Analysis of the time-step dependency of parameters in conceptual hydrological models

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Abstract

The estimation of parameters in deterministic hydrological models is highly disturbed by multiple, partly unkown error impacts. Many research activities have been devoted to the analysis of model uncertainty induced by such error impacts. In this context, spatial and temporal scale transfer issues have been emphasized as important sources of model uncertainty. In literature the spatial scale has been analysed in detail. Also variations of temporal scale impacts on parameters have been named, but not analysed in greater detail. Several model applications have proved empirically, however, that systematic linear and nonlinear parameter changes were induced by the application of different time steps, e.g. to account for the differing spatio-temporal resolution of the hydrological system investigated or the temporal resolution of available data. Only recently a subgroup of the PUB initiative named TRUMPER has been formed by IAHS (2007) which declared their special interest in the investigation of time dependency of hydrological model parameters. It is the hypothesis of this paper that data resolution both of climatic model forcing as well as measurements used for parameter estimation including feedback interaction with model structures have a strong impact on the estimation of optimum parameters. In this paper the analysis of parameters depending on time steps is carried out with a physically defined soil moisture model with data from an experimental hydrological catchment in Austria where longterm data at high spatio-temporal resolution was available. The existence of near functional linear and non linear relationships is clearly confirmed empirically. For saturated hydraulic conductivity and maximum infiltration rates as key hydrologic parameters it is shown that for the approximation of the differential equation by increasingly smaller difference equations the parameter values are approximating published values from laboratory experiments. The values remained rather constant below a threshold time step in the range of 15 to 30 minutes. Parameters determining flow accumulation, however, showed rather linear dependencies, some of them were real constants. In addition there are indications that changing time steps might lead to an internal change of model structures during the model inversion process. The linear and non linear functional relationships between parameter values and time step determined might be directly implemented in time discrete models to create models independent of timestep. The results might also be used for regionalisation or model application to ungaged basins, when parameters estimated with one time step are used in another basin with a different time step. The use of parameters estimated with daily data would create unacceptable errors. It must be emphasized that the results and conclusions are only valid for the semi-distributed time discrete models dominantly based on infiltration excess runoff formation applied here in small catchments under 20 km^2. It would be desirable to test the methodology with other model structures applied to the same catchments or the same model structures applied to different spatial scales. The hypothesis for future research is that the time dependency will occur for any time discrete model independent of its structure.

1 Introduction

Published parameters in hydrological models vary widely. Different reasons have been identified, much attention has been and still is payed to the analysis of different types of errors and resulting uncertainty as summarised in Fig. 1.

The problem of multiple error superposition and propagation through the hydrological modelling process has been in the scientific focus as were spatial scale issues. General temporal scale issues have been addressed, but not investigated at the same detail. As a basis for further theoretical analysis this study is dominantly focussing on the analysis of empirical timestep dependencies.

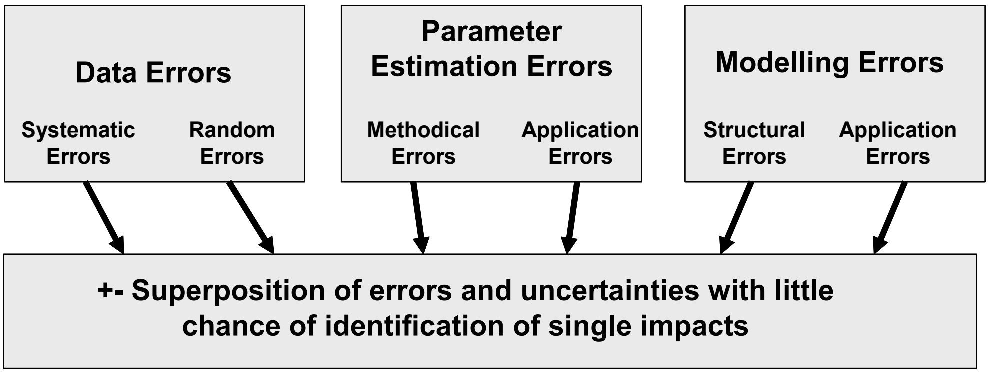

Fig. 1 Superposition of single error sources (from Ostrowski & Wolf (1984), modified)

Despite some resignation the vision of the identification of unique sets of parameters for a given catchment and model is still existing. Parameters changing with temporal resolution have been frequently observed and found to be problematic in this respect. Some authors e.g. Cullmann et al (2006) propose the re-estimation of model parameters for a different time step. Jothityangkoon et al (2001) describe the development and test of different model structures to model water balances on a yearly, monthly and daily time step basis. Others e.g. Ostrowski & Wolf (1984), Littlewood & Croke (2008) and Littlewood (2008) identified nonlinear empirical relationships between time step and parameters and they indicate potential solutions. Wang et al (2009) apply a conceptual model on the spatial mesoscale based on an infiltration excess layered soil moisture model and they also identify relationships between rate parameters with a dimension L/T and time step.

This study is based on the application of a specific model structure frequently applied in science and practice using multiple time steps to two Austrian experimental research basins. Relationships between time steps and selected sensitive parameters were determined. It was analysed how parameter estimation uncertainty might be reduced by integrating time step dependency into the modelling process. It might also support an improved compatibility of parameters from model applications with different temporal resolution. These models might even have different model structures as long as the physical significance of parameters defined is compatible, e.g. effective vertical saturated hydraulic conductivity as one dominant key hydrological parameter.

2 Problem definition

Momentaneous precipitation intensity i(t) is the time derivative of the recorded precipitation mass curve P(t) [mm], i.e. $i(t) = dP(t)/dt$ [mm/h]. For modelling purposes this information is frequently discretised applying mostly constant time steps Δt, a few exceptions are known, however, where varying time steps are used. These are discussed in Chapter 3. Intensity between discrete points is assumed to be constant, which is a most simplifying assumption. Bergmann & Stubenvoll (1986) and Bergmann (1993) stressed the significant loss of information due to averaging precipitation measurements over fixed time periods; this was a major motivation to equip the experimental catchment Poellau with high resolution rainfall recorders.

From mere theoretical consideration it is obvious that the averaging of either measured input driving the model and measured output data used for optimum parameter estimation is highly connected with the loss of information on the process dynamics of the hydrological system investigated. Once the single runoff contributions from subelements of distributed models are aggregated over space, the origin of a drop of water cannot be exactly traced backwards, although modern tracer technology helps of course to identify at least compartments of origin and volumes released. Most conceptual models have modules incorporated for fast, medium and slow reaction to rainfall; if claimed to be physically based, these are frequently defined as direct, inter and base flow. While the situation for base flow seems less critical within the time steps of maximum 24 h considered here, the situation is non unique for direct and inter flow. If the decision space for parameters is wide, for larger e.g. daily time steps measured high flows might have been alternatively produced by slow direct runoff or by fast inter flow or both. This means that the model inversion process can lead to multiple model structures. In summary, the time dependency of hydrological parameters is certainly induced by averaging continuously measured rainfall intensities and discharge, but at the same time can be caused by changing model structures during the automatic parameter estimation process. It might be argued that the parameter dependency on time steps is only existing for models where the direct runoff formation is restricted to infiltration excess. It should be kept in mind that any model claiming to be fully physically based must account for both direct runoff production processes. Physically spoken there is no lateral saturation excess runoff in one location without former vertical infiltration in another location. Nevertheless, this research accounts for infiltration excess runoff with limited reference to saturation excess runoff only.

3 Literature review

This review is focussing on parameter timestep dependency. It is clearly far beyond the scope and horizon of the paper also to account for spatial scale dependency.

Adequate selection of time steps must observe several requirements. One major issue is the stability of numerical solutions of strongly physically based hydrologic models, e.g. models containing the Darcy-Richards equation for soil moisture simulation or the Saint Venant equations for shallow water wave simulation on surfaces and in channels. As model application in this paper is limited to physically oriented, but still conceptual models, we only address modelling approaches with analytical solutions.

Hydrologically founded recommendations of time step limitations have been defined empirically, e.g. that time steps should not exceed one third to one fifth of the time to peak of a discharge event (see Maniak et al. (1997)). This should guarantee that the resolution sufficiently reproduces the dynamics of the system and catches e.g. peak runoff at an adequate accuracy. They relate the required time step to the catchment size and connected time of concentration as given in Figure 2.

