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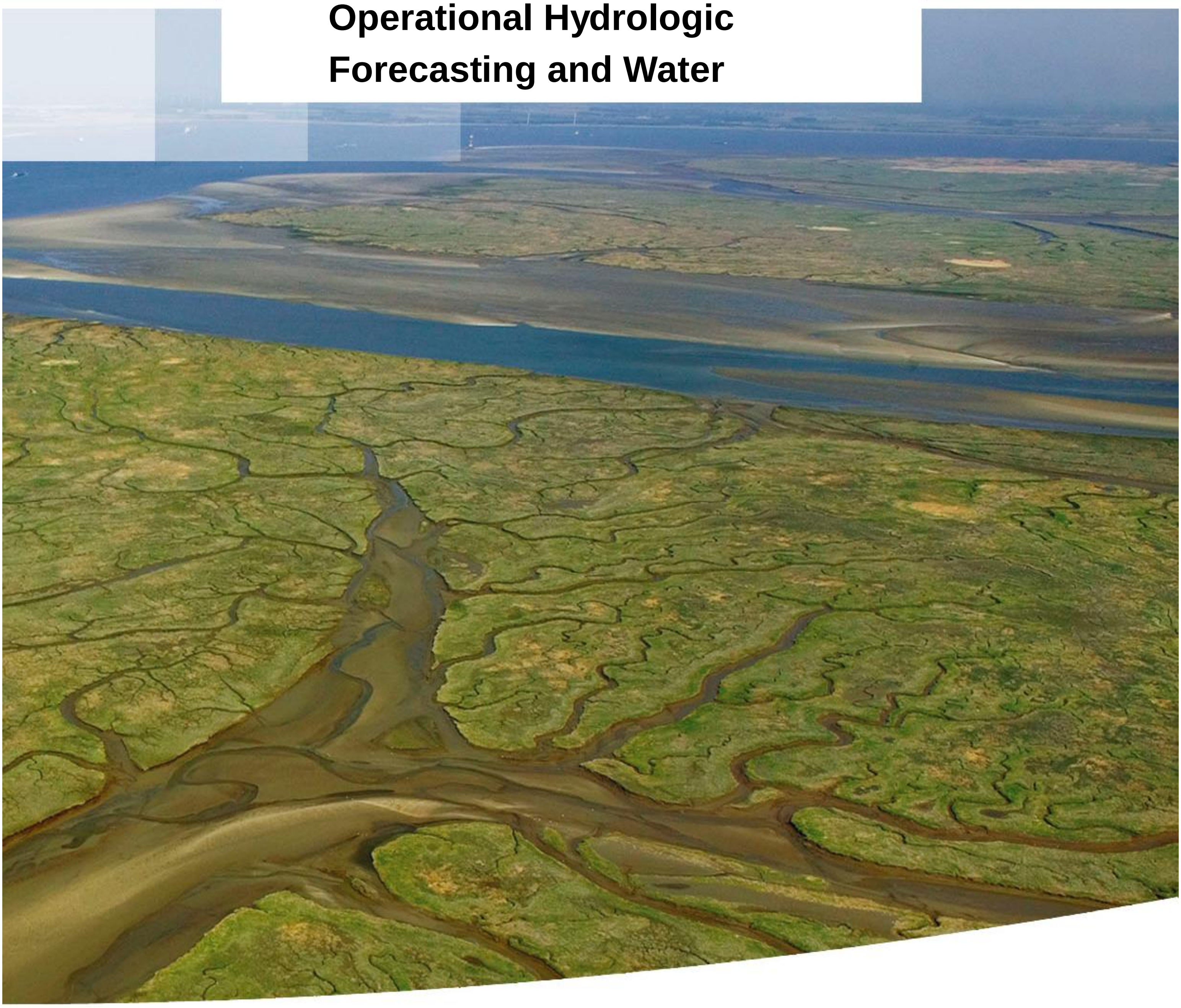
International Workshop on Data Assimilation for Operational Hydrologic Forecasting and Water



Deltares

International Workshop on Data Assimilation for Operational Hydrologic Forecasting and Water Management (November 1-3 2010)

Albrecht Weerts (Deltares)
Yuqiong Liu (NWS)

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Hydrology, Hydraulics, Modelling, Data Assimilation, Uncertainty, Forecasting

Summary
This reports contains the program & abstracts of the workshop organized 1-3 November 2010, Delft, Deltares. The outcomes are briefly described as these will be finalized in 2011.

Version	Date	Author	Initials	Review	Initials	Approval	Initials
	26-11-2010	Albrecht Weerts	AW	Dirk Schwanenberg		Tom Schilperoort	

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final

Contents

1 Background of the Workshop

This 2.5-day workshop at Deltares in Delft, the Netherlands, on November 1-3, 2010, aims at bringing together expert scientists, engineers, operational forecasters and water managers to share experience, ideas, techniques and tools in the broad area of data assimilation (DA) for operational hydrologic forecasting and water resources management. The goal of the workshop is to develop and foster community-based efforts for collaborative research, development and synthesis of techniques and tools, and cost-effective science-to-operations transition of them. This workshop is co-organized by Deltares and the NOAA National Weather Service Office of Hydrologic Development, and co-sponsored by the Hydrologic Ensemble Prediction Experiment (HEPEX, http://hydis8.eng.uci.edu/hepex/) and the innovation Flood Control 2015 project (http://www.floodcontrol2015.com).

The workshop will feature keynote, oral, and poster presentations and breakout discussions on:
1) theoretical and mathematical aspects of hydrologic DA applications such as real-time updating of initial conditions, parameter estimation/optimization, and supervised calibration;
2) objective utilization of new and existing sources of data (in-situ or remotely-sensed, quantitative or qualitative), and analysis and fusion of such data/information for DA applications;
3) modeling and quantification of structural, parametric, observational, and anthropogenic (e.g. flow regulation) uncertainties for DA applications; and
4) open-source and community-based tools for hydrologic DA in support of single-valued or ensemble analysis and prediction.

