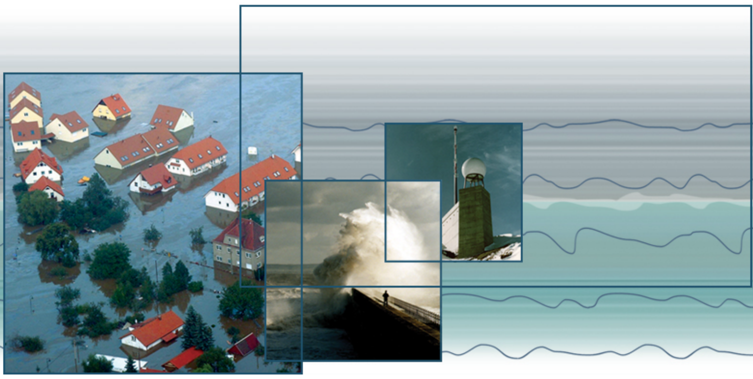
Integrated Flood Risk Analysis
and Management Methodologies



Real-time updating procedure for flood forecasting in small flash flood exposed catchments

Date January 2006

Report Number T01-06-01

Revision Number 1_0_p43

Deliverable Number: D1.1
Due date for deliverable: February 2006
Actual submission date: January 2006
Task Leader Sandrine Anquetin (INPG/partner no. 8)

FLOODsite is co-funded by the European Community
Sixth Framework Programme for European Research and Technological Development (2002-2006)
FLOODsite is an Integrated Project in the Global Change and Eco-systems Sub-Priority
Start date March 2004, duration 5 Years

Document Dissemination Level

PU Public
PP Restricted to other programme participants (including the Commission Services)
RE Restricted to a group specified by the consortium (including the Commission Services)
CO Confidential, only for members of the consortium (including the Commission Services)

Co-ordinator: HR Wallingford, UK
Project Contract No: GOCE-CT-2004-505420
Project website: www.floodsite.net

SIXTH FRAMEWORK PROGRAMME

DOCUMENT INFORMATION

Title	**Real-time updating procedure for flood forecasting in small flash flood exposed catchments**
Lead Author	**F. Lennartz**
Contributors	**T. Wöhling**
Distribution	**No distribution**
Document Reference	**No reference**

DOCUMENT HISTORY

Date	Revision	Prepared by	Organisation	Approved by	Notes
13/01/06	1_0_P43	F. Lennartz			

ACKNOWLEDGEMENT

The work described in this publication was supported by the European Community's Sixth Framework Programme through the grant to the budget of the Integrated Project FLOODsite, Contract GOCE-CT-2004-505420.

DISCLAIMER

SUMMARY

An increasing climatic variability leads to an increasing occurrence probability of extreme events. Especially in small flash flood exposed catchments with short reaction times accurate flood forecasting is highly important. Unfortunately the available rainfall-runoff models do, especially for extreme events in small catchments, not allow for an acceptable prediction accuracy. In order to use these models for flood forecasting for emerging flood events and to ensure an acceptable accuracy the model outputs have to be continuously updated using real time river gauge measurements. Various updating procedures have been published which are, however, mostly not suitable for short forecast periods and a steep flood hydrograph characteristic which is typical for small, quick reacting mountainous catchments. In such catchments it is the primary goal to extend the forecast lead time. This requires procedures that update the state variables that govern the runoff generation process of the used rainfall runoff model. Classical updating procedures (e.g. Auto Regression Moving Average approaches) are focussed on the river flow itself which leads to a significant loss of forecast lead time in small, quick reacting catchments. Therefore, it was our intention to develop a simple updating procedure that allows for the updating of sensitive state variables that control the runoff generation approach of an appropriate rainfall runoff model. At first we investigated WASIM-ETH model in this respect. The analysis yielded that this model was too complex for the envisaged purpose. As an alternative we investigated the model PREVAH (Precipitation-Runoff-Evapotranspiration-Hydrotope Model, Gurtz et al. 1999). This more conceptual rainfall-runoff model represents the catchment characteristics using hydrologic response units (HRU). Runoff generation processes are represented by linear reservoirs in this model. This allowed for the adjustment of the pre-event state of the system, i.e. the soil moisture content using a simple procedure that is based on the comparison between the predicted and the measured development of the flood wave. Several tests of the updating procedure using data from mountainous catchments in Switzerland and Germany showed a significant increase in prediction accuracy with respect to peak discharge at a very early state of the flood.