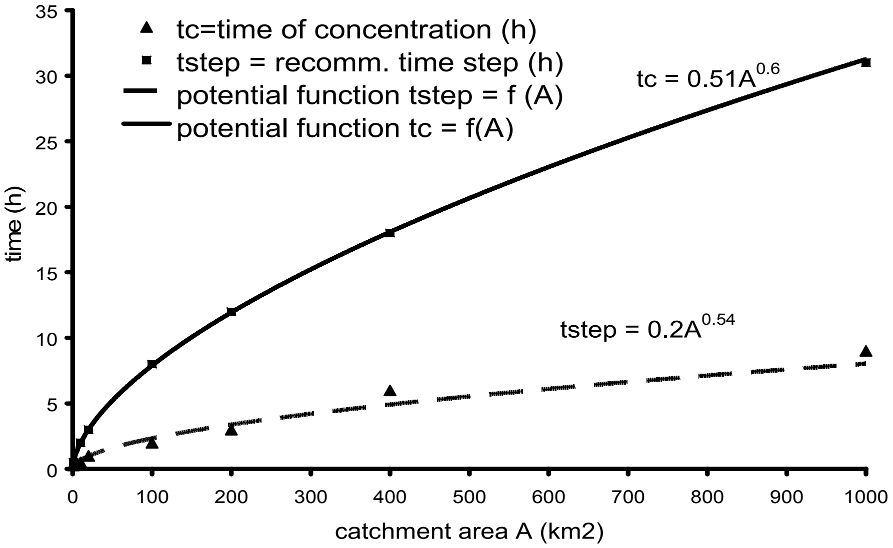

Figure 2: Estimated time of concentration and recommended temporal decomposition in relation to catchment area, Maniak (1997)

Thus, at least the same temporal resolution is required for the driving climatic data with emphasis on precipitation when floods are considered. While more and more high resolution information on precipitation becomes available, long term historic data often stem from digitised paper records and their time resolution is limited to 15 minutes, if at all. Consequently, time resolution below 15 minutes has been scarce in the past as long as rural hydrological models are concerned. Today this data is frequently digitally recorded at 1 minute time intervals. For hydrological catchment models this data is often aggregated to larger time intervals, mostly hours, but also down to 5 minutes. 5 minute data is used in this study for optimum parameter estimation.

For synthesis of extreme runoff peaks tables are often available with spatially highly resolved probability density functions (pdf) of rainfall intensity $i= f(\Delta t,T_n)$, where i is the intensity (mm/h), Δt (h) being the storm duration and T_n (a) the recurrence interval. In many countries these regionalised pdf's are used to drive hydrological models to derive design floods for practical purposes. It is clear that considerable error can occur and thus additional risk or costly overdesign, if the time-step dependency of parameters is not taken into consideration. Kandel et al (2005) address the problem of time dependent parameters, but still propose one parameter set for all recurrence intervals. However, other important facts are summarised concerning the relevant time scales for physical processes. It is correctly stated that the runoff production process, particularly infiltration excess runoff often occurs within minutes. Basically, it is common physical understanding that any deviation of the differential equation independant of its degree of linearity towards an averaged discrete solution is connected with a reduction of physical significance. In the field of hydrological modelling this has led to the definition of effective parameters, which are mostly spatially weighted averages of physical values when soil moisture modelling is applied for determining runoff formation. What is widely known, but hardly considered during model application is the fact that they are also temporally averaged values. As long as the relationships between time step and model parameters remain unknown it is impossible to use regionalised values based on different time steps as considerable over or under estimation of hydrological design variables such as peak flow and volumes will occur.

Following the ongoing discussion on time step dependency the authors re-evaluated some publications from the early eighties. At that time first near functional non linear relationships between hydrological model parameters and time step were identified, plausible explanations were given and practical approaches to solve the problem were proposed. Starting from this early analysis the intermediate discussion will be summarized.

Interestingly, by definition an early deterministic model explicitly contained parameters as a function of time step, which are the co-ordinates of the Unit Hydrograph (UH) first developed by Sherman (1932). Expressions like the 30 minute UH indicate this dependence. The definition of the instantaneous Unit hydrograph (for $\Delta t \rightarrow 0$) followed but did not solve the problem of time dependency as demonstrated by Littlewood (2008).

Ostrowski et al (1982) realised that parameters in deterministic physically oriented, but conceptual models changed significantly during multiple automatic parameter estimation for varying time intervals. After further investigation Ostrowski (1982) and Ostrowski & Wolf (1984) identified a systematic relationship between time step and soil moisture parameters. It became evident that vertical and lateral hydraulic conductivity as well as maximum infiltration at dry soil decreased non linearly with increasing time intervals. The search for an explanation led to the obvious evidence that averaging of rainfall intensities during the chosen time interval is partly responsible for this decrease. It also became clear that the use of averaged flow values for the parameter estimation process is another reason for time step dependency of parameters. The analysis was extended to snow melt models (temperature index method) and was confirmed by Ostrowski (1984). It was and still is, however, not clear, whether the change of parameters during the model inversion process is induced by the forward impact of averaged rainfall or the backward impact of averaged runoff.

Lutz (1984) derived empirical relationships for time dependent parameters of hydrological response functions and geographic characteristics of small catchments as well as for varying intensities of the design storms. The time step dependency is reflected by the definition of three empirical non linear relationships for 15, 30 and 60 minute time steps. The method has been successfully applied in Germany during the last two decades.

Winchell et al (1998) analysed the effect of spatial and temporal scaling on the production of infiltration- and saturation-excess overland flow. The rainfall intensity derived from radar measurements was averaged between 6 and 60 minutes. They use constant published soil parameters for all time steps. Model results show that saturation excess runoff is hardly dependent on time step variation, while infiltration excess shows decreasing volumes compared to assumed true volumes. The conclusions drawn, however, do not take into account potential impacts of constant parameters.

Cullmann et al (2006) also identify the high dependency of hydrological parameters on the time resolution. This was also observed by Haddeland et al (2006) for soil moisture simulation on a large spatial scale, but they argue that besides rainfall averaging the time step dependency is also strongly induced by the temporal resolution of potential evapotranspiration as a major driver for soil moisture. This is certainly highly relevant for longterm water balance simulation.

Lee et al (2007) observed that the use of a parameter estimated on the base of daily time steps created inaccuracies when applied with hourly time steps, and they stress the necessity for further investigations.

Recently, Merz et al (2009) comprehensively investigated temporal scale effects on parameters, but did not analyse time step dependency. The effect was eliminated by the consistent use of hourly rainfall data. However, they state that the length of records and the range of observed values defining process intensities influence the optimum parameter values significantly. They also found out that runoff formation parameters did not vary substantially which is in line with the use of a constant time step. Directly related to this field of modelling is the contribution by Littlewood and Croke (2008) and Littlewood (2008). The authors varied the simulation time step between 1 and 24 hours and identified close to functional relationships for all sensitive model parameters of the model IHACRES, which is using conceptual indices for surface runoff formation and baseflow retention without a direct physical translation.

Tang et al (2007) investigated different sensitivity analysis methods, also applying different time steps, 6, 12 and 24 h respectively to a North-American catchment using the well known Sacramento model (see Burnash (1995)). They conclude that the parameters estimated are highly dependent on the time step. They did not identify systematic relationships, although there are some indications of their existence at least for one sensitivity method applied. Finnerty et al (2009) also describe a strong relationship between sensitive parameters and time step for the same model.

Wang et al (2009) investigated the problem in more detail. They argue that spatial scale parameters with the dimension L should not be depending on the time step. They applied hourly and daily rainfall averages to the model and optimised parameters with a gradient search algorithm. The model performance of the aggregated hourly values was compared to the daily flows using the mean relative error (MRE) as an evaluation criterion; the higher resolution runs outperform daily rainfall simulations. Then they analysed multiple storm events at a still higher resolution of 10 min. Again the simulation at higher temporal resolution led to better results concerning MRE. Finally they analysed the time dependency of model parameters in relation to the probablity density function of precipitation. This analysis is closest to this research and will be discussed in detail later.

