, d_k)$$

Since the simulation is iterative in every time step, tracing back the iterations in AD reverse mode is disadvantageous both from a conceptual and technical point of view. As an alternative, we use a Langrangian form L and exploit the fact that the adjoint states are equal to the Lagrangian multipliers.

$$L = J(\tilde{x}_k(u,d), u_k) + \hat{x}_k[x_k - f(x_{k-1}, x_k, u_k, d_k)]$$

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Handling models with implicit time stepping
Example: Implicit pool routing model

Assume the following implicit pool routing model:

$$s_k = s_{k-1} + \Delta t[d_k - u_k - f(s_k)]$$

After setting-up the Langrangian form

$$L = J(\tilde{s}_k(d,u),u_k) + \hat{s}_k[s_k - s_{k-1} + \Delta t(d_k - u_k - f(s_k))]$$

and applying a variational analysis, we receive the adjoint model

$$\hat{s}_k = \frac{\hat{s}_{k+1} - \partial J / \partial s_k}{1 + f'(s_k)} \qquad \frac{\mathrm{d}J}{\mathrm{d}u_k} = \frac{\partial J}{\partial u_k} + \Delta t\, \hat{s}_k$$

Adjoint modeling framework
for blockwise combination of model in simulation and adjoint mode

The main idea behind the adjoint modeling framework
is the provision of an architecture for block-wise integration of
simulation models and their related adjoint models.

$$x_k = f(x_{k-1}, u_k, d_k)$$
$$\hat{x}_{k-1} += \hat{x}_k \partial f(x_{k-1}, u_k, d_k) / \partial x_{k-1}$$
$$\hat{d}_k += \hat{x}_k \partial f(x_{k-1}, u_k, d_k) / \partial d_k$$

$$x_k = f(x_{k-1}, u_k, d_k)$$
$$\hat{x}_{k-1} += \hat{x}_k \partial f(x_{k-1}, u_k, d_k) / \partial x_{k-1}$$
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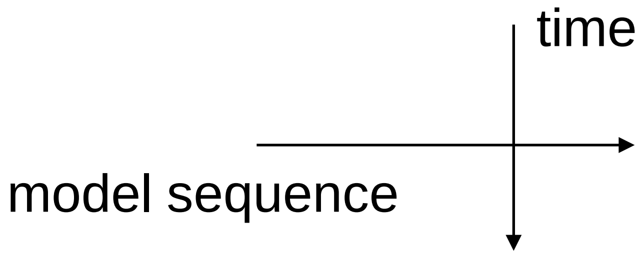
$$\hat{x}_{k-1} += \hat{x}_k \partial f(x_{k-1}, u_k, d_k) / \partial x_{k-1}$$
$$\hat{d}_k += \hat{x}_k \partial f(x_{k-1}, u_k, d_k) / \partial d_k$$



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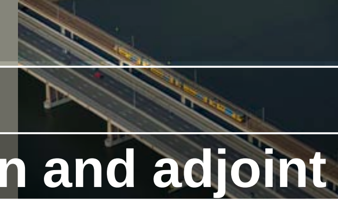