CONTENTS

Tables

Figures

1. Introduction

An increasing climatic variability leads to an increasing occurrence probability of extreme events. Especially in small flash flood exposed catchments with short reaction times accurate flood forecasting is highly important. Unfortunately the available rainfall-runoff models do, especially for extreme events in small catchments, not allow for an acceptable prediction accuracy. In order to use these models for flood forecasting for emerging flood events and to ensure an acceptable accuracy the model outputs have to be continuously updated using real time river gauge measurements. Various updating procedures have been published which are, however, mostly not suitable for short forecast periods and a steep flood hydrograph characteristic which is typical for small, quick reacting mountainous catchments. In such catchments it is the primary goal to extend the forecast lead time. This requires procedures that update the state variables that govern the runoff generation process of the used rainfall runoff model. Classical updating procedures are focussed on the river flow itself which leads to a significant loss of forecast lead time in small, quick reacting catchments. Therefore, it was our intention to develop a simple updating procedure that allows for the updating of sensitive state variables that control the runoff generation approach of an appropriate rainfall runoff model. We conducted the investigations in the following steps:

- Intensive review of the state of the art literature
- Analysis of suitable rainfall runoff models with respect to the goals of the investigation and model selection.
- Conceptual set up of the updating procedure and test of the first version. Analysis of the results.
- Design of the improved version and implementation in the model.
- Test of updating procedure using data sets from different catchments.
- Assessment of results.

2. Analysis of updating procedures and models

2.1 Literature review

At the beginning of the project we conducted in intensive review of the state of the art literature with respect to updating procedures for flood forecasting (see references). The most of the published approaches aim at the updating of river discharge which is not an suitable approach for small, quick reacting catchments were the forecast lead time is short. Approaches that aim at the pre event updating of state variables were rare and it became clear that such approaches are tailored solutions that have to bee seen in close context with the applied model. We considered two updating procedures, (1) Kalman Filter and (2) the approach of Yang and Michelle (2001). Measurements are assumed to be reliable and therefore no measurement update is required (one feature of the Kalman filter). The time update on the other hand, i.e. projecting forward the current state estimates, is done by our chosen model PREVAH (see below). We have found few examples of the Kalman filter application for updating procedures in literature. For a conceptual model like PREVAH, however, the filter is not the adequate choice and mathematically much too complex. In addition, PREVAH's model structure would make the implementation very difficult (see the loop structure of the model core below). Therefore we discarded the (extended) Kalman filter approach.

The approach of Yang and Michelle (2001) is based on a variation of both state and model parameters (including the reservoir constants etc.). Since we consider the watershed properties to be static and not a (random) function of the time, we discarded this approach also. Therefore, we decided to develop a simple procedure for the updating of model state variables after we selected a suitable model for our investigations.

2.2 Analysis of rainfall runoff models

At first we analysed the model WASIM-ETH (see fig. 1). The analysis led to the conclusion that this model is not suitable for the intended updating procedure. Our consideration were also confirmed at the Grenoble meeting in September 2005 by the authors of the model. The key results of the model analysis are:

- The model complexity is too high.
- It is difficult to calibrate because to many variables are involved.
- The updating of state variables leads to stability problems because of iteratively linked modules.
- The solution of the Richards equation exhibits non-convergence and stability problems when the soil moisture content was updated.
- A model run requires too much computational time.