Hearman and Hinz (2007) analysed the effect of temporal resolution at the point scale for a combined infiltration/saturation excess soil moisture approach strongly based on a bucket overflow concept containing threshold soil parameters. As is stated the model cannot represent spatial saturation excess processes. However, they state that implications of their findings for larger spatial scales are uncertain. In general, however, it is not surprising that high resolution rainfall showing higher intensities tend to produce higher infiltration excess runoff.

Recently, IAHS has established a sub working group (TRUMPER, see IAHS (2007)). This working group is also engaged in the further identification of time step dependencies, also to find adequate solutions to the problem. So far, only a few contributions have been published related to this obvious sub problem of robust parameter estimation.

The observed problem of time step dependent parameter described above asks for a practical solution. Ostrowski & Wolf (1984), propose three potential solutions, tested for the continuous model NASIM first developed by Ostrowski (1982). This model has been applied for practical planning purposes on different spatial and temporal scales. At that time, computational effort was of much more concern than today, still the methods might be feasible and recommendable approaches also under present conditions. The approaches are related to the occurrence of high rainfall intensities and expected direct runoff. Method 1 establishes a non linear relationship between time step and effective rainfall intensity determined by pre-analysis of a sensitive HRU, method 2 uses a linear relationship and method 3 applies stepwise changing time steps. The approaches are summarised in Figure 3. Hughes (1993) gives an overview of approaches developed by other authors and finally proposes a method, which is similar to method 2 by Ostrowski and Wolf (1984). Other authors, however, state that the models need to be "recalibrated", when the time step is changed. This will not be required if we succeed to establish close relationships between time step and parameters as envisaged by TRUMPER and proposed in this paper.

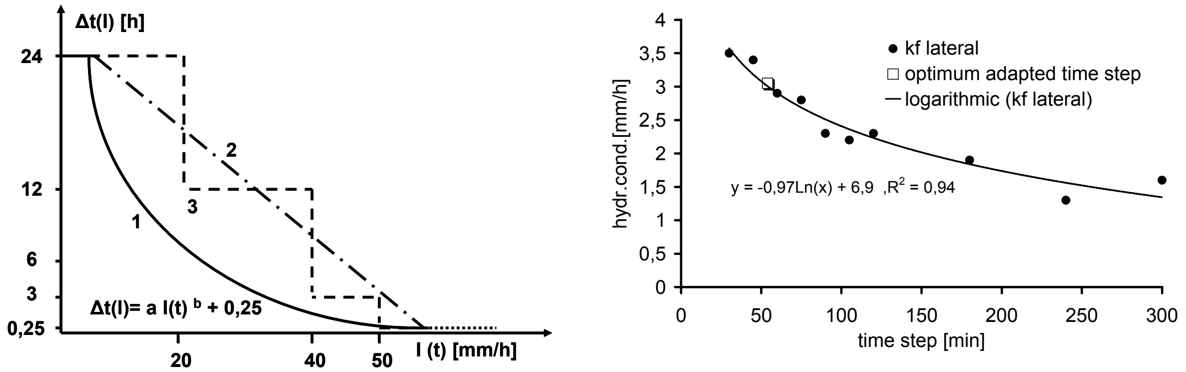

Figure 3: Coping with time step dependency (methods 1 to 3) and the effect of method 2 (from Ostrowski & Wolf (1984)) for lateral conductivity

It is obvious that the variable time step approach fulfilled its purpose. With the continuous increase of computer power such methods might not be necessary any more in daily engineering practice for medium sized catchments in the range of a few hundred km^2. For the application of highly distributed models to large catchments and real time forecasts they might still be an efficient option. However, it would be much more desirable to implement timestep dependency directly in the model.

Wang et al (2009) observed that the relationship between parameters P_1 and P_2 is inversely proportial to the division of time steps Δt_1 and Δt_2. ($P_2 = P_1 \surd (\Delta t_1 / \Delta t_2)$); they propose the use of a transferable functional relationship.

4 The analysis tools

The analysis was carried out with the modeling package BlueM which is a combination of simulation, optimisation and analysis support tools developed by the Institute of Engineering Hydrology and Water Management of Technische Universität Darmstadt. Essential parts of the package are public domain software. A description of the package is given by Bach et al (2010). The software can be accessed under ihwb (2009).

4.1 The modelling system

The modelling system is an assembly of tools for integrated river basin management containing also hydrologic simulation models. Within BlueM distributed models are used which are based on subcatchments, further split into hydrological response units (HRU). A layered non linear soil moisture model developed by Ostrowski (1991) is applied which will be explained in higher detail, as this is the key part of any hydrological model and will play a major role in this investigation.

The runoff formation module contains a larger set of parameters per HRU, which can be partly derived directly from digital land use and soil maps. In this study we concentrate on vertical surface and sub surface dynamics after accounting for interception processes based on leaf area index and canopy density parameters, which are not further considered here for simplification purposes, and on lateral flow accumulation subprocesses. The vertical soil moisture processes and the lateral accumulation of flow components and the parameters used are indicated in Figure 4.

The model uses the parameters given in Table 2. Many of them can be directly derived from digital maps. It must be stressed that the parameters are not considered as physically correct, but the best possible initial estimates of effective parameters.

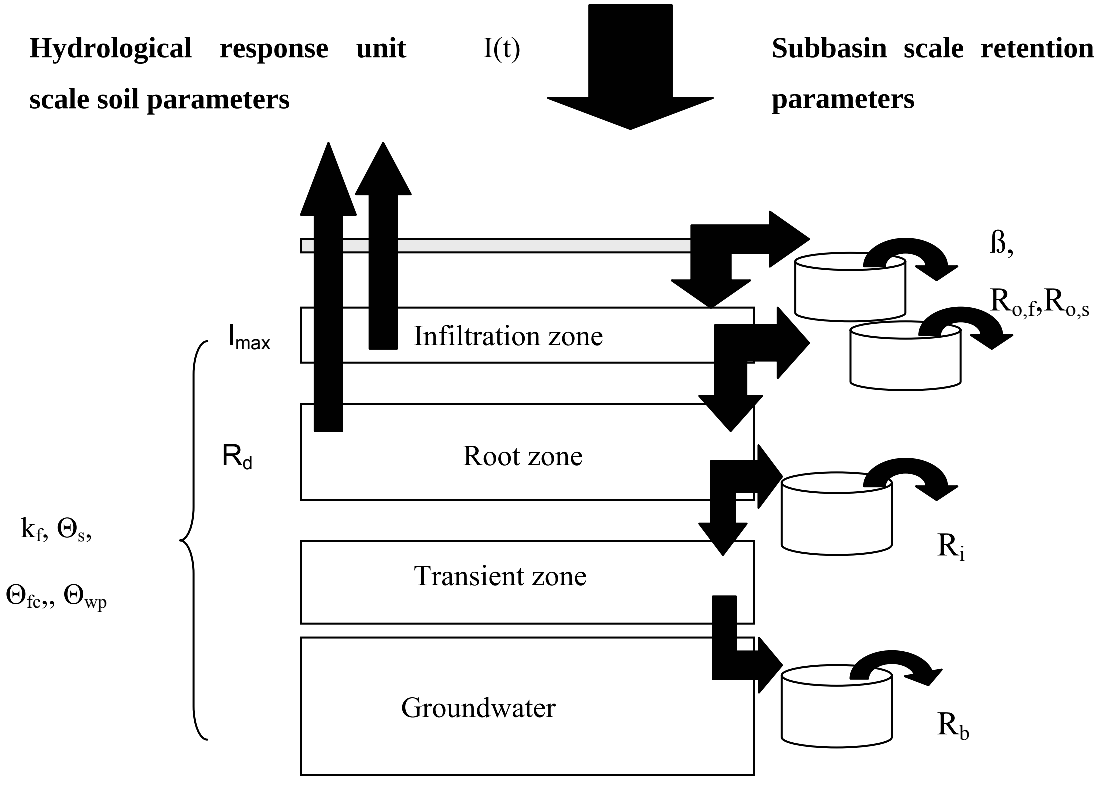

Figure 4: Model structure and related parameters

The number of parameters is far too high to be used for performing efficient parameter estimation. From many model applications and from literature, however, the range of plausibility limits of most parameters is fairly well known.