The expected outcome of this workshop is a special issue of a hydrologic journal, including a jointly-authored position paper that puts forth a community research agenda for DA for operational hydrologic forecasting and water resources management. An envisioned longer-term outcome of the workshop is an evolving, open source toolbox of hydrologic DA and closely related applications for both the research and the operational communities.

For questions on how to participate, or for general questions and comments, please contact the co-organizers, Albrecht Weerts (albrecht.weerts@deltares.nl) of Deltares and Yuqiong Liu (yuqiong.liu@noaa.gov) of the NWS Office of Hydrologic.

2 Program

2.1 Monday (Deltares Colloquium Room)

09:00 – 9:30	Jaap Kwadijk & Pedro Restrepo Yuqiong Liu & Albrecht Weerts	Arrival and welcome Workshop goals
09:30 - 10:10	Dong-Jun Seo	Bridging the gap in operational hydrologic data assimilation - Challenges and a way forward
10:10 - 10:30	Tanja Goethals	Fine-tuning of hydraulic updating in operational flood-forecasting systems: examples from the Demer basin with FloodWorks/InfoWorks software
10:30 - 10:50	Harrie Jan Hendricks Franssen	Operational management of a groundwater well field with data assimilation techniques
10:50 - 11:10	coffee break	
11:10 - 11:50	Robert Hartman	Operational Forecaster Perspectives on Hydrologic Model Data Assimilation
11:50 - 12:10	Bob Moore	Data assimilation and uncertainty estimation for flood forecasting: perspectives and prospects in a UK context
12:10 - 12:30	John Schaake	Transfer function approach to data assimilation
12:30 - 13:30	lunch	
13:30 - 13:50	Albert van Dijk	New international working group on seasonal forecasting for hydrological applications
13:50 – 14:10	Ioanna Zalachori	Evaluation of ensemble hydrological forecasts based on TIGGE weather predictions at different catchment scales
14:10- 14:30	Maria-Helena Ramos	Comparative studies on the use of streamflow data assimilation for short-term forecasting using deterministic or ensemble precipitation predictions
14:30 - 14:50	David Leedall	A Data Based Mechanistic (DBM) adapter module for the UK Environment Agency National Flood Forecasting System
14:50 - 15:10	Seong Jin Noh	Sequential Monte Carlo methods for river flow forecasting using multiple hydrologic models
15:10 – 15:30	coffee/tea break	
15:30 – 16:10		
16:10 – 16:30	Dirk Schwanenberg	Contribution of data assimilation techniques to model predictive control of water resources systems
16:30 -17:30	group discussion	Focus: propositions on operational DA
17:30	Drinks	

2.2 Tuesday (Deltares Colloquium Room)

09:00	Arrival	
09:20 - 10:00	Sujay Kumar	Utilization of Hydrologic remote sensing data in land surface modeling and data assimilation: Current status and Challenges
10:00 - 10:20	Susan Steele-Dunn	Assimilating GRACE observations into a conceptual hydrology model
10:20 - 10:40	Ben Gouweleeuw	Data assimilation of space-based passive microwave brightness temperature observations and the correction for a dynamic open water fraction
10:40 - 11:10	coffee break	
11:10 - 11:30	Carsten Montzka	Estimation of Hydraulic Parameters by Remotely-Sensed Top Soil Moisture Observations with the Particle Filter – A Synthetic Experiment
11:30 - 11:50	Andrew Slater	Uncertainty in seasonal snow reconstruction
11:50 - 12:30	Martyn Clark	Representing uncertainty in hydrologic models
12:30 - 13:30	lunch	
13:30 - 14:10	Martin Verlaan/Nils van Velzen	Speeding up data-assimilation with OpenDA
14:10 - 15:20	breakout 1	4 groups each focusing on one of the four topics Room - Innovation
15:20-16:30	breakout 2	4 groups switching topics Room - High Touch
16:30-17:30	discussion	Report from groups, including discussion on the workshop paper

Tuesday night: workshop dinner.
Restaurant de Kurk
Drinks start at 19:00, dinner starts at 20:00

2.3 Wednesday (Hotel De Plataan)

09:00	Arrival	
09:15-09:35	Paul Smith	Adaptive correction of deterministic models to produce accurate probabilistic forecasts
09:35-09.55	Douglas Plaza	Sequential Monte Carlo-based data assimilation using a coupled hydrologic-hydraulic model for analysis of flood forecasting
09:55-10:15	Oldrich Rakovec	Quantification of input uncertainty within a spatially conceptually grid-based model using streamflow data assimilation
10:15-10:30	coffee break	
10:30-11:30	4 break out groups discussion/writing outline of workshop position paper	
11:30-12:30	Discussion and wrap-up 1. breakout group reports 2. special journal issue journal, deadline, initial assessment of participation 3. follow-up efforts working group, next workshop, community-based DA tools, potential funding opportunities	
12:30-13:00	lunch and go home or join FEWS User days	

3 Workshop Participants

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4 Information on Special Issue HESS

As a tangible results of the workshop a special issue entitled "Latest advances and developments in data assimilation for operational hydrologic forecasting and water resources management" as part of the journal HESS will be organized.

This special issue will feature the latest advances and developments in hydrologic data assimilation (DA) for operational hydrologic forecasting and water resources management as an outcome of the 2.5-day international workshop in Delft, the Netherlands, on November 1-3, 2010. Focusing on data assimilation for operational hydrologic forecasting and water resources management, this special issue will include high-quality papers on various related topics including 1) theoretical and mathematical aspects of hydrologic DA applications, 2) objective utilization of new and existing sources of data (in-situ or remotely-sensed, quantitative or qualitative), for hydrologic DA applications, 3) modeling and quantification of structural, parametric, observational, and anthropogenic uncertainties in DA applications, and 4) open-source and community-based tools for hydrologic DA in support of single-valued or ensemble analysis and prediction.