Models in RTC-Tools

Implementation of functions for simulation and adjoint mode

arma.cpp | kwNode.h | kwNode.cpp | kwNetwork.cpp | schematisation.cpp

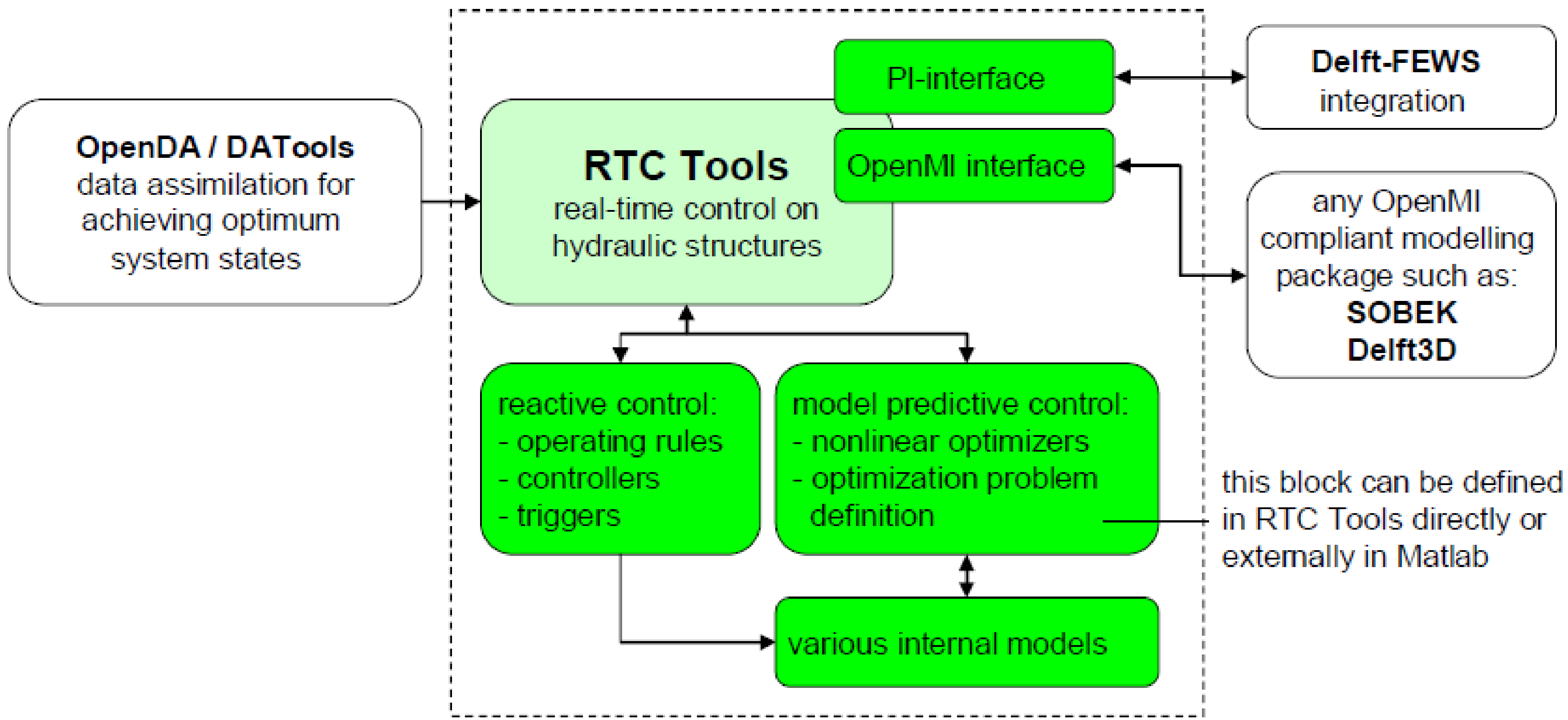
(Global Scope)

```
arma::~arma()
{
}

void arma::solve(double *stateOld, double *stateNew, long long t, double dt)
{
    if (stateNew[iObsIn]==stateNew[iObsIn]) {
        stateNew[iArmaOut] = stateNew[iObsIn];
    } else {
        stateNew[iArmaOut] = stateNew[iSimIn] + arCoef*(stateOld[iArmaOut]-stateOld[iSimIn]);
    }
}

void arma::solveDer(double *stateOld, double *stateNew, long long t, double dt, double *dStateOld, double *dStateNew)
{
    if (stateNew[iObsIn]==stateNew[iObsIn]) {
        dStateNew[iObsIn] += dStateNew[iArmaOut];
    } else {
        dStateNew[iSimIn] += dStateNew[iArmaOut];
        dStateOld[iSimIn] += -arCoef*dStateNew[iArmaOut];
        dStateOld[iArmaOut] += arCoef*dStateNew[iArmaOut];
    }
}
```

Deltares

- Modular architecture for modeling and control in ANSI C++ (Windows, LINUX, UNIX) for hosting feedback / predictive controllers and related process models, e.g. pool routing, kinematic / diffusive wave, neural network, simple lumped hydrological models, etc.
- Open Source under GNU General Public License, version 2 (GPL2)
- General features for time series management (including ensembles), interfacing (Delft-FEWS, Matlab, OpenDA, OpenMI), XML configuration
- Seamless integration into Delft-FEWS as front end with full support of Interactive Forecasting Display (IFD), Mimic Display, General Adapter, etc.
- Nonlinear Model Predictive Control with embedded open source optimizer IPOPT or (commercial) Matlab toolboxes such as TOMLAB (CONOPT, SNOPT, MINOS, etc.)
- Website is under construction: https://oss.deltares.nl/web/rtc-tools/
  official release is scheduled for Q1-2012

RTC-Tools
Functional architecture



RTC-Tools APIs – Implementing Extensions

Models, Objective Functions, Constraints

Models:

Easy extension of the model library by implementing derived classes from a base class. The user needs to supply a time integrator, an adjoint integrator (for SeMPC mode only) and a Jacobian (for SiMPC mode and implicit time integrators). The framework enables the combination of arbitrary models in simulation or optimization.

Objective Functions:

Additional types of objective function terms can be added by supplying the value of the term and its partial derivatives.

Constraints:

So far only block constraints on control input as hard constraints.
Functionality will be significantly extended in early 2012. Options for soft constraints are various.