The soil moisture module is applied here as an infiltration excess approach. The lateral sub surface interflow components, however, are also computed in a nonlinear way according to the vertical percolation. Surcharge effects in layered soil are modelled.

Table 2: List of parameter values (parameters considered in this study bold)

Parameters at HRU-scale			
Parameter	Name	Unit	Range
Maximum infiltration	**i_{max}**	**mm/h**	**5-3000**
Rooting depth	R_d	m	0-2.5
Satur. hydr. conductivity	**K_f**	**mm/h**	**0.5-500**
Maximum soil moisture	Θ_s	mm/dm	38-52
Residual Soil moisture	Θ_r	mm/dm	0-10
Exponent van Genuchten	N	-	1.0-1.7
Soil moisture at wilting point	Θ_{wp}	mm/dm	3-31
Soil moisture at field capacity	Θ_{fc}	mm/dm	8-51
Parameters at sub catment scale			
Impervious area	A_{imp}	%	0-100
Retention constant urban	R_{imp}	h	0.1-0.5
Ratio fast/slow direct runoff	ß	-	0.3-0.7
Retention constant fast direct runoff	**$R_{o,f}$**	**h**	**0.2-2,0**
Retention constant slow direct runoff	**$R_{o,s}$**	**h**	**2-20**
Retention constant inter flow	**R_i**	**h**	**20-400**
Retention constant base flow	**R_b**	**h**	**200-5000**

It is known from experience that from the list the most sensitive parameters are vertical saturated hydraulic conductivity, maximum infiltration rates and direct, inter aswell as base flow retention constants. Those are the 6 parameters which will be considered in this study. The model structure thus is similar to the one used by Littlewood & Croke (2008) and Finnerty et al (2009). Initial conditions for soil moisture were optimised beforehand (90 % field capacity) and soil parameters and retention constants were assumed to be the same for all sub catchments in a river basin.

The unsaturated soil moisture layer between soil surface and saturated groundwater surface in each HRU is separated into 3 zones, the infiltration zone, the rooting zone and the transient zone. For each storage zone the mass balance equation is solved analytically using a piecewise linearized representation of empirical nonlinear relationships between vertical and lateral processes responsible for soil moisture changes according to an approach developed by Ostrowski (1991). In mathematical terms, eq. 1 describes the soil moisture changes e.g. in the infiltration zone (see Figure 5) , while eq. 2-5 define the considered processes.

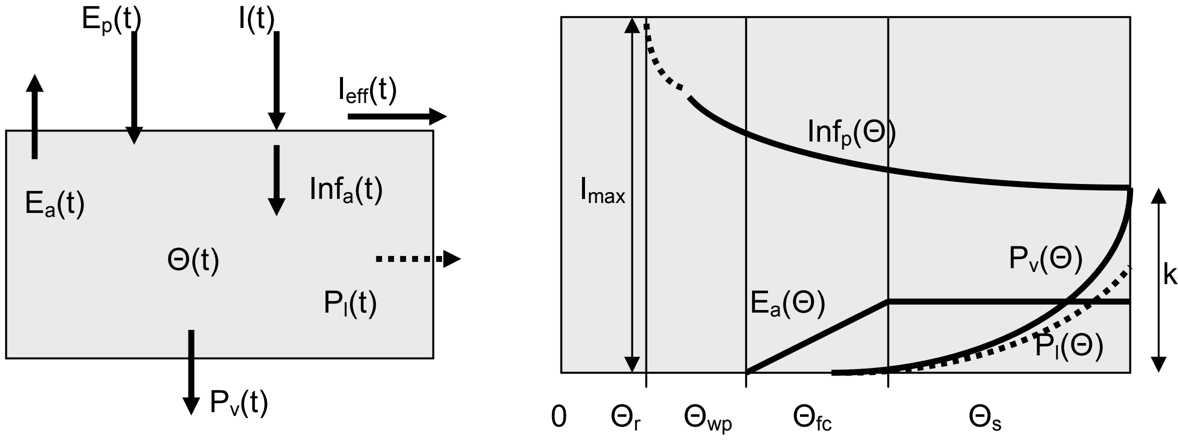

Figure 5: Mass balance and governing processes for the infiltration zone

$$\frac{d\Theta}{dt} = Inf_a(t) - P_v(t) - P_l(t) - E_a(t) \qquad \text{[mm/h]} \qquad (1)$$

$\frac{d\Theta}{dt}$ = change of soil moisture [mm/h]

$Inf_a(t) =$ actual infiltration [mm/h]

$Inf_a(t) = Inf_p(t)$ for $Inf_p > I(t)$ [mm/h]

$Inf_a(t) = I(t)$ for $I(t) < Inf_p(t)$ [mm/h]

$P_v(t) =$ vertical percolation [mm/h]

$P_l(t) =$ lateral percolation (near surface interflow) [mm/h]

$E_a\ (t) =$ actual evapotranspiration [mm/h]

Infiltration is defined according to Holtan's formula (see Holtan (1961)), the van Genuchten (1980) formula is used for vertical and lateral percolation, while a piecewise linear approach is used for actual evapotransiration. Mass balance equations are used for the rooting and transient zones accordingly.

$$Inf_p(t) = a_v(\Theta_s - \Theta)^{1,4} + k_f \qquad \text{[mm/h]} \qquad (2)$$

$$P_v\ (t) = k_f \cdot \left(\frac{\Theta - \Theta_r}{\Theta_s - \Theta_r}\right)^{1/2} \cdot \left[1 - \left(1 - \left(\frac{\Theta - \Theta_r}{\Theta_s - \Theta_r}\right)^{1/m}\right)^m\right]^2 \qquad \text{[mm/h]} \qquad (3)$$

$$P_l(t) = a * P_v(t), \text{ here a = 1} \qquad \text{[mm/h]} \qquad (4)$$

$$Ea\ (t) = Ep(t) \cdot \left(\frac{\Theta - \Theta_{wp}}{\Theta\ \ - \Theta_{wp}} \right) \quad \text{for} \quad \Theta \leq \Theta_{wp} \qquad [\text{mm/h}]] \qquad (5)$$

$$Ea\ (t) = Ep(t) \quad \text{for} \quad \Theta > \Theta_{wp} \qquad [\text{mm/h}] \qquad (6)$$

For this soil zone the following parameters must be estimated:
$a_v =$ vegetation index for infiltration [$1/h^{1/1.4}$]
a_v is determined via the maximum infiltration rate $\inf_m$
$k_f =$ vertical saturated hydraulic conductivity [mm/h]
$\Theta_s =$ soil moisture at saturation [mm/dm]
$\Theta_r =$ residual soil moisture [mm/dm]
$\Theta_{fc} =$ soil moisture at field capacity [mm/dm]
$\Theta_{wp} =$ soil moisture at wilting point [mm/dm]
$m =$ van Genuchten parameter 1/n [-]

The thickness of the infiltration layer is fixed to 0.2 m here for simplification purpose, the separation ratio between the two reservoirs describing fast direct runoff was set to ß=0.5.

Another set of parameters must be estimated for the rooting and the transient zones, respectively. The relevant processes for the rooting zone are actual evapotranspiration and vertical as well as lateral percolation, while for the transient zone only percolation to the groundwater zone is considered. Overall, for each HRU the parameter set consists of about 20 parameters for the three zones in a complete HRU column. It is obvious that these parameters can by no means be estimated individually. To come to an acceptable solution, further simplifying assumptions had to be made and the process functions must be pre-estimated to the best degree possible to account for relative differences among soil types, or at least soil textures.