Thus, we selected a more conceptual and simple approach. The alternative model PREVAH (Precipitation-Runoff-Evapotranspiration-Hydrotope Model, Gurtz et al. 1999) is a conceptual model based on hydrologic response units (HRU) and utilizes linear reservoirs. The most sensitive parameters of this model were identified by a sensitivity analysis:

- Soil moisture storage (SSM) and
- Upper runoff storage, (SUZ)
- Hypodermic flow

The conceptual outline of both models is displayed in Figure 1.

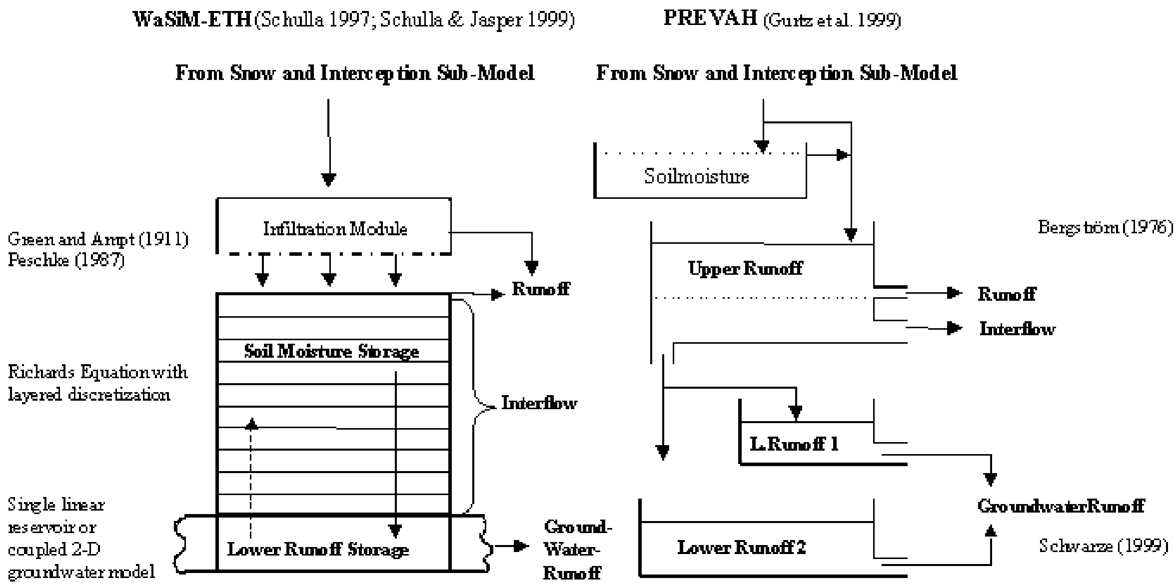


Figure 1: Conceptual outline of WASIM-ETH (Schulla, 1997; Schulla & Jaspa, 1999) and PREVAH (Gurtz et al., 1999)

3 Development and implementation of an updating procedure

3.1 Development of an updating procedure

Our proposed updating procedure is based on the simple assumption that the calculated storage of the upper soil reservoirs do not match with the real conditions. The precision criteria is the difference between the calculated and observed runoff. If it exceeds a certain threshold, the state of the upper runoff storage (and the soil moisture storage) is modified. This approach requires an iterative solution (Figure 2).