RTC-Tools, R&D in progress

Ongoing in 2012

Short-term research and development issues:

- Simultaneous MPC option, pilot available for simple reservoir system (Xu & Schwanenberg, HIC2012, Hamburg, Germany, 14-18 July), final version in RTC-Tools expected in the first half of 2012
- General definition of hard constraints for all variables, first half of 2012
- Implementation of derivative-free optimizer for model calibration, P-MPC mode (online optimization of model parameters such as set points), TIO-MPC mode (optimization of time instances for switching components on/off) in the course of 2012
- Performance improvements: multi-core BLAS library for IPOPT, sparse linear equation solver for IPOPT and implicit time integrators, better line search for implicit reservoir model, 64bit version

Using RTC-Tools

Many levels of cooperation depending on your interest and your resources:

1) Download and use the code on your own
2) Outsource all services related to model set-up and optimization set-up to Deltares or partners
3) Cooperate with us on R&D issues.

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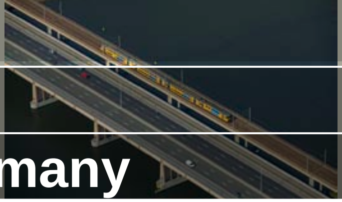
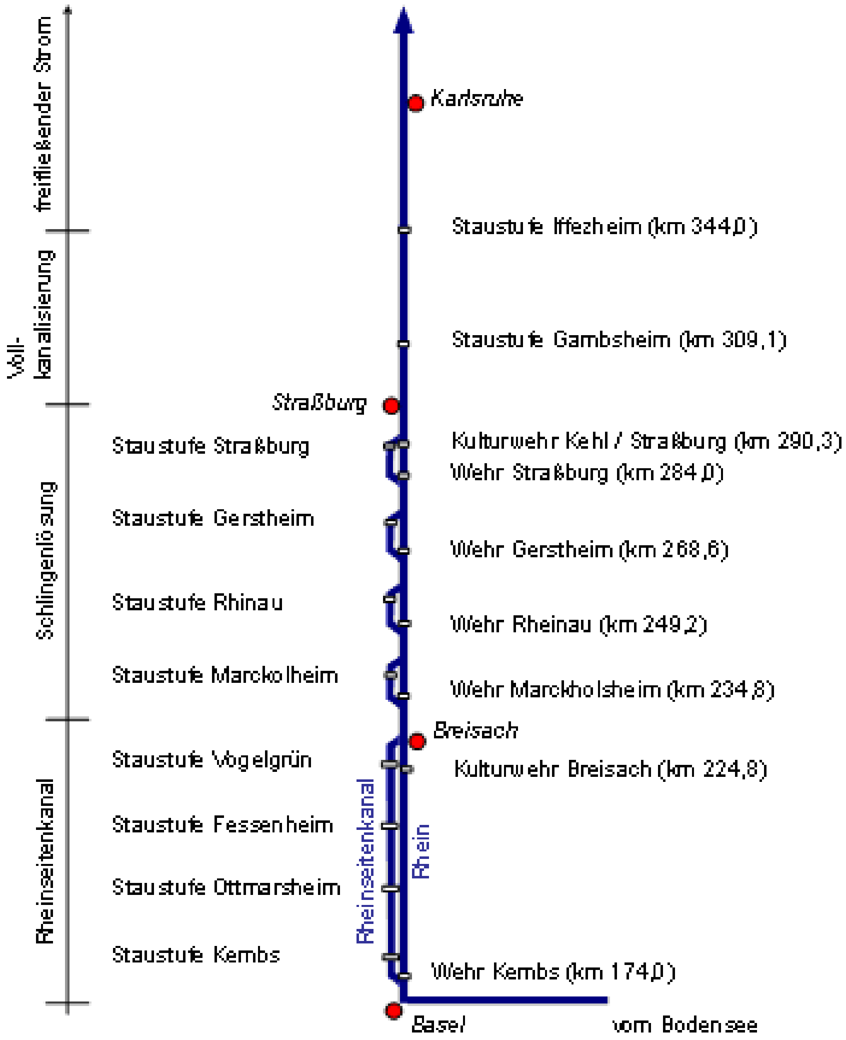
Use case: Upper Rhine model

Client: Federal Institute of Hydrology, Germany





Characteristics:
Complex multi-purpose river reach with 10 large hydropower plants, many weirs and controlled flood detention polders

Control strategy:
Existing feedback control strategy relies on more than 400 triggers and 150 operating rules and controllers

Scope of the project (till summer 2011):
Set-up of hydraulic model in SOBEK and control strategy in RTC-Tools, model coupling via OpenMI