The pre estimation of soil parameters is based on published parameters, which are available for the larger part of Germany provided by the soil assessment guidelines of Ad-hoc-Working Group Soil (2005) including the parameters of the Van Genuchten (1980) approach of unsaturated hydraulic conductivity. Ostrowski & Klawitter (2006) showed that such pre-estimated parameters can lead to reasonable soil moisture simulation results without calibration compared to longterm lysimeter data. Results for percolation, however were less acceptable. The hypothesis of physically plausible soil parameters is further strengthened by the results of this study. Such results might encourage to further follow the concept of physically based modelling as a possible important step towards the reduction of uncertainty in hydrological simulation results for ungaged river basins. Derived from soil maps the soil was classified as a sandy loam. Soil pore space parameters were set to $\theta_s = 420$, $\theta_r = 0$, $\theta_{wp} = 180$ and $\theta_{fc} = 330$ [mm/m] homogeneously for all three layers. Tabulated values of hydraulic conductivity range between 4 mm/h for highly compacted, 11 mm/h for normally compacted and 34 mm/h for less compacted soils (see Table 3)

Table 3: Soil parameters according to the German soil classification system

	Θ_r	Θ_s^*	n	kf_{12}	kf_3	kf_{45}	Θ_{fc12}	Θ_{fc3}	Θ_{fc45}	Θ_{wp12}	Θ_{wp3}	Θ_{wp45}	Θ_{12}	Θ_3	Θ_{45}
	%	%		mm/h	mm/h	mm/h	%	%	%	%	%	%	%	%	%
Ss	4.3	37.1	1.58	155.0	112.5	50.4	14	11	10	5	4	3	50	43	38
mS	0	38.1	1.37	281.3	204.2	104.2	14	10	8	5	4	3	50	42	36
mSgs	4.2	37.1	1.62	281.3	204.2	104.2	14	10	8	5	4	3	50	42	36
mSfs	4.8	38.5	1.64	170.8	125.0	83.3	16	14	12	6	5	4	50	45	37
fS	0.6	40.1	1.46	170.8	125.0	83.3	16	14	12	6	5	4	50	45	37
fSms	2.1	38.2	1.49	170.8	125.0	83.3	16	14	12	6	5	4	50	45	37
Sl2	0	38	1.26	55.8	32.1	17.9	28	25	23	8	7	6	51	43	38
Sl3	0	36.4	1.22	40.0	21.3	8.3	34	27	25	12	9	8	52	42	37
Sl4	0	33.9	1.18	43.3	15.8	7.1	36	30	26	14	12	11	54	42	38
Slu	0	38.6	1.23	24.2	10.0	4.2	38	33	30	15	12	11	52	43	40
St2	0	38.1	1.23	65.0	39.2	22.1	26	22	18	8	6	5	50	42	37
St3	3	36.8	1.14	53.8	20.4	8.8	35	30	26	17	15	14	53	44	39
Su2	5.1	38.2	1.44	65.4	35.8	19.2	26	23	21	6	5	4	50	44	38
Su3	0	36.3	1.28	34.6	16.7	5.8	35	29	26	10	8	6	52	43	39
Su4	0	37.4	1.28	25.0	10.8	2.9	39	32	28	12	9	7	53	43	40
Ls2	0	39.8	1.13	23.8	10.0	3.8	40	34	31	19	18	17	53	43	40
Ls3	0	35.6	1.12	34.2	11.3	4.2	39	33	30	18	17	16	54	42	39
Ls4	0	34.3	1.11	36.7	13.8	4.6	39	32	28	19	16	15	54	43	39
Lt2	0	41	1.10	18.8	7.5	3.3	42	36	32	24	22	21	53	43	41
Lt3	0	43.3	1.08	13.3	5.8	2.5	45	39	35	28	27	25	53	44	42
Lts	0	37.8	1.09	15.4	7.1	2.9	44	37	31	27	23	20	54	43	42
Lu	0	42.1	1.13	21.3	8.3	2.5	41	36	33	20	19	18	53	43	40
Uu	0	42.1	1.34	11.7	3.3	2.1	43	38	35	13	12	12	53	45	41
Uls	0	40.1	1.21	17.9	7.1	2.1	39	35	33	15	13	12	52	43	40
Us	0	41.7	1.25	14.2	4.2	1.7	41	35	32	13	10	10	52	44	39
Ut2	0	40.8	1.25	14.6	2.9	0.4	40	37	35	12	11	12	50	43	40
Ut3	0	40	1.23	15.8	4.2	1.7	39	37	35	13	12	12	50	43	40
Ut4	0	40	1.17	21.3	5.8	1.3	39	37	35	16	16	16	51	44	40
Tt	0	55	1.08	10.0	1.3	0.8	51	43	35	36	30	26	55	46	45
Tl	0.4	50.1	1.06	14.6	4.6	1.3	48	41	35	33	28	24	53	45	44
Tu2	0	48.7	1.09	9.2	2.9	1.3	47	42	36	31	30	26	52	46	45
Tu3	0	44.6	1.09	9.6	5.8	2.1	45	38	35	28	25	25	53	44	41
Tu4	0	42.1	1.11	18.3	7.1	2.1	41	37	35	22	20	19	51	43	40
Ts2	0	0		12.5	2.5	0.4	47	39	34	31	26	22	52	43	42
Ts3	0	0		28.3	6.3	3.3	45	37	32	29	24	21	52	43	42
Ts4	0	0		45.0	15.8	4.6	43	32	30	26	18	19	56	42	38

Abbreviations: S = Sand, L = Loam, U = Silt, T = clay, f = fine, m = middle, leading large character = major fraction, from left to right small characters indicate next fraction in descending order, numbers 2 = small fraction, 3 = mean fraction, 4 = high fraction. Values are given for average dry bulk density, values for sandy clay partly missing: Examples: Slu = silty loamy sand, Tu4 = highly loamy clay. Index 12: low compaction class, index 3: medium compaction class, index 45: high compaction class

The three vertically determined lateral flow components direct runoff on and near the soil surface, the inter flow components from the infiltration and root zone respectively and base flow are transformed via single (base and inter flow) or cascades of linear reservoirs to the receiving water. Flow transformation and retention within river reaches are simulated with non linear flood routing methods. All processes are simulated with a standardised piecewise linearised multiple input output module as given in Fig. 6, which is also used for the simulation of soil water processes.

In this subsystem I1 and I2 are dynamic forcing functions (precipitation and potential evapotranspiration), I3 is measured system output used for parameter estimation (discharge) and Q_i are nonlinear functions (infiltration, actual evapotranspiration and percolation) of actual system state, here a volume (soil moisture). The method is a special exponential Euler type integration approach developed by Ostrowski (1992) for the simulation of water resources systems. The use of a homogeneous modelling concept might possibly have a positive impact on the optimisation process.

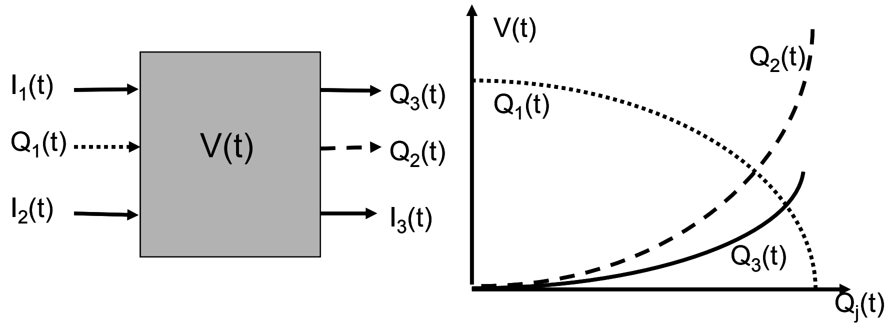

Fig. 6 Multiple analytical input/output module for simulation of arbitrary hydrological sub processes (Ostrowski (1992))

It should be emphasized that the soil moisture model is based on non linear differential equations, while lateral flow accumulation is based on linear differential equations.

4.2 The optimisation approach

The BlueM package contains a number of support modules for parameter analysis. Two of them were intensively used in this this study. The first one is the automatic sensitivity analysis. This analysis allows an easy assessment of the objective function response surface. The other one is one of the optimisation strategies implemented, in this case the Parametric Evolution Strategy (PES). This is a multicriteria strategie according to Rechenberg (1994) and

Schwefel (1995), as described and modified by Muschalla (2006). The algorithm proved to be highly efficient during multiple applications in different fields (see Muschalla (2008)). The optimum parameters used to establish the empirical functions are the arithmetic mean values of the five or less values on the pareto front closest to the origin (MRE, 1-NSC = zero).