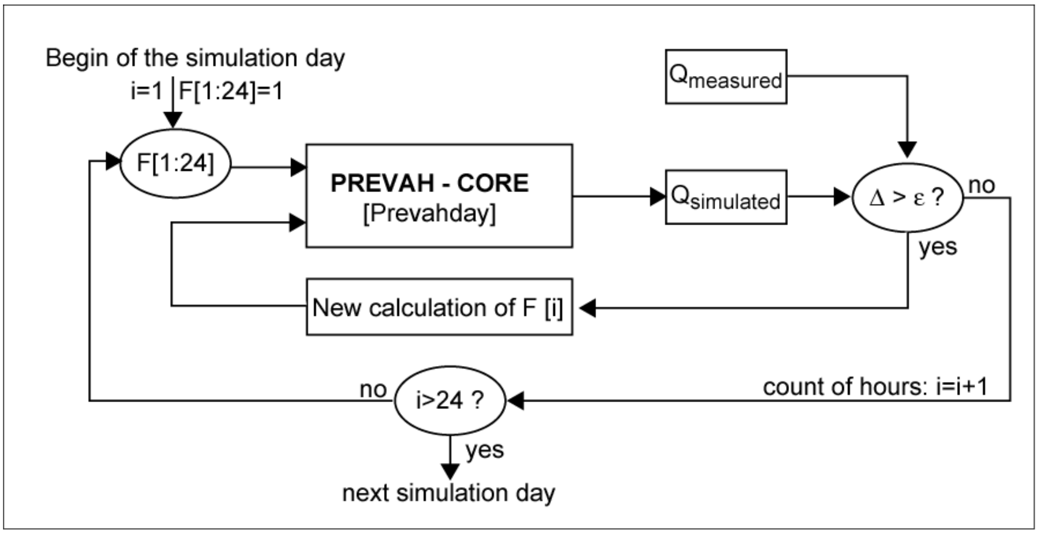


Figure 2: Principles of the PREVAH updating procedure

3.2 Implementation of the updating procedure

We selected the state variables SUZ and SSM to be modified by the proposed updating procedure. The value of these variables is calculated for each HRU in the catchment and it is possible to modify the variables of selected regions in the watershed. Since we usually do not have the spatially information of the current state of our catchment, we decided to equally modify the state variables in all HRUs.

The implementation of an updating procedure for hourly time steps was complicated by the specific model structure of PREVAH. The loop structure of the PREVAH model core is:

[Years [Months [Days [HRUs [Hours]]]]]

The calculations are conducted sequentially for all 24 hours of a day for one HRU in the catchment and then sequentially for all HRUs in the catchment. Total hourly flow components and state variables of the entire watershed are calculated by superposition of the flow from the single HRUs only at the end of the simulation day. A stepwise simultaneous assessment of hourly state variables of the catchment (total runoff, interflow, base flow, …) is therefore not possible. In accordance to this, updating would be only possible for daily intervals. But these are far to long intervals for flood forecasting in small, flashflood exposed catchments. The way out of the dilemma is to use a vector of updating factors **F**(*i*=1..24), where *i* denotes the count of the hours of a simulation day. At the begin of each day, an initial run without updating (**F**[1..24]=1) is conducted. The model results are evaluated at daily intervals. If ΔQ (*i*=1) (simulated discharge minus measured discharge) exceeds the precision criteria ε, the factor F(*i*=1) is calculated by Eq. (1) and the calculations of the day are repeated (Figure 2). Now the values of *SUZ* / *SSM* are multiplied by **F**(1) at the time t=1h within the loop of the HRUs. The calculations proceed as by the original PREVAH code for all coming hours of the simulation day. At the end of the day, $\Delta Q(i=1)$ is evaluated again. The procedure is repeated until $\Delta Q(i) < \varepsilon$. Then calculations proceed to the next hour where this criteria is not met.

It is possible to select the hours for which updating is required. A column in the data record of the measured discharge containing an integer value controls the updating: "0" – no updating and "1" – with updating. An example for the file „q_measure.txt" is given below:

1993	9	29	21	0.5203	0
1993	9	29	22	0.5096	0
1993	9	29	23	0.4982	0
1993	9	30	0	0.4870	1
1993	9	30	1	0.4763	1
1993	9	30	2	0.4668	1
1993	9	30	3	0.4574	1

Column 1 to 4 are reserved for the datum. Column 5 contains the observed discharge in [m³/s] and the 6th column is the updating switch. Accordingly to the value in this column, the updating is conducted never, once, at selected times, or always. It should be noted that the updating is only conducted when the difference between the simulated and observed runoff exceeds the user defined tolerance criteria ε. This criteria can be defined by the control file „update.inp" which contains only three relevant lines (2-4):

1st Line: Dummy / standard
2nd Line: "Master" updating switch: [y / n]
3rd Line: Detailed output on the screen: [y / n]
4th Line: Tolerance criteria, 0.01 = 10%