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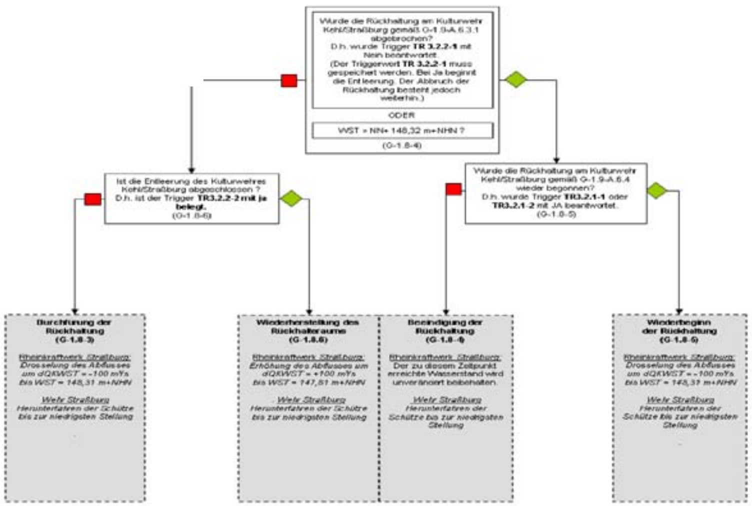
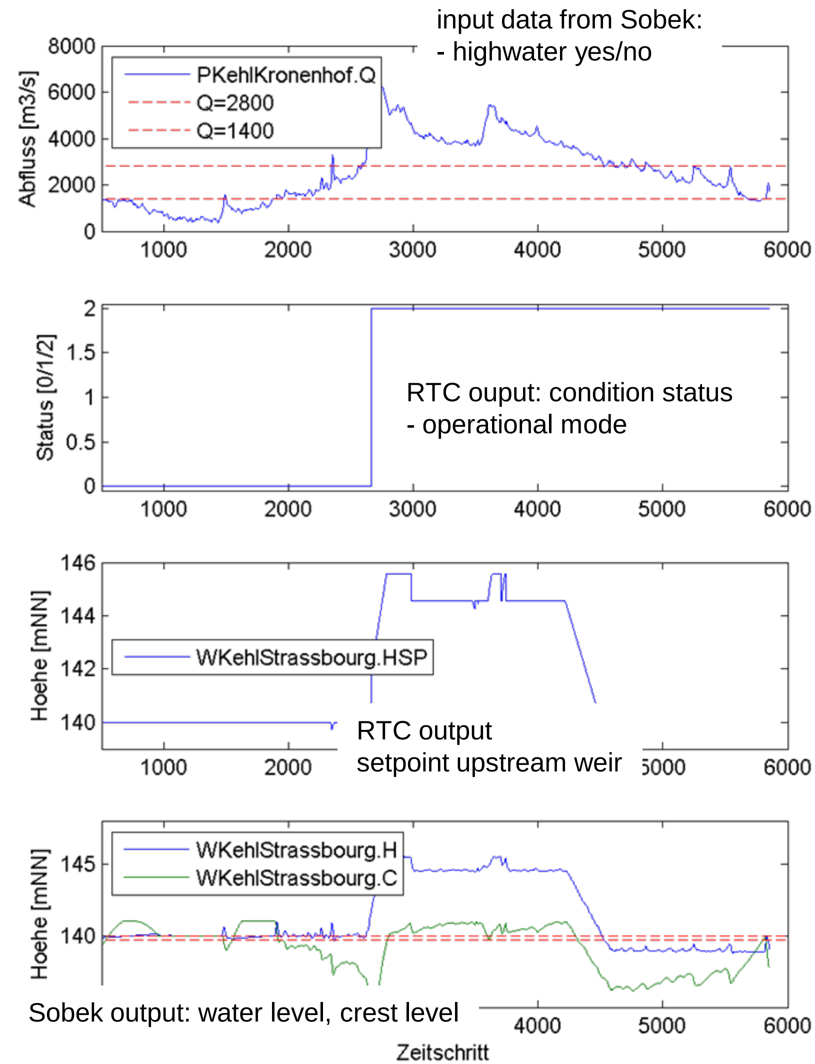
Use case: Upper Rhine model (2)
Client: Federal Institute of Hydrology, Germany