The HESS editor is Florian Pappenberger, the guest editors are Yuqiong Liu and Albrecht Weerts.

From 1st December 2010 on authors can submit their contributions by using the online registration form on the HESS website: http://www.hydrology-and-earth-system-sciences.net/submission/manuscript_submission.html. The deadline for submission is 1st April 2011. **During the registration process it is important that the correct special issue is chosen!!!**

5 Contents list Abstracts

6 Abstracts

Bridging the gap in operational hydrologic data assimilation - Challenges and a way forward

D.-J. Seo[1], Yuqiong Liu[2,3], Haksu Lee[2,4], Victor Koren[2], Jiarui Dong[5,6], Michael Ek[5], Pedro Restrepo[2]

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(6) Science Applications International Corporation, McLean, VA, USA

Data assimilation (DA) in operational hydrologic forecasting, in manual or automatic form, predates popularization of DA in weather forecasting and oceanography. In spite of the early discovery of the potential and the long history, hydrologic DA as an objective tool is, in general, yet to take firm root in operational hydrologic forecasting. In the meantime, the need for effective assimilation of all available data into the forecast process is ever increasing. In this talk, we share experiences with hydrologic DA in the U.S. National Weather Service, identify scientific and engineering challenges for widespread acceptance and use of hydrologic DA, and offer a strategy for the research and operational communities to move faster forward by capitalizing on new developments such as the Community Hydrologic Prediction System (CHPS), and the increasing overlap and synergism between catchment-scale hydrologic modeling and regional/continental-scale land surface modeling.

Fine-tuning of hydraulic updating in operational flood-forecasting systems: examples from the Demer basin with FloodWorks/InfoWorks software

Tanja Goethals[1]

(1) System manager at VMM (Vlaamse Milieumaatschappij), department of Operational Water Management

One of the tasks of the department of Operational Water Management of the Vlaamse Milieumaatschappij (VMM, Flemish Environmental Agency) is flood forecasting along the 1st order non-navigable waterways in Flanders. For this end, several operational hydraulic forecasting and warning systems have been set up (OBMs), in the Yser, Dender, Dijle and Demer basins; these complement a general hydrologic forecasting and warning system for Flanders; see www.overstromingsvoorspeller.be.
For forecasts to listen as closely as possible to the situation on the field, hydraulic updating is executed: measured stages or flows are used to adjust simulated stages or flows.
Out of the four options to perform updating in the FloodWorks/InfoWorks software (by MWHSoft) – state correction, error prediction (ARMA), IWRS update unit and abstraction with definition of logical control – the last one was chosen and fine-tuned. Through the implementation of an abstraction unit, a certain amount of flow can be added or subtracted at the abstraction location, the amount being dictated by an adaptable formula based on the differences between measured and observed stage or flow.
Stage updating is applied at water control infrastructure; flow updating works best at stage gauges. In the case of stage updating, the operator can choose to apply updating or not, and to scale the updating or not to the stage gap to bridge. The scaling to stage gap proved a very successful way of updating: it avoids oscillations around the measured values and also makes it unnecessary to use a deadband around measurements. Flow updating on the other hand is applied by means of relaxation coefficients (α and β).
Both stage updating and flow updating are applied only when the simulated stage is between adjustable minimum and maximum stage boundaries and when the flow is above a certain threshold (Q_{min}), to prevent that the updating causes the hydraulic models to crash.
The system handles gaps in the measurements by falling back to a preset value or stopping hydraulic updating. To ensure that the runs do not crash because of leaps between simulated and measured flow at these transitions, the value added or subtracted at the abstraction unit dies out over a series of timesteps instead of falling to 0 in one timestep (by means of a third factor γ).
The resulting updating system is maximally adaptable by the operators: updating can be set on and off, the scaling to stage gap can be set on and off, α/β/γ are adjustable, a Q_{min} value can be set and stage boundaries -between which updating can take place- can be changed.
Overall, the Demer examples proved that it's quite robust in operational environments and delivered quite reliable and accurate results, notwithstanding the limited use of parameters (α/β/γ). Nonetheless, the application of hydraulic updating is merely a tool to "embellish" the model results; it does not cancel out the need for improving the hydraulic model itself and keeping it up-to-date with field reality (e.g. construction of new storage areas).

Tanja Goethals (VMM-AOW), based on work by Ivan Rocabado (Soresma) & Stijn Rombauts (VMM-AOW)

Operational management of a groundwater well field with data assimilation techniques

H.J. Hendricks Franssen[1], G. Bauser[2], H.P. Kaiser[3], U. Kuhlmann[4], F. Stauffer[2], R. Müller[3] and W. Kinzelbach[2]

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Abstract

The increasing availability of on-line sensors allows a better management of groundwater well fields which are threatened by pollution. The monitoring of the temporal variations in hydraulic heads in and around a well field assists in adapting the management strategy in order to extract groundwater of drinking water quality. An example from the city of Zurich (Switzerland) is presented. The Ensemble Kalman Filter (EnKF) is used for optimally combining an on-line model for the real-time characterisation of subsurface flow and data from the on-line sensors. The subsurface flow was modelled with a 3D finite element model for variably saturated groundwater flow including river-aquifer interactions. First, experiments on the basis of historical data from the period January 2004 - December 2007 were performed. It was concluded that updating the model with help of piezometric head data with EnKF helps to improve the characterisation of groundwater levels in the area. This improvement in the predictions holds for a time horizon longer than at least ten days. In some of the experiments, not only states but also parameters (hydraulic conductivity and leakage) were updated. The 1-day and 10-day piezometric head predictions, are better with than without updating of parameters. In order to investigate better the improvement of the parameter estimates, also a synthetic model for the same site was constructed, the only difference being that certain parameter values were selected as the unknown "true" conditions. It was found that EnKF indeed successfully updates unknown parameters. The mean absolute error of estimated log-leakage coefficients decreased by up to 63%, for log-hydraulic conductivity a decrease of up to 27% was observed.