We applied the secant method for the iterative determination of the factor **F**:

$$\mathbf{F}(i)^{j+1} = \mathbf{F}(i)^{j} - \left[Q_s^j(i) - Q_m(i)\right] \cdot \frac{\left[\mathbf{F}(i)^{j} - \mathbf{F}(i)^{j-1}\right]}{\left[Q_s^j(i) - Q_m(i)\right] \cdot \left[Q_s^{j-1}(i) - Q_m(i)\right]} \qquad \text{(Eq.1)}$$

where, $i = [1...24]$ is the count of hours during a simulation day, $j = [1...12]$ is the iteration count of the updating loop, Q_s is the simulated runoff and Q_m is the measured runoff. Convergence is usually achieved within 3 or 4 iterations.

For certain (theoretical) model states, the updating of SUZ and SSM will not lead to a minimization of the objective function to the required precision criteria. If simulated runoff is over-predicted and SUZ/SSM already empty for example, it can not be further reduced. In such a case the best solution is kept and the iteration proceeds to the next time step. As a side effect, this approach also damps the effect of measurement errors (extreme values).

4. Test and application

At first we tested the updating procedure on the well observed Verzasca catchment - a mountainous catchment in Switzerland with an area of 186 km². Figure 3 shows the observed discharge, the full calibrated simulation results of PREVAH and a run with updating of the same event. Until the simulation time 2/10/1993, 7:00 a.m., the updating procedure is applied. From this simulation time onwards, PREVAH predicts the discharge (without updating). The prediction of the peak discharge at 2:00 p.m is significantly better compared to the model result of the calibration run.

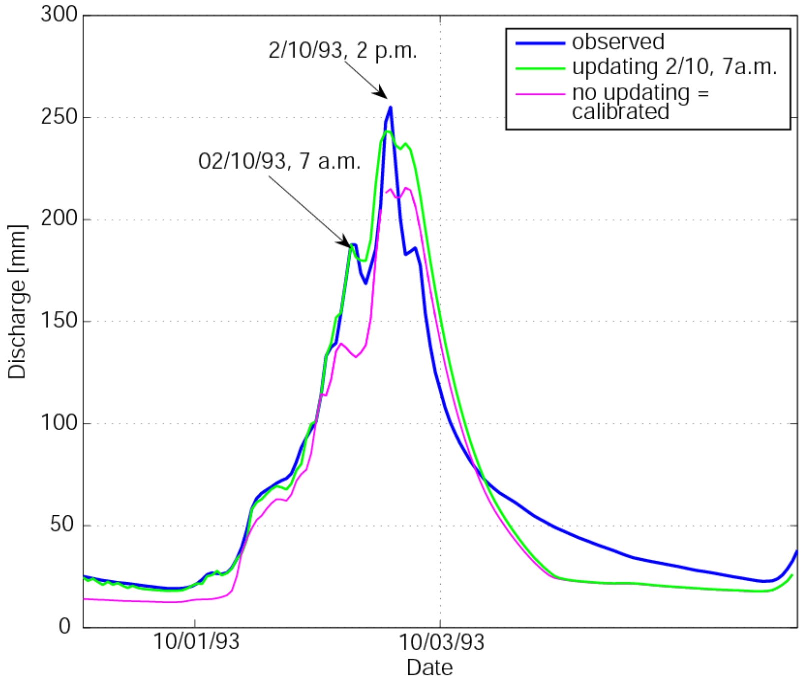


Figure 3: Comparison of measured and simulated discharge (Verzasca catchment): 1) the calibrated run and 2) a run with updating and projection

For test purposes, the above flood event was simulated assuming runoff measurements available for the entire event. Updating the model state hourly yields a perfect match of the calculated runoff and the measurements (Figure 4). The volume added/subtracted to the storage (SUZ, SSM) as a result of the updating is shown in Figure 4. If the model state is continuously (hourly) updated, the balance