Highlight:
Schematization of hierarchical triggers in binary decision trees





-> Becker et al. (2012), HIC2012, Hamburg, Germany, 14-18 July

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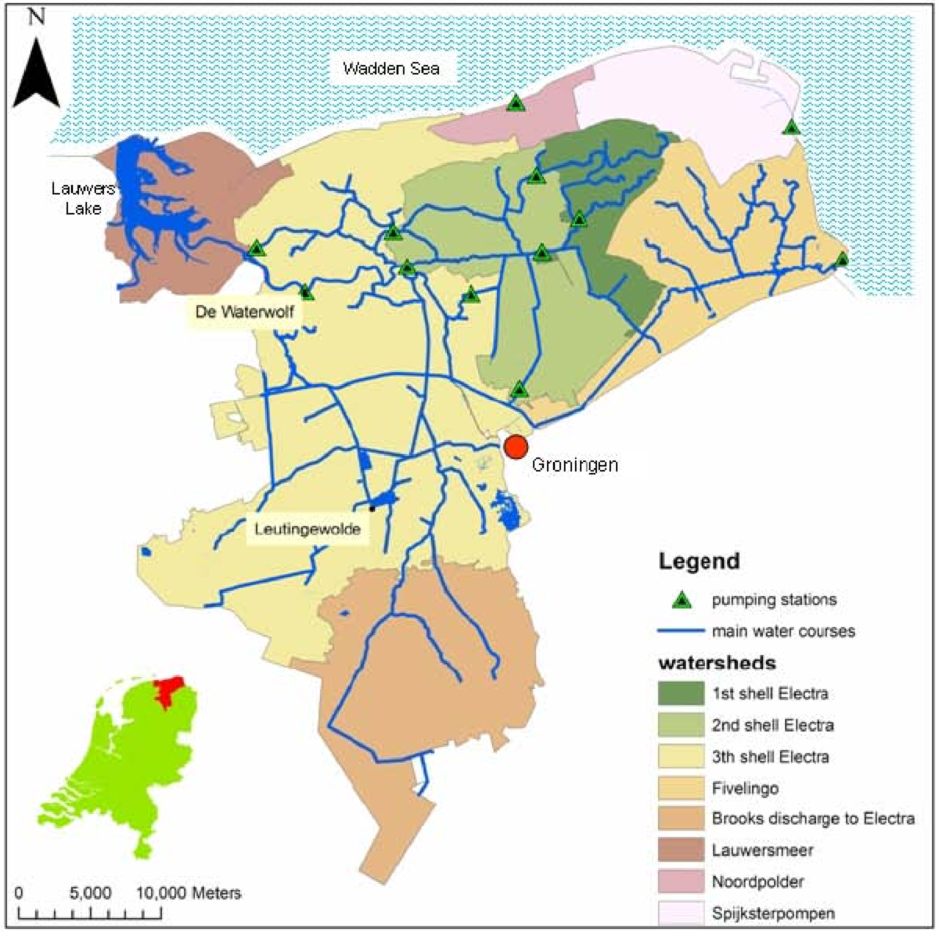
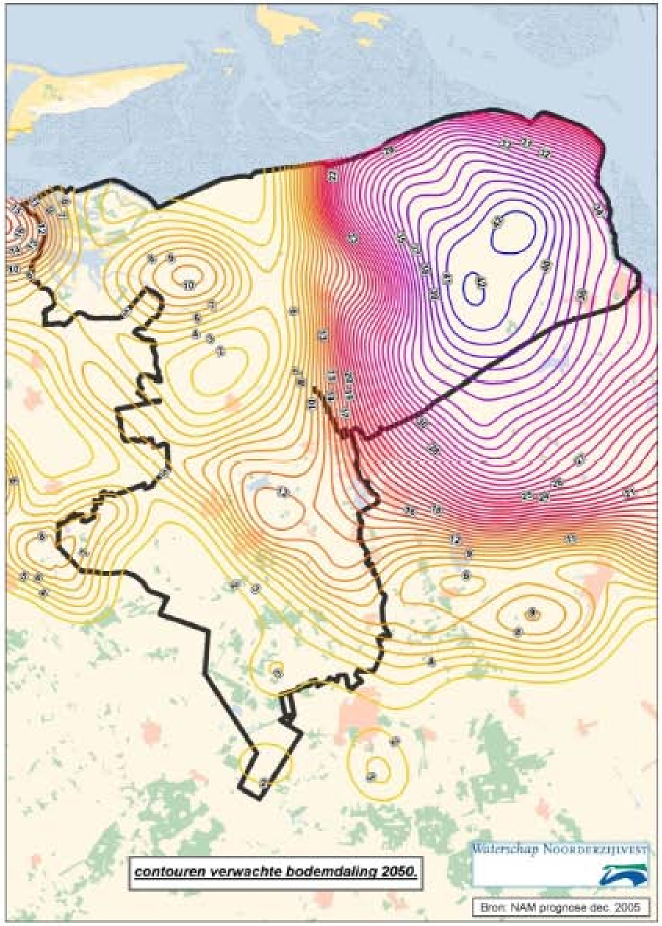
Use case: Pump management in NL
Regional water authority Noorderzijlvest



a)



b)