The on-line predictions were combined with on-line optimization of the management (pumping at different wells, artificial recharge in different basins and wells) of the Water Works Zurich. The optimization was carried out with a hierarchical control method, combining fuzzy based rules and genetical algorithms. It could be shown, both for off-line experiments and in an operational setting, that real-time control of the water resources management at the site results in a reduced risk of attracting urban pollutants.

This methodology (real-time modelling and real-time control) are operational at the Water Works Zurich from January 2009 onwards and showed a remarkable performance.

Operational Forecaster Perspectives on Hydrologic Model Data Assimilation

Robert K. Hartman[1]

(1) Hydrologist in Charge, California-Nevada River Forecast Center, Sacramento, California USA

Operational forecasters have been using simple methods of data assimilation for a long time. Those methods are typically straightforward, easy to apply, and easy to understand. Examples include updating of snow model states and the use of observed streamflow to make short-term adjustments to the simulated streamflow in the future (forecasts). More technical and less transparent procedures, such as Kalman Filter updating of model states have been met with resistance and have not, as a result, been widely applied by the U.S. National Weather Service's River Forecast Centers. Criteria and baselines for operational implementation will be offered toward the objective of developing data assimilation techniques and procedures that can be embraced and utilized by operational hydrologic forecasters.

Data assimilation and uncertainty estimation for flood forecasting: perspectives and prospects in a UK context

R.J. Moore[1], S.J. Cole[1] and A.J. Robson[1]

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Methods for data assimilation used operationally for flood forecasting in the UK will be reviewed together with ongoing developments aimed at including uncertainty estimates. Existing methods for state correction and ARMA error prediction as applied to lumped catchment models are first outlined.

The challenge of developing state-initialisation and state-correction methods for distributed flood forecasting models, configured at catchment to national scales and embracing ungauged areas, are then discussed. Providing uncertainty estimates for area-wide flood forecasts on a 1km grid through the use of ensemble rainfall forecasts is illustrated on case study storms. A visual portrayal is obtained of evolving flood risk over a forecast period, with reference to flood return period thresholds defined on the same grid and the probability of them being exceeded.

Uncertainty attributed to model error for a lumped flood forecast model is represented by a parametric ARMA error model scheme. The method is compared to use of quantile regression for estimating forecast confidence intervals. An uncertainty assessment that jointly considers model error and forecast rainfall error is made possible through the use of ensemble rainfall forecasts.

Transfer function approach to data assimilation

John Schaake[1]

(1) Consultant to Office of Hydrologic Development, NWS, NOAA

This presentation explores a transfer function approach to using recent streamflow observations as well as past and future model simulated values to create ensemble simulations of future streamflow values. The objective is to produce ensemble streamflow simulations that correct for model biases, account for and reduce effects of uncertainty in initial hydrologic conditions, and that give reliable probability estimates of future streamflow events. Examples will be presented where the procedure has been applied using both the Sacramento model and the Continuous API model to the same data sets. Results show that past streamflow observations can be used to make substantial reductions in the mean absolute error in future streamflow simulations with improvements lasting as long as two weeks during dry periods.

New international working group on seasonal forecasting for hydrological applications

Albert van Dijk (chair)[1], Martyn Clark[2], Julie Demargne[3], Qingyun Duan[4], Jason Evans[5], Lifeng Luo[6], John Schaake[7], QJ Wang[8], Albrecht Weerts[9], Eric Wood[10], Ross Woods[11]

A working group on Seasonal Forecasting was instated in July 2010 under the Hydrological Applications Project in the Global Energy and Water Cycle Experiment (GEWEX, one of four World Climate Research Programme projects). The objective of this working group is "to develop the science behind skilful hydrological seasonal forecasts and useful applications". The emphasis is on dynamic seasonal forecasts derived from climate models and their propagation through hydrological models. Topics considered include:

- Assessing current conditions: initialisation of hydrological models in near-real time; combining historic data and short-term forecasts for operational monitoring (now-casting); assimilation of hydrometric and hydrological remote sensing data; dealing with data latency and lead time.
- Using seasonal climate forecasts: accessing forecasting services; assessing skill in alternative forecasts; ensemble, downscaling and bias-correction procedures for hydrological application.
- Measuring hydrological re-forecast (or hind-cast) skill: assessing skill from alternative climate re-forecasts and/or hydrological models; assessing performance against more naive or statistical climate and/or hydrological forecasting methods; design of benchmarking experiments and infrastructure to test improvements.
- Understanding hydrological forecasts: understanding the source of skill, importance of initial hydrological state versus climate forecasts, exploration of feedbacks between hydrological state and climate.
- Useful products and services: assessment of variables and skill required for useful applications; monitoring and seasonal forecasting of streamflow, water level or water resources availability; hydrological or agricultural drought early warning systems.

The working group is still in its formative stages. Participation is on a best-effort basis and new members are much welcomed. Research activities will be pursued in collaboration with other initiatives and include:

- With HEPEX, carry out one or more regional pilot projects to downscale and evaluate seasonal climate and derived hydrological re-forecasts, and to develop and test hydrological ensemble prediction techniques and their impact on seasonal hydrologic prediction.
- With the IAHS Prediction in Ungauged Basins (PUB) initiative, determine and demonstrate the contribution of remote sensing to hydrologic modelling with particular focus on un-gauged and poorly gauged basins.

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- With GEWEX Global Land/Atmosphere System Study (GLASS), evaluate the predictive capability from land initialization conditions to the prediction of terrestrial hydrological variables at different time scales.