5 Data base

The analysis was carried out with the data base of the experimental research basin Poellau, East Styria, Austria provided by Institute of Urban Water Management and Landscape Water Engineering, Graz University of Technology. The basin was described by Bergmann and Stubenvoll (1986) with special emphasis on precipitation measurement. The basin was equipped with large collection area tipping buckets recording 0.1 mm impulses. The river basin area is about 58 km^2, it contains 4 runoff gages, seven high resolution recording precipitation gages and one climate station providing temperature and other data for computation of potential evapotranspiration. The flow is disturbed by two flood control reservoirs. A digital soil map was available as well as a digital elevation map. The gages have been in operation since 1979. A sketch of the relevant system details is given in Fig. 7.

The catchment was divided into 13 subcatchments, further split into 48 hydrological response units. The average subcatchment size is 4.8 km^2, and 1.16 km^2 of the HRU's respectively. Sub catchments were connected by 19 stream reaches, the flood defense reservoirs and there operation rules were also simulated.

The runoff gages used for the analysis of time step dependency are located at transport elements S05 (Wildholzrechen-Praetisbach (WHR)) and S8 (Duerre Saifen (DS)). The two gages have about the same catchment area (19 km^2 and 22 km^2, respectively). It is assumed that effects resulting from spatial scale are similar for both gages. The other two gages were not used as they are affected by reservoir storage and operation.

The period simulated is a wet, multiple flood period from June 10 to August 31.

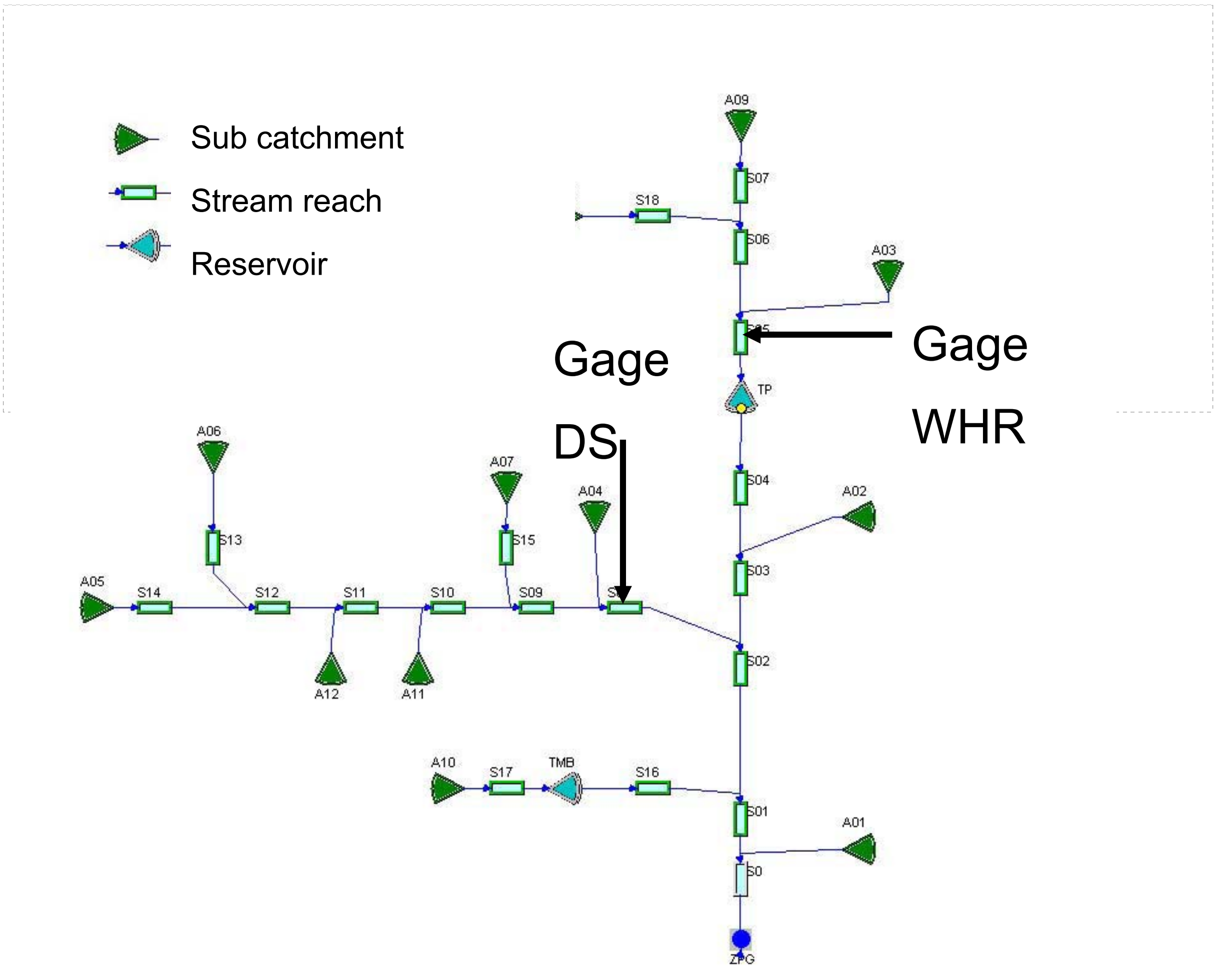

Fig. 7 Model diagram of the Poellau experimental river basin

6 Methodology

The basic approach is the optimum automatic parameter estimation for varying time discretisation Δt = 5, 10, 15, 30, 60, 120, 360, 720 and 1440 minutes, respectively. For this reason the underlying 5 minute precipitation and runoff measurements were averaged for increasing time intervals. The massive differences for small catchments are well known and demonstrated for a single event in one of the catchments investigated (DS) in Figure 8. The analysis is based on time discrete mean values of precipitation for driving the model and on average discharge for parameter estimation. This is of significance as the use of time continuous models and discharge data for parameter estimation will lead to rather different quantitative results and conclusions. Young & Romanowicz (2004) demonstrate that the use of a continuous form of the linear reservoir approach leads to time step independent parameters. However, it must be emphasized that in their case study they used effective rainfall as model input; thus the runoff formation process was not part of the analysis.

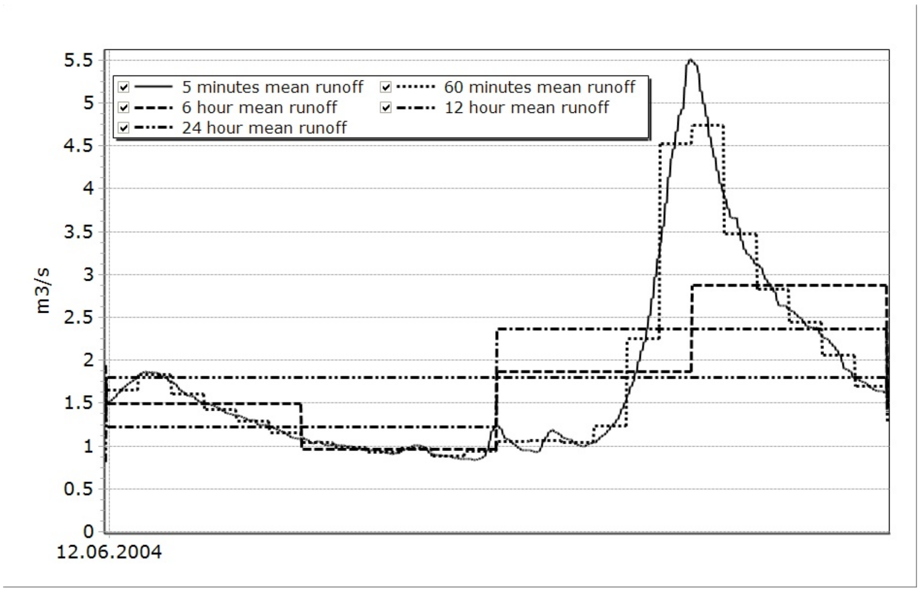

Figure 8 Mean discharge values for increasing time intervals for a 1-day period at gage DS

The discretised precipitation and runoff time series were further analysed for extreme values. Figure 9 and 10 show the results of this analysis. The close to functional relationship between time step (tstep) averaged maximum measured precipitation intensity i_{max} and average measured maximum flow Q_{max}, respectively is obvious. For maximum flows a natural logarithm function produced the best approximation of measured values, while for maximum rainfall intensities these were potential functions.