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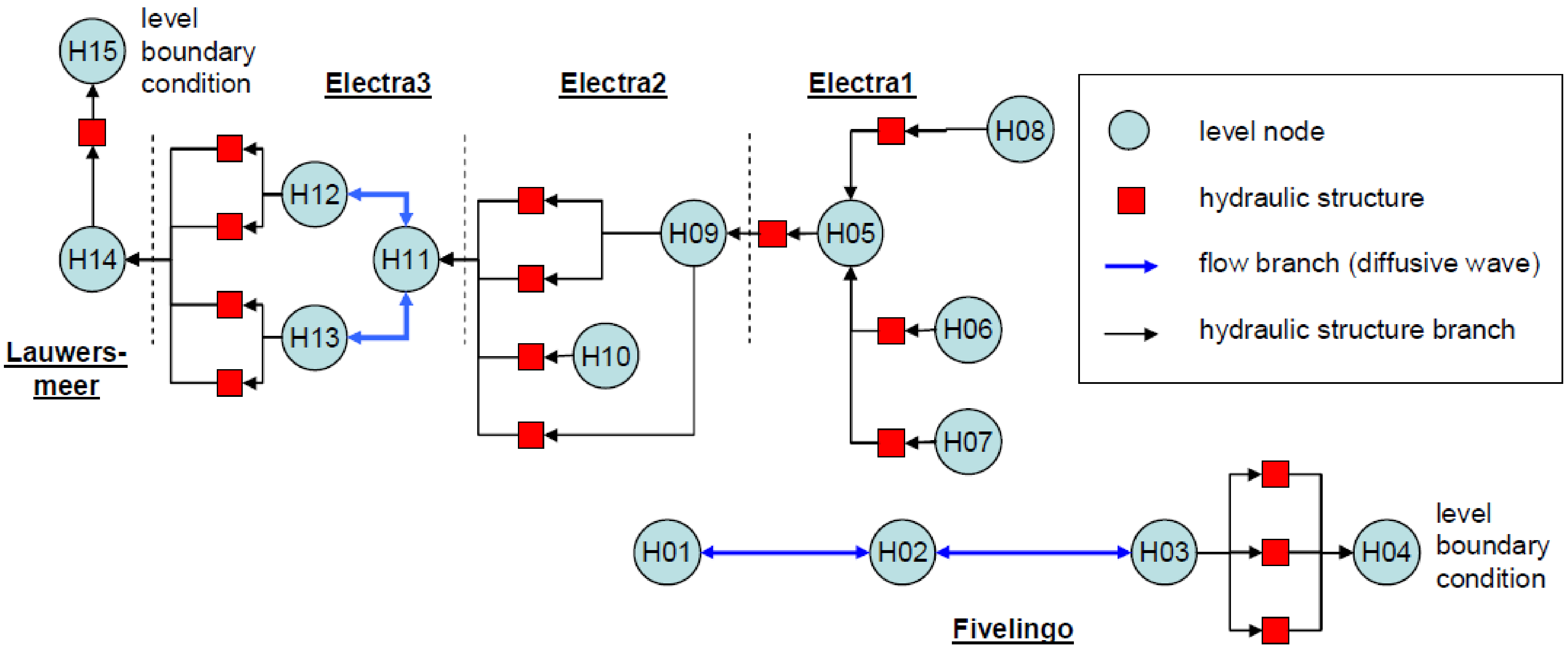
Use case: Pump management in NL (2)

Regional water authority Noorderzijlvest



Internal model schematization (diffusive wave)