Evaluation of ensemble hydrological forecasts based on TIGGE weather predictions at different catchment scales

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The integration of ensemble rainfall forecasts to explore the probabilistic framework for flood forecasting is a topic of increasing interest within the hydrometeorological community. As part of the TIGGE initiative, a key component of the THORPEX Interactive Grand Global Ensemble program of WMO, meteorological ensemble forecasts from several centres have been archived since October 2006. Hydrologists are encouraged to use this database to carry out researches on hydrological ensemble prediction. Although hydrological studies based on the TIGGE database are still few, their results indicate that TIGGE can be a promising tool for ensemble streamflow and flood forecasting (see Pappenberger *et al.*, 2008 and Yi *et al.*, 2009 & 2010). Even though these studies are enlightening, they may lack generality, since they are based on a limited number of catchments. The present study proposes an evaluation of hydrological forecasts based on the TIGGE database over a larger set of catchments, under varied climate conditions, to better assess robustness and generality of forecast performance. The study is carried out over 74 catchments in France, with areas ranging from 1000 km² to 44,000 km². Hydrological forecast evaluation is performed at catchment-based spatial scales and for lead-times up to 15 days. Streamflow forecasts are issued by the GRP rainfall-runoff model, driven by ensemble weather predictions from 8 meteorological centres of the TIGGE database. The performances of the ensemble forecasts are evaluated over a 2-year period, from October 2006 to October 2008. Single ensemble prediction systems from each centre, with a number of members ranging from 15 to 51, according to the meteorological centre, are considered in the hydrological model, as well as a combined multi-model ensemble that takes into account all members available at each day of the forecast period.

References:

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Comparative studies on the use of streamflow data assimilation for short-term forecasting using deterministic or ensemble precipitation predictions

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Comparative analyses are conducted to assess the impact of streamflow data assimilation on the quality of hydrological forecasts. Hydrological predictions are issued by a lumped soil-moistureaccounting type rainfall-runoff model (GRP model developed at Cemagref). The model was applied to a large set of catchments in France, representative of a variety of climate and physiographic conditions. In this study, results from the evaluation of short-term streamflow forecasts (up to 2-3 days) are presented. Two configurations were considered: 1) the model is driven by "perfect precipitation forecasts", i.e., observed precipitation is used as input, and 2) the model is driven by a weather ensemble prediction system. In the first case, different assimilation techniques are tested to update the model's parameters, states and outputs at an hourly time step.

The main results show that state updating proved to be more effective than output updating for the forecasting model studied. Additionally, optimising the model's parameters directly for a forecasting objective proved to be more efficient than optimising the hydrological model in a simulation mode, and then adjoining an updating procedure when forecasting. In the second configuration considered, weather forecasts from the ensemble prediction system PEARP of Météo-France (11 perturbed members and a forecast range of 60 hours) are used. Based on the evaluation of typical forecast verification scores, the impact of the model state updating is assessed at the daily time step. The results highlight the benefits of streamflow data assimilation for ensemble short-term forecasting.

A Data Based Mechanistic (DBM) adapter module for the UK Environment Agency National Flood Forecasting System

David Leedal[1], Paul J. Smith[1], Albrecht H. Weerts[2], Keith J. Beven[1,3] and Peter C. Young[1,4]

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Abstract: The UK Environment Agency has adopted the Delft-FEWS (Flood Early Warning System) data storage/retrieval, model interfacing, data analysis and data visualization software framework for its National Flood Forecasting System (NFFS). The flexibility of the Delft-FEWS framework to provide interfacing for any suitably formatted model is one of its key strengths. This ensures the system is not tied to a fixed model provider but rather can scale with advances in methods and research. This paper demonstrates how the DBM real-time flood forecasting approach incorporating data assimilation, an approach popular in the research field but only previously prototyped within NFFS, has now been developed and implemented as a robust module within the Delft-FEWS NFFS framework. Adapters have been developed for two flood-sensitive catchment sites in the UK: the River Eden, and the River Severn. The format of the DBM adapter and results from the two sites are presented. Of particular interest is the data assimilation algorithm based on a modified Kalman Filter. This algorithm operates within an inherently probabilistic scheme and therefore provides not only the benefits of incorporating real-time data in forecasting but also of providing an estimate of the uncertainty associated with the forecast. This uncertainty information can be added to data visualisation and communication within the Delft-FEWS NFFS.

Sequential Monte Carlo methods for river flow forecasting using multiple hydrologic models

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The applications of data assimilation techniques have been increasing to improve upon the predictability of hydrologic modeling. Among various data assimilation techniques, sequential Monte Carlo methods (known as “particle filter”) provide the capability to handle non-linear and non-Gaussian stat-space models. In this study, sequential Monte Carlo (SMC) methods are applied for river flow forecasting using multiple hydrologic models from conceptual one to process-based and spatially-distributed one. Dual state-parameter updating approach based on SMC methods is implemented for the estimation of both state and parameter variables of hydrologic models.

Two hydrologic models, storage function (SF) model and water and energy transfer processes (WEP) model (Jia et al, 2009) are implemented for the middle-sized Japanese catchment. The storage function (SF) model is one of the most commonly used conceptual models for flood runoff prediction in Asian countries due to its simple numerical procedure and proper regeneration of nonlinear characteristics of flood runoff. Water and energy transfer processes (WEP) model is a distributed hydrological model to be developed for simulating spatially variable water and energy processes in catchments with complex land covers. Two different hydrologic models are applied to the Katsura river catchment to forecast the river flow through SMC methods. This catchment is located in Kyoto, Japan and covers an area of 1,100 km^2 (887 km^2 at the Katsura water level gauging station). Hourly observed precipitation, weather data and discharge data are used for data assimilation.

Performance results of various versions of SMC methods such as SIR, ASIR and RPF with MCMC move step are compared under the same simulation condition. Sensitivity analysis is also performed concerning effects of particle numbers on the prediction accuracy.