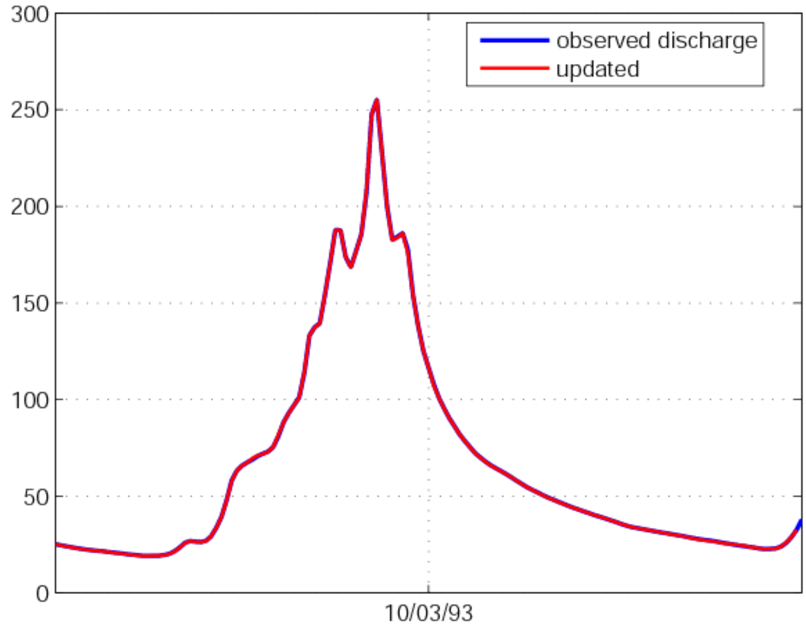


Figure 4: Comparison of the observed and simulated discharge (Vercasca catchment) with full (continuous) updating

of added/removed water volume during the entire event is +26.3mm. It should be noted that it is much less, if the model state is only updated at specific times of the rising discharge hydrograph (see above) and the flood peak prediction still can be significantly improved. Usually, the tailing (falling) discharge hydrograph is of lesser importance in flood forecasting.

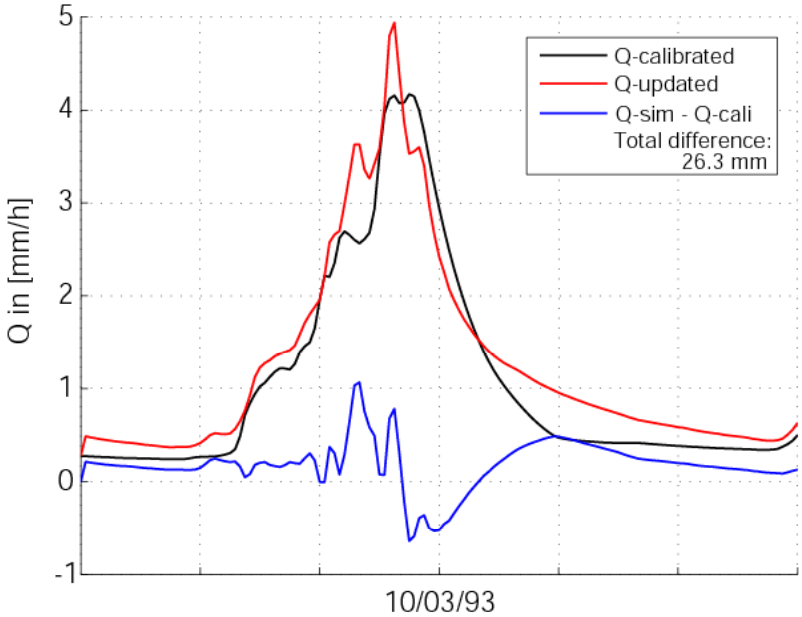


Figure 5: Measured discharge, calibrated PREVAH simulation, updated volume during flood event