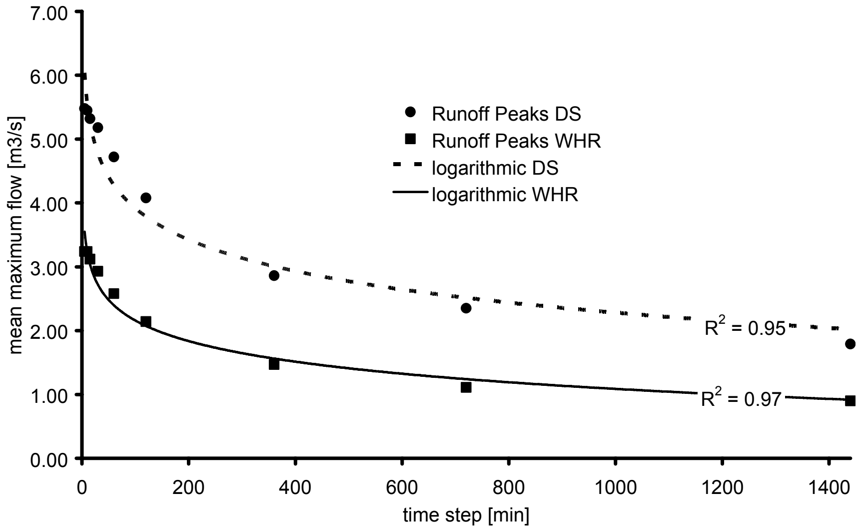

Figure 9 Non linear relationship between mean maximum measured flow $Q_{max}$and time step

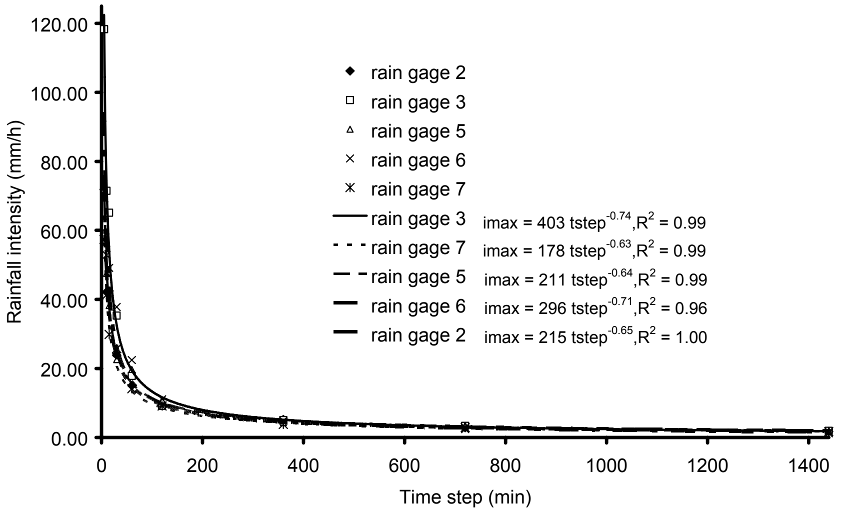

Fig. 10 Non linear relationship between mean maximum intensity i_{max} as a function of time step for five rainfall gages

The next step was the selection of suitable objective functions for the assessment of model performance under parameter variation. The generally known Nash- and Sutcliffe (1970) criterion (NSC) was chosen to assess the similarity of measured and computed flows, while the absolute mean relative error was selected for assessing mass balance deviations (MBE). Note that 1 –NSC was used to account for a minimisation problem.

A two-dimensional sensitivity analysis gives a good visual impression of the type of response function surfaces. It is common knowledge that smooth response surfaces facilitate efficient automatic optimum parameter estimation. Figure 11a and b show the results of an analysis of hydraulic conductivity versus maximum infiltration for the 1-NSC and MBE for a 15 minute time interval. It can be considered as a sensitivity analysis and a direct search at the same time. The example was chosen as it contains combined information on areas of high and low as well as lacking sensitivity. The diagram shows a smooth surface with hydraulic conductivity being more sensitive than maximum infiltration. The question arises, whether the response surfaces change in principal for a different time step. This is demonstrated by Figures 12a and 12 b for a 24 h time step. It must be stressed that this analysis was first carried out for the same plausibility limits as for 15 minutes, but then focussed for visibility reasons. Such diagrams principally leave open space for subjective interpretation and new hypotheses. What can be concluded in any case is that the smooth surface for small time steps becomes more irregular for larger time steps. While the 1-NSC diagram does not principally change as compared to the 15 minute analysis except for the minimum (3,3 to 0,7), the situation is different for MBE, where a second minimum is identified. As will be demonstrated later this is probably caused by an internal change of model structure.

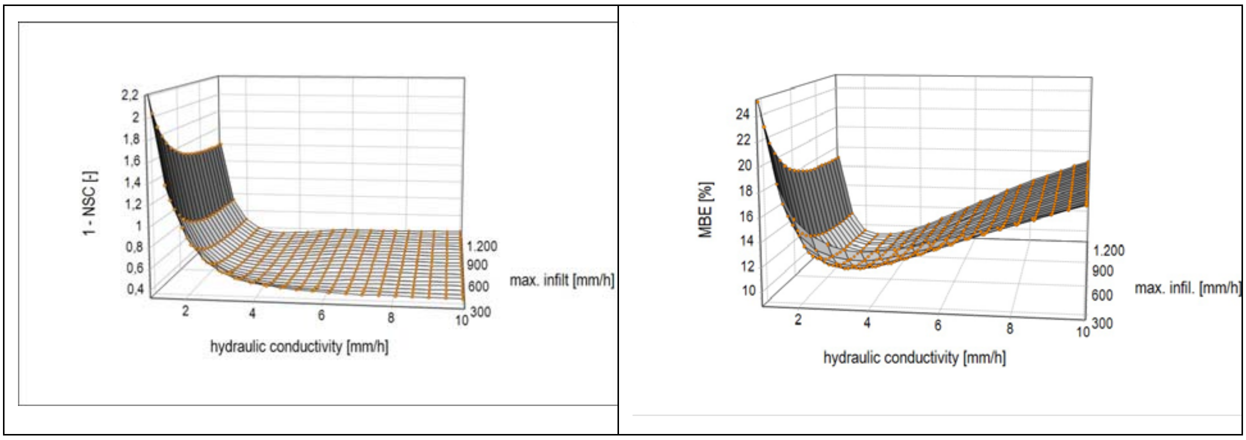

Figure 11a and b: Objective function Response surfaces for 1-NSC and MBE for hydraulic conductivity and maximum infiltration for a 15 minute time step

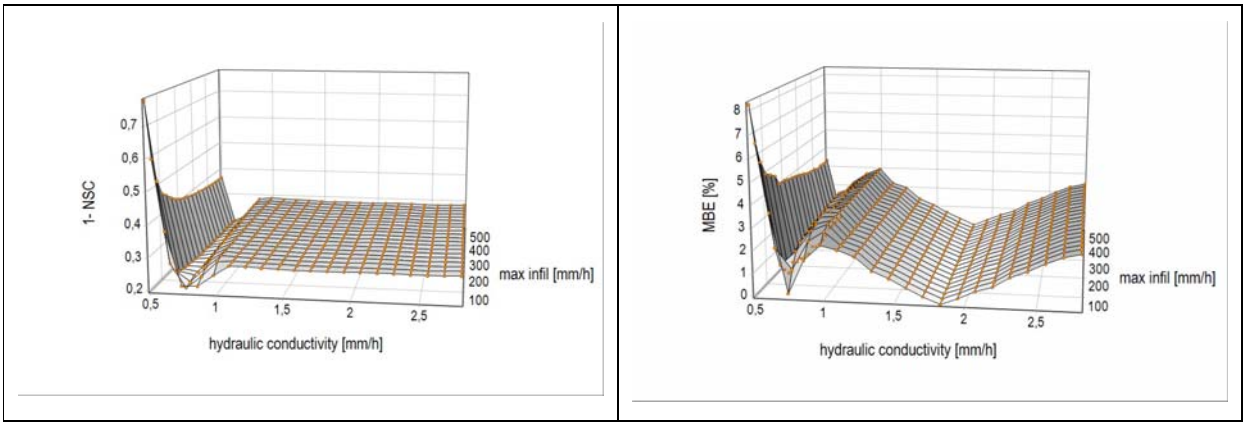

Figure 12 a and b: Objective function response surfaces for 1-NSC and MBE for hydraulic conductivity and maximum infiltration for 1- NSC and MBE for a 24 hour time step.