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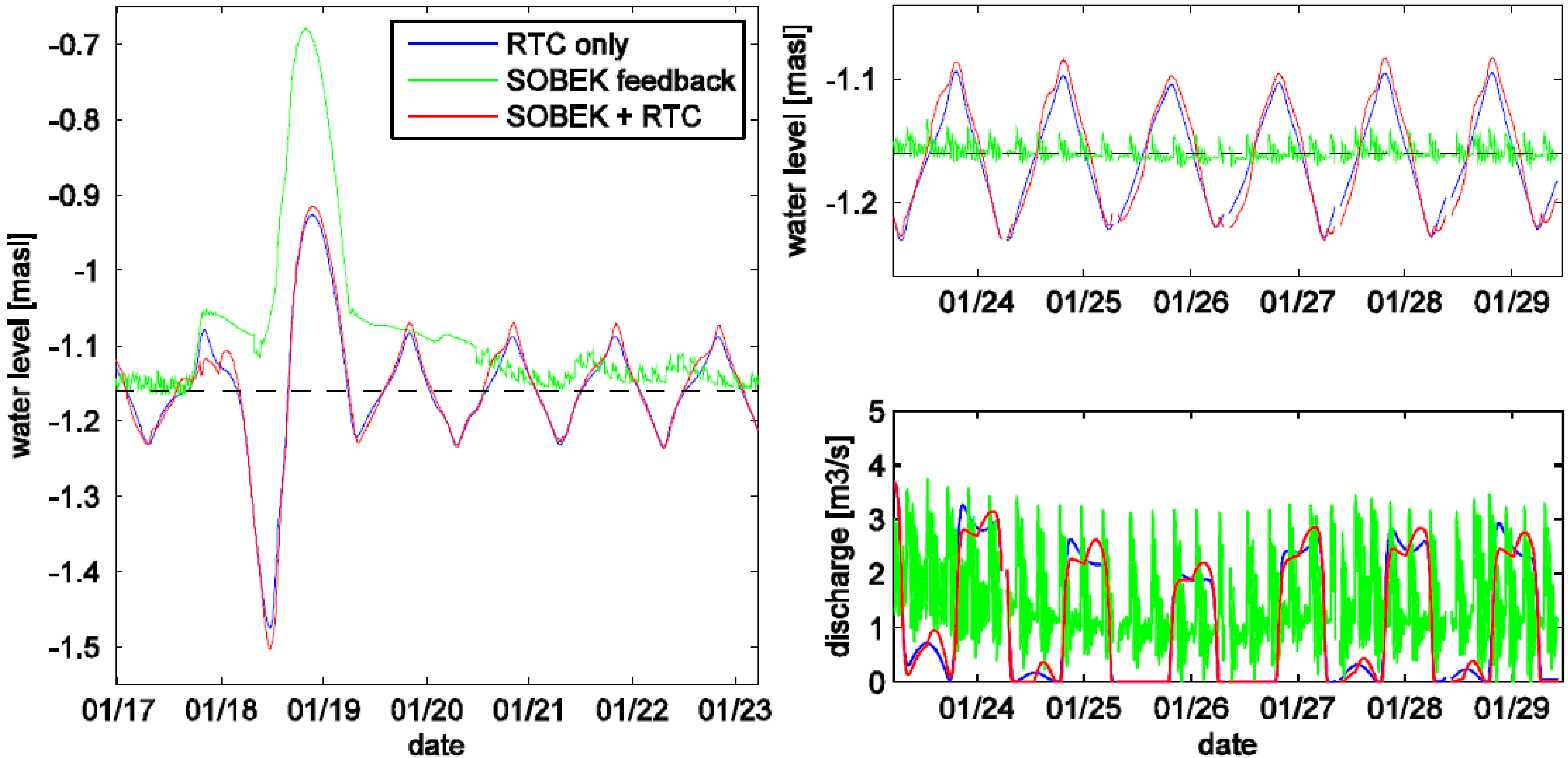
Use case: Pump management in NL (3)

Regional water authority Noorderzijlvest



-> Schwanenberg et al. (2012), HIC2012, Hamburg, Germany, 14-18 July

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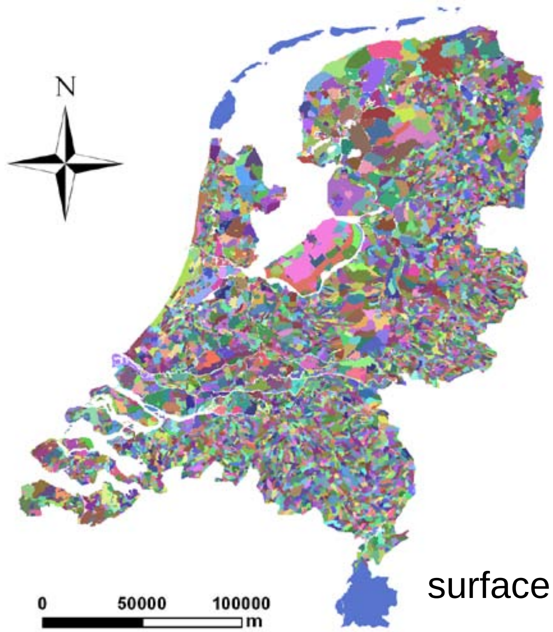
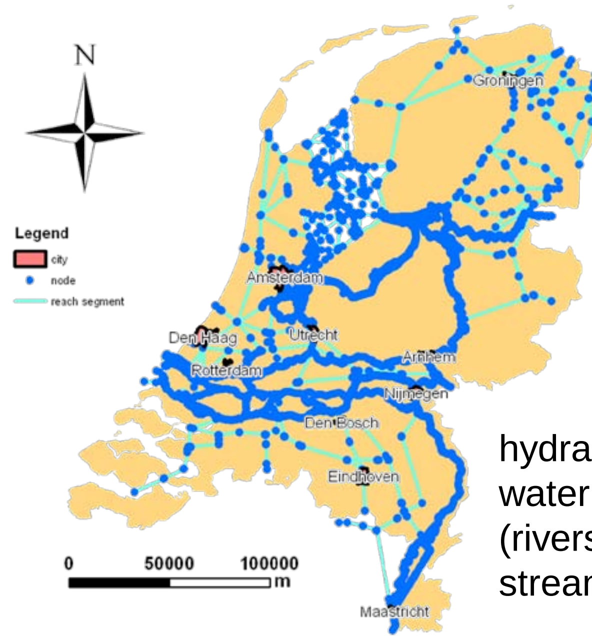
Use case: National Hydrological Instrument

National Dutch water allocation during draughts



surface water units



hydraulic model of the water distribution network (rivers, canals and major streams)

Characteristics:

Model (http://www.nhi.nu/nhi_uk.html) includes about 8000 surface water units connected by a complex river network in the delta of the rivers Rhine and Meuse.