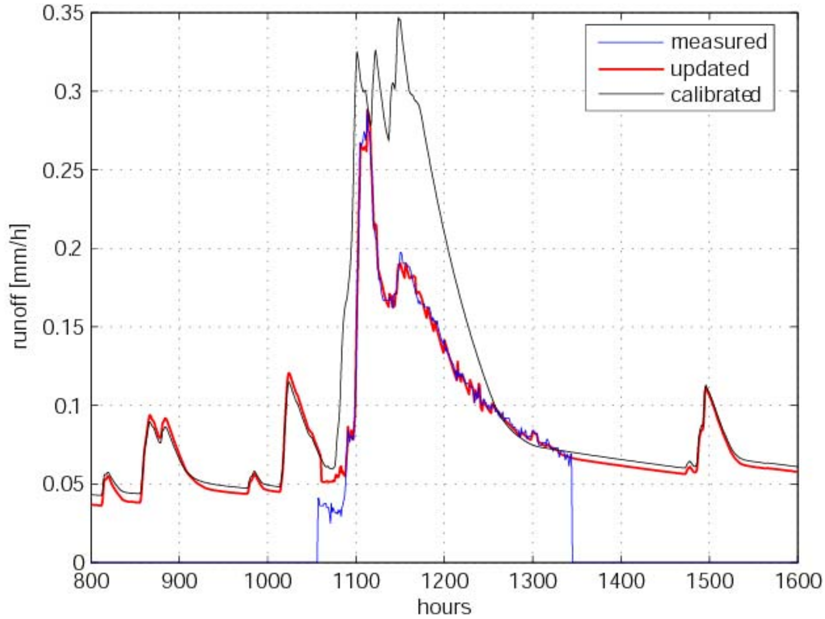


Figure 6: River Mulde catchment, gauge Wechselburg: Comparison of the calibrated PREVAH run, the updated PREVAH run and the measurements of a single flood event

The developed updating procedure was meanwhile implemented in the PREVAH model and successfully tested on some additional examples by M. Zappa (WSL, Switzerland).

5. References

1. **Anctil, F. Perrin, C. Andréssian, V.:** Impact of length of observed records on the performance of ANN and of conceptual parsimonious rainfall-runoff forecating models. Environmental Modelling and Software, 19, 2004, S. 357 – 368. – ISSN 1364-8152

2. **Aubert, D., Loumagne, C., Oudin, L.:** Sequential assimilation of soil moisture and streamflow data in a conceptual rainfall-runoff model. Journal of Hydrology, 280, 2003, S. 145 – 161. – ISSN 0022-1694

3. **Bertoni, J. C., Tucci, C. E., Clarke, R. T.:** Rainfall-based real-time flood forecasting. Journal of Hydrology, 131, 1992, S. 313 – 339. – ISSN 0022-1694

4. **Brudy-Zippelius, T.:** Wassermengenbewirtschaftung im Einzugsgebiet der Ruhr: Simulation und Echtzeitbetrieb. Universität Karlsruhe, Fakultät für Bauingenieur- und Vermessungswesen, Dissertation 2003.URL: www.ubka.uni_karlsruhe.de

5. **Georgakakos, K. P., Smith, G. F.:** On improved hydrologic forecasting – results from a WMO real-time forecasting experiment. Journal of Hydrology, 114, 1990, S. 17 – 45. – ISSN 0022-1694

6. **Georgakakos, K. P.:** Real-time prediction for flood warning and management. U.S.-Italy Research Workshop on the Hydrometeorology, Impacts and Management of Extreme Floods, Perugia, Italy, November 1995

7. **Hall, M. J.**: How well does your model fit the data? Journal of Hydroinformatics, 1, 2001, S. 49 – 55. – ISSN 1464-7141

8. **Henrich, K., Rode, M., Bronstert, A.:** 6. Workshop zur großskaligen Modellierung in der Hydrologie – Flußgebietsmanagement. Universität Potsdam, Kassel University Press, 2003. – ISBN 3-89958-031-1

9. **Kalman, R. E.:** A New Approach to Linear Filtering and Prediction Problems. Journal of Basic Engineering, 82 (Series D), 1960, S. 35 – 45. – ISSN 0021-9223 http://www.cs.unc.edu/~welch/kalman/kalmanPaper.html

10. **Kuczera, G., Parent, E.:** Monte Carlo assessment of parameter uncertainty in conceptual catchment models: the Metropolis algorithm. Journal of Hydrology, 211, 1998, S. 69 – 85. – ISSN 0022-1694

11. **Lettenmaier, D. P., Wood, E. F.:** Hydrologic Forecasting. Chapter 26 in Handbook of Hydrology. Ed. By D. R. Maidment, McGraw-Hill, New York, USA, 1993.