The Role of Data Assimilation in Reducing the Hydrologic Model Structural Uncertainty

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Bayesian model averaging techniques in streamflow forecasting significantly improve upon the systematic bias and general limitations of a single model. This is done by establishing a new model as a linear combination or a weighted average of several models with weights based on individual model performance in previous time steps. Early application of this technique for hydrological systems assumed a fixed distribution around an individual model's forecast in establishing the prior and used a calibration time period to determine static weights for the new model. More recent work has focused on sequential Bayesian model selection technique with weights that are adjusted each time step in an attempt to accentuate the dynamics of an individual model's performance with respect to the system's response. However these approaches still assume a fixed distribution around the individual model's forecast. In this presentation, in addition to reporting recent enhancement in hydrologic data assimilation, a new sequential Bayesian model averaging paradigm is discussed. This new technique incorporates a sliding window of individual model performance around the forecast and relaxes the fixed distribution assumption in establishing the prior utilizing data assimilation that reflects both the performance dynamics of the models' forecasts along with their uncertainty.

Contribution of Data Assimilation Techniques to Model Predictive Control of Water Resources Systems

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Model Predictive Control (MPC) algorithms in water resources systems aim at the optimum control of hydraulic structures by combining optimization techniques and simulation models. The latter have to fulfil strict performance criteria for enabling the operational use of such schemes. Therefore, model reduction is frequently applied by lumping the spatial or temporal resolution of the original model or simplifying underlying physical phenomena.

We present an integrated data assimilation / MPC framework based on the software packages 'openda' and 'RTC Tools' and discuss how data assimilation can be used both for offline system identification, i.e. calibration, of reduced model as well as online model updating. Different approaches are compared in terms of forecasting performance based on real-world test cases such as the control of the bifurcation points of the Dutch Rhine / Meuse delta.

It turns out that results become highly competitive with the forecast performance of more complex models. This mainly results from the relative straightforward application of data assimilation techniques on simple reduced model. The high runtime performance of these models is furthermore an attractive feature when conducting ensemble forecasting.

Key words: model predictive control, flood forecasting, data assimilation

Utilization of Hydrologic remote sensing data in land surface modeling and data assimilation: Current status and Challenges

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Recent advances in remote sensing technologies have enabled the monitoring and measurement of the Earth's land surface at an unprecedented scale and frequency. The myriad of these land surface observations must be integrated with the state-of-the-art land surface model forecasts using data assimilation to generate spatially and temporally coherent estimates of environmental conditions. These analyses are of critical importance to real-world applications such as agricultural production, water resources management and flood, drought, weather and climate prediction. This need motivated the development of NASA Land Information System (LIS), which is an expert system encapsulating a suite of modeling, computational and data assimilation tools required to address challenging hydrological problems. LIS integrates the use of several community land surface models, use of ground and satellite based observations, data assimilation and uncertainty estimation techniques and high performance computing and data management tools to enable the assessment and prediction of hydrologic conditions at various spatial and temporal scales of interest. This presentation will focus on describing the results, challenges and lessons learned from the use of remote sensing data for improving land surface modeling, within LIS. More specifically, studies related to the improved estimation of soil moisture, snow and land surface temperature conditions through data assimilation will be discussed. The presentation will also address the characterization of uncertainty in the modeling process through Bayesian remote sensing and computational methods.

Assimilating GRACE observations into a conceptual hydrology model

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Terrestrial water storage is a key component of the terrestrial and global hydrological cycles, and plays a major role in the Earth's climate. The Gravity Recovery and Climate Experiment (GRACE) twin satellite mission provided the first space-based dataset of TWS variations, albeit with coarse resolution and limited accuracy. Here, we examine the value of assimilating GRACE observations into a well-calibrated conceptual hydrology model of the Rhine river basin.

In this study, the ensemble Kalman filter (EnKF) and smoother (EnKS) were applied to assimilate the GRACE TWS variation data into the HBV-96 rainfall run-off model Three GRACE datasets were used: the DMT-1 models produced at TU Delft, the CSR-RL04 models produced by UT-Austin and a second data product from TU Delft derived using radial basis functions. These measurements were assimilated into the hydrology model from February 2003 to December 2006.

We examined the sensitivity of the results to the different observation datasets, the definition of the state vector and to whether or not leakage was taken into account. The impact of data assimilation was assessed by comparing the model estimated discharge after data assimilation to the measured discharge at three locations.

Data Assimilation of Space-based Passive Microwave Brightness Temperature Observations and the Correction for a Dynamic Open Water Fraction

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Near-surface soil moisture derived from remotely sensed low-frequency microwave emissions has the ability to improve hydrological and meteorological modelling. For example, the Land Parameter Retrieval Model (LPRM, Owe *et al.*, 2008) has demonstrated significant potential for providing independent estimates of land surface parameters, such as near-surface moisture, land surface temperature (LST) and vegetation optical depth (OD). Satellite retrievals of these parameters may be combined with simulated and observed data in an assimilation scheme in order to generate the best possible data fields. These data may then be used to initialize numerical weather prediction and hydrological models and aid in continuous model bias correction.

Conditions under which soil moisture cannot be accurately retrieved from passive microwave sensors include precipitating clouds, dense vegetation, snow cover, frozen soil and (inland) surface water. Typically, quality control masks are provided to screen data affected by these conditions. While most of these masks are dynamic and can be derived from ancillary data, the mask for open water is generally static and considers coastal areas and large continental lakes only (Njoku *et al.*, 2003; Scipal *et al.*, 2008; Owe *et al.*, 2008). While static water bodies cause a constant positive bias and do not affect temporal patterns, temporal changes in open water fraction do and are not accounted for. Jones *et al.* (2009) recently released a global daily record of land surface parameters retrieved from AMSR-E, which as a first does include a dynamic open water fraction.

Surface soil moisture content inferred from space-borne active and passive microwave observations have proven useful in evaluating and understanding uncertainties in continental simulations by the Australian Water Resources Assessment (AWRA) model. Their value in data assimilation (DA), however, still needs to be demonstrated. To this end, experiments will be designed whereby historical soil moisture retrievals are assimilated into the AWRA water balance model. Alternatively, robust observational model operators will be developed for time-of-overpass passive microwave emissions by coupling the LPRM passive microwave transfer model to AWRA-L. These experiments will help to determine which of the alternative MDF techniques (e.g., sequential or non-sequential, state or parameter updating) are robust yet efficient means to fuse data fields, either retrieved soil moisture or observed brightness temperature, in the distributed water balance model.