Ongoing work: Migration of the water allocation (DM / Mozart) to RTC-Tools

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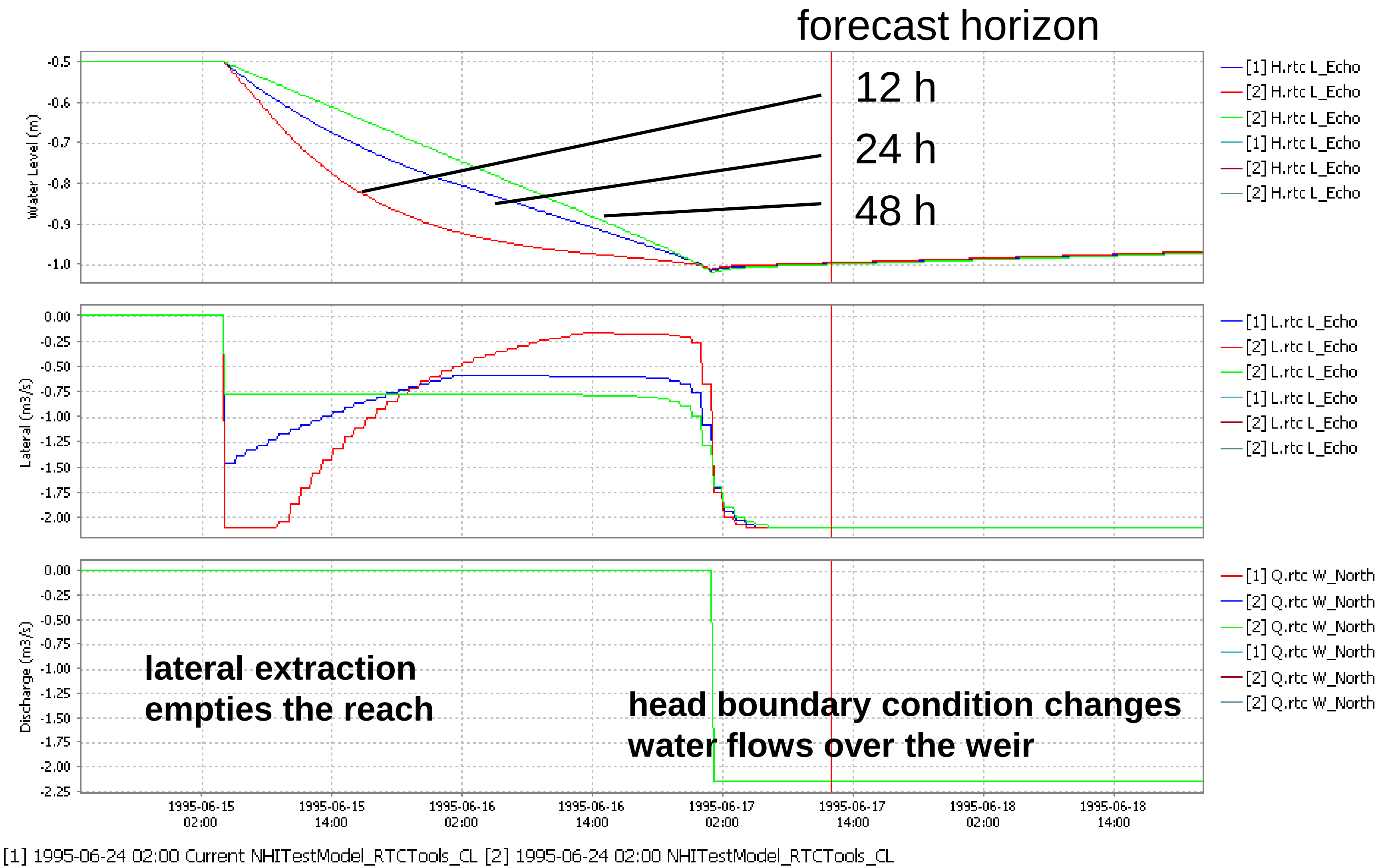
Use case: National Hydrological Instrument (2)

National Dutch water allocation during draughts



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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

Details on Automatic / Algorithmic differentiation:
http://www.autodiff.org/

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