12. **Mein, R. G., Brown, B. M.:** Sensitivity of Optimized Parameters in Watershed Models. Water Resources Research, 14 (2), 1978, S. 299 – 303. – ISSN 0043-1397

13. **Messal, H. E. E.:** Rückkopplungen und Rückwirkungen in der hydrologischen Modellierung am Beispiel von kontinuierlichen Niederschlag-Abfluß-Simulationen und Hochwasser-vorhersagen. Technische Universität Berlin, Institut für Wasserbau und Wasserwirtschaft, Mitteilung Nr. 135, Dissertation 2000. – ISSN 0409-1744. URL: http://edocs.tu-berlin.de/diss/2000/messal_hilmar.htm

14. **O'Connell, P. E., Clarke, R. T. :** Adaptive hydrological forecasting – a review. Hydrological Scienes Bulletin, 26 (2), 1981, S. 179 – 205. – ISSN 0303-6936

15. **Rao, S. G., Rao, A. R.:** Recursive estimation of kernels of nonlinear rainfall-runoff models. Journal of Hydrology, 95, 1987, S. 341 – 364. – ISSN 0022-1694

16. **Refsgaard, J. C.:** Validation and Intercomparison of Different Updating Procedures for Real-Time Forecasting. Nordic Hydrology, 28, 1997, S. 65 – 84. – ISSN 0029-1277

17. **Schönwiese, C.-H.:** Praktische Statistik für Meteorologen und Geowissenschaftler. 3. Auflage, Gebrüder Borntraeger, Berlin, Stuttgart, 2000. – ISBN 3-443-01043-1

18. **Schulla, J. and K. Jasper, 2000:** Modellbeschreibung WaSiM-ETH. ETH Zürich, unpublished

19. **Sun, H., Cornish, P. S., Daniell, T. M.:** Spatial Variability in Hydrologic Modeling Using Rainfall-Runoff Model and Digital Elevation Model. Journal of Hydrologic Engineering, 6, 2002, S. 404 – 412. – ISSN 1084-0699

20. **Tyagi, A. Haan, C. T. :** Uncertainty analysis using corrected first-order approximation method. Water Resources Research, 37 (6), 1978, S. 1847 – 1858. – ISSN 0043-1397

21. **Ulrich, M.:** Modellgestützte Entwicklung und Testung eines einfachen methodischen Ansatzes zur Bestimmung des aktuellen Feuchtezustandes von Einzugsgebieten im Mittelgebirgsraum. Technische Universität Dresden, Institut für Hydrologie und Meteorologie, Diplomarbeit, 2004.

22. **U.S. Army Corps of Engineers:** SSARR User Manual. North Pacific Division, Portland, Oregon, 1987/1991. URL: http://www.nwd-wc.usace.army.mil/report/ssarr.htm

23. **Welch, G., Bishop, G.:** An Introduction to the Kalman Filter. University of North Carolina at Chapel Hill, Department of Computer Science, 2004. URL: http://www.cs.unc.edu/~welch/kalman/kalmanIntro.html

24. **World Meteorological Organization (WMO):** Simulated real-time intercomparison of hydrological Models. Operational hydrology report no. 38, WMO no. 779, Genf, 1992. – ISBN 92-63-10779-3

25. **Yang, X., Michel, C.:** Flood forecasting with a watershed model: a new method of parameter updating. Hydrological Sciences Journal, 45 (4), 2000, S. 537 – 546. – ISSN 0262-6667