Estimation of Hydraulic Parameters by Remotely-Sensed Top Soil Moisture Observations with the Particle Filter – A Synthetic Experiment

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Abstract
In a synthetic study we explore the potential of using surface soil moisture measurements obtained from different satellite platforms to retrieve soil moisture profiles and soil hydraulic properties using a sequential data assimilation procedure and the HYDRUS-1D model. Four different homogeneous soil types were investigated including loamy sand, loam, silt, and clayey soils. With the aid of a forward model run, a synthetic data set was designed and observations were generated. The virtual top soil moisture observations were then assimilated to update the states and hydraulic parameters of the model by means of a Particle Filtering data assimilation method. Our analyses include the effect of assimilation strategy, measurement frequency, accuracy in surface soil moisture measurements, and soils differing in textural and hydraulic properties.
With this approach we were able to assess the value of periodic spaceborne observations of top soil moisture for soil moisture profile estimation and identify the adequate conditions (e.g. temporal resolution and measurement accuracy) for remotely sensed soil moisture data assimilation. Updating of both hydraulic parameters and state variables allowed better predictions of top soil moisture contents as compared with updating of states only. An important conclusion is that the assimilation of remotely sensed top soil moisture for soil hydraulic parameter estimation generates a bias depending on the soil type. Results indicate that the ability of a data assimilation system to correct the soil moisture state and estimate hydraulic parameters is a function of pressure head.

Uncertainty in Seasonal Snow Reconstruction

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Reconstruction of the seasonal snowpack in mountainous areas has been suggested as a useful tool in assessing hydrologic quantities that may be used for further evaluation of models or retrospective management practices. The techniques involves running a snow model backwards in time and computing the potential melt per timestep (which is typically daily). However, as we know, there are many areas of uncertainty in any modeling problem; these include the inputs, the parameters, the model structure and the initial conditions of the problem.

Using 10,000 individual station-years of data for reconstructing snow water equivalent (SWE) at SNOTEL stations in the US West, we determine the relative importance of correctly identifying timing of snow cover as compared to biases in forcing data such as air temperature or solar radiation. To eliminate the problem of model structural error and parameter choices, the model is calibrated to each station-year, after which a "perfect model" scenario is applied where we look at sensitivities relative to the modeled reconstruction using observed instances of snow disappearance and observed forcing data. It was seen that a bias of 2C in air temperature is equivalent to about a 10 day error in the date of final snow removal in terms of maximum reconstructed SWE.

We also look at the probability of snow covered area becoming unavailable from satellite imagery. Twice daily MODIS imagery is used to compute the length of time that clouds or instrument error obscure the view of snow covered regions during the final instances of snow covering the ground. For 75% of ground that has annual snow cover for 60 or more days, there is less than 2 days of missing imagery during the transition from snow covered to snow free ground, according to the MODIS algorithm.

A hypothesis-based approach to hydrological model development: The case for flexible model structures

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Ambiguities in the appropriate representation of environmental processes have manifested themselves in a plethora of hydrological models, differing in almost every aspect of their conceptualization and implementation. This current overabundance of models is symptomatic of insufficient scientific understanding of environmental dynamics at the catchment scale, which can be attributed, at least partially, to difficulties in quantifying the impact of sub-catchment heterogeneities on the catchment's hydrological response. In this presentation we advocate the use of flexible modeling frameworks during the development and subsequent refinement of catchment-scale hydrological models. We argue that the ability of flexible modeling frameworks to decompose a model into its constituent hypotheses – necessarily combined with incisive diagnostics to scrutinize both individual process representations and the overall model architecture against observed data – provides hydrologists with a very powerful and systematic approach for improving process representation in models. Flexible models also support a broader coverage of the model hypothesis space and hence facilitate a more comprehensive quantification of the predictive uncertainty associated with system and component non-identifiabilities that plague many model analyses. As part of our discussion of the advantages and limitations of flexible model frameworks, we critically review major contemporary challenges in hydrological hypothesis-testing, including exploiting data to investigate the fidelity of alternative process representations, accounting for model structure ambiguities arising from major uncertainties in environmental data, quantifying regional differences in dominant hydrological processes, and the grander challenge of understanding the self-organization and optimality principles that may functionally explain and describe the heterogeneities evident in most environmental systems. We assess recent progress in these research directions, and how such progress can be exploited within flexible model applications to advance the community's quest for more scientifically defensible catchment-scale hydrological models.

Speeding up data-assimilation with OpenDA

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Most applications of data-assimilation make use of a dedicated implementation of the data-assimilation algorithm and processing of the observations. OpenDA is a generic toolbox that can assist the development of data-assimilation applications. The use of a generic toolbox has several benefits. It reduces development time, it increases the reliability of the code, it stimulated research into algorithms and it facilitates comparison with alternative solutions.
OpenDA provides an interface specification of a model and various other components together with the data-assimilation algorithms that use these interfaces to work with the model and observations. In this object oriented framework the algorithms can be programmed independent of any particular model, as they all implement the same interface. Efforts have been made to make coupling of a model to the data-assimilation algorithms efficient and easy. OpenDA has been applied to calibration and real-time data-assimilation for a number of models, ranging from hydrodynamics to atmospheric chemistry.
OpenDA also provides methods to handle parallel processing. For some algorithms parallel processing is possible even if the model itself does not provide this feature. It is possible e.g. to distribute the computations of an Ensemble Kalman filter around a cluster, without additional programming for the user. If the model itself can run in parallel then this can be taken into account.
Here we will explain how the OpenDA framwork is set up and how models, sources of observations and efficient algorithms can be combined. We will consider the calibration of roughness parameters for river hydrodynamics. For this application we compare several calibration strategies and the impact of these on accuracy and performance. Parallel computing is examined to further reduce the computation times. Another example is parallel computation for the members of an Ensemble Kalman filter. This has been applied e.g. to a storm-surge model for the North Sea.
Ongoing research efforts aim at including variational data assimilation, model reduction and new Kalman filtering algorithms. At the same time we intend to widen the range of applications, e.g. to rainfall-runoff models, ground water models, morphodynamic models and petroleum reservoir models.

The OpenDA toolbox is available to interested modelers and assimilation code developers as open source software under LPGL (www.openda.org).

Note: OpenDA is the new name for the merger of the COSTA developments initiated by TUDelft and VORtech and the DATools developments started by Deltares/Delft Hydraulics.

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Sequential Monte Carlo-based data assimilation using a coupled hydrologic-hydraulic model for analysis of flood forecasting.

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Nonlinearity and non-Gaussianity of Hydrological or Hydraulic Models is increasing the attention of scientific community in the development of new estimation algorithms. Particle Filtering is being widely used among different fields such as nonlinear system identification or nonlinear state estimation. Some recent literature on data assimilation presents important results in the application of particle filters, when comparing to traditional nonlinear filters. The aim of this work is to analyze the results for flood forecasting when a coupled hydrologic-hydraulic model is used and remote sensed hydrologic or hydraulic data is assimilated with the Particle Filter.

The data assimilation framework involves the hydrological and the hydraulic assimilation separately. For the hydrologic assimilation, the Sampling Importance Resampling Particle Filter (SIR) and the Community Land Model (CLM2.0) are used to assimilate soil moisture observations for soil moisture estimation. The discharge generated by the hydrologic model serves as input of a 1-D hydraulic model.

For the hydraulic assimilation, the SIR filter and the HEC-RAS model with the discharge generated by CLM2.0 as input are used to assimilate Synthetic Aperture Radar-derived water stages. Finally, the validity, strengths and weaknesses of the assimilation methodology are analyzed.

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Quantification of input uncertainty within a spatially distributed conceptual grid-based model using StReamflow data assimilation

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More accurate and reliable hydrological forecasts can be obtained through data assimilation by updating the hydrological model initial states with measured variables like streamflow (prior to a model forecast). Uncertainty in the hydrological model initial states is caused by errors in the forcing (observed precipitation, temperature and estimates of potential evaporation) and errors in the hydrological model used.

Before applying ensemble hydrological data assimilation, it is necessary to quantify these sources of uncertainty. Our aim is to quantify the input uncertainty in spatially distributed conceptual grid-based models. There is a large potential for improving the hydrological simulations and forecasts mainly because of an increased availability and better quality of spatially measured data. This spatial information can be employed to improve lumped uncertainty estimates as well. Another advantage for distributed models is the ability to simulate and predict hydrological variables at interior points of the catchment domain. Although it is difficult to beat hydrological simulations or short-term forecasts obtained from a data-driven or a lumped conceptual model, nevertheless, with increasing lead time, the hydrological information contained in the spatially distributed model states is crucial.

A grid-based hydrological model is developed and forced with spatially distributed rainfall. The kinematic wave model is used for channel routing. The simulations are carried out for the Upper Ourthe river (1600 km^2), a tributary of Meuse, which originates from the hilly region of the Belgian Ardennes. Several assumptions on the spatially distributed input uncertainty of precipitation fields are tested by quantifying different input error models. The precipitation fields are obtained by both uniform and spatial precipitation fields based on interpolation techniques as follows: Thiessen polygons, Delauney triangles, Inverse distance weights and kriging. Subsequently, these spatially distributed error models are applied to drive the grid-based hydrological model and observed streamflow is assimilated using sequential data assimilation methods like the particle filter and the ensemble Kalman filter. The effect of the different input error models is tested by looking on performance of the model forecasts over longer periods, Strengths and weaknesses of the data assimilation methods (including calculation time) will be addressed. Future research will include implementation of precipitation estimates derived from ground-based radar, as well as upscaling the focal area to the whole Meuse basin.

7 Workshop report

7.1 Summary

The workshop was attended by approximately 34 participants from 12 different countries (representing 23 different organizations) and included a mix of senior scientists and graduate students from a range of entities such as universities, government agencies, operational centers, and non-profit research institutions. The size of workshop participation was intentionally limited to 40 people to enable a fruitful discussion. The workshop featured oral presentations and breakout discussions that exploited limitations and opportunities in the following five areas: 1) theoretical and mathematical aspects of hydrologic DA applications, 2) objective utilization of new and existing sources of data (in-situ or remotely-sensed) for hydrologic DA applications, 3) modeling and quantification of structural, parametric, observational, and anthropogenic uncertainties in DA applications, 4) open-source and community-based tools for hydrologic DA, and 5) DA applications in real-time control of hydraulic structures and operational hydrologic forecasting.

The final workshop program, abstracts submitted, and presentations given at the workshop can be downloaded from the workshop website (http://www.floodcontrol2015.com/daworkshop2010). Follow-up activities include 1) a joint-authored position paper by the workshop participants that puts forth a community research agenda for DA for operational hydrologic forecasting and water resources management, and a special issue on Hydrology and Earth System Sciences (HESS), entitled "Latest advances and developments in data assimilation for operational hydrologic forecasting and water resources management". Both the workshop position paper and the HESS special issue are currently under development and expected to be published in 2011. This workshop was jointly organized by Deltares and the National Oceanic and Atmospheric Administration (NOAA) National Weather Service Office of Hydrologic Development, with major funding through the innovation Flood Control 2015 project (http://www.floodcontrol2015.com). A second workshop will be held, tentatively, in South Korea in 2012.

7.2 Workshop outcome

HESS special issue on DA for operational hydrologic forecasting and water management;

Jointly-authored position paper that puts forth a community research agenda for DA for operational hydrologic forecasting and water resources management;

Good memories of Delft, Deltares and the workshop participants!

Basis for future cooperation on hydrologic operational DA!