7 Results

The first analysis was aiming at the hypothesis by Wang et al (2009), that parameters non containing a time dimension should be independent from the time step. As can be seen from Fig. 13, this is only partially confirmed.

While for field capacity the hypothesis is confirmed, for wilting point and total pore volume some dependency is obvious, although moderate. Although the pore space parameters have the dimension L, they are part of the non linear equation to define unsaturated hydraulic conductivity, thus they are also slightly sensible against the time step.

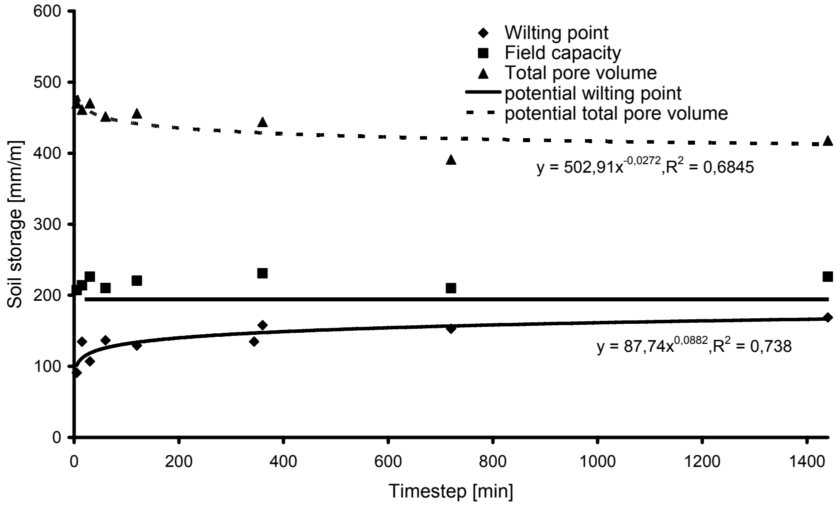

Figure 13 Pore space parameters as a function of the time step

The second analysis was concentrating on the question, which impact of temporal averaging is most responsible for the time step dependency of parameters. Is it the forward propagation of the model driver rainfall or is it rather the backward propagation of runoff as the base for parameter estimation? In Figure 14 the three time step dependent functions i_{max} (tstep), Q_{max}(tstep) and k_f(tstep) are shown. The non linear relationships are obvious. Both non linear regression functions for k_f show good correlation, R^2 of the logarithmic function is 0.9, R^2 and 0.81 for the potential function respectively. Hydraulic conductivity shows some inconsistency between $\Delta t = 60$ min and $\Delta t = 120$ min which will be discussed later. However, it would be mere guessing to decide for one of the function as the better one without further analysis of the computational mechanisms involved.

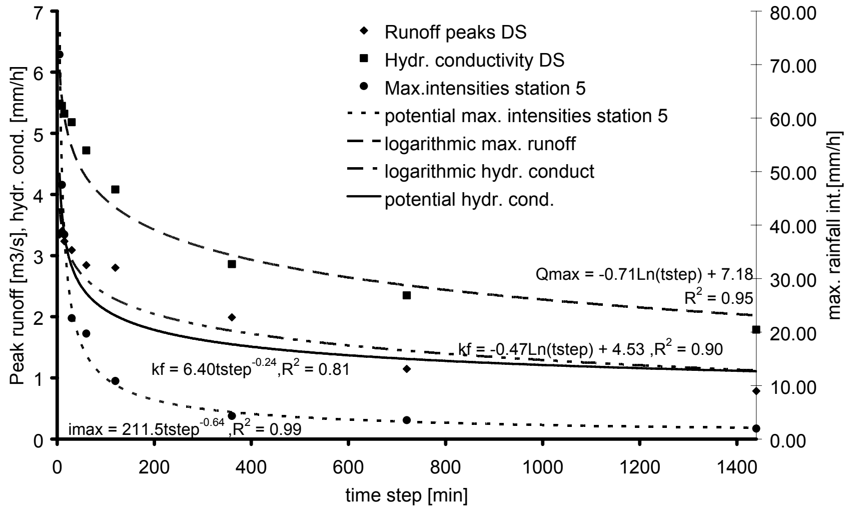

Figure 14: Non linear regression functions i_{max}(tstep), Q_{max} (tstep) and k_f (tstep)

Based on the optimisation runs for the DS catchment a short multiple peak flood period was then analysed. The simulation was performed with Δt = 60 min with formerly optimised parameters. The same parameters were then applied with Δt = 15 and Δt= 360 min resolution respectively to get a quantitative estimate for the impact of the inadequate use of the 60 min parameter. It is obvious from Figure 15 that the effective rainfall changes significantly. The parameters were then modified according to the functional relationships as indicated in Figure 14 for k_f.

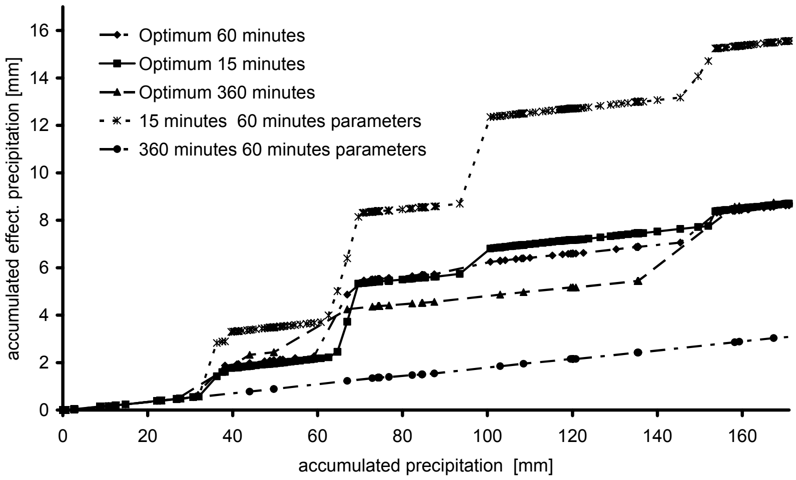

Figure 15: Double mass curves for total and effective rainfall for Δt= 15,60,360 min.

With these parameters MBE could be reduced to less than 1%. It is again interesting to see in Figure 15 that for Δt = 360 min one small direct runoff event is no more identified. Simply speaking, it got lost through averaging. The three different hydrographs are shown in Figure 16. It becomes obvious that not only the mass balance, but also peaks change significantly.

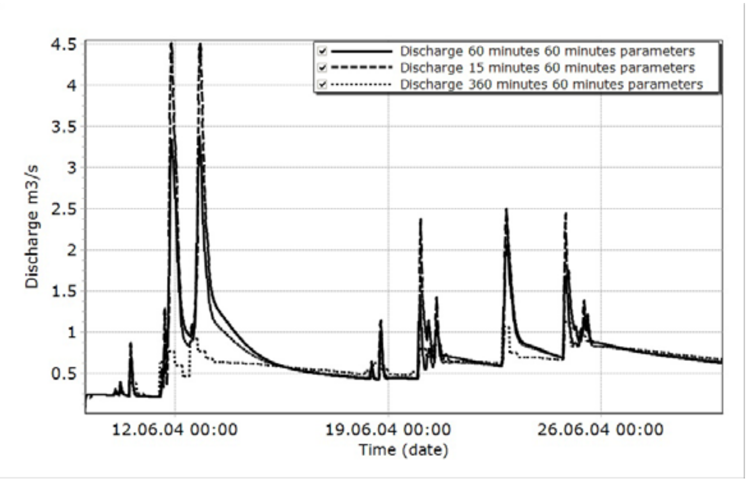

Figure 16 Comparison of runs with tstep 15 and 30 compared to 60 minutes with optimum parameters at gage DS

Finally the results of the time dependency functions for the six parameters are presented. In Figure 17 the two functions are shown for saturated hydraulic conductivity k_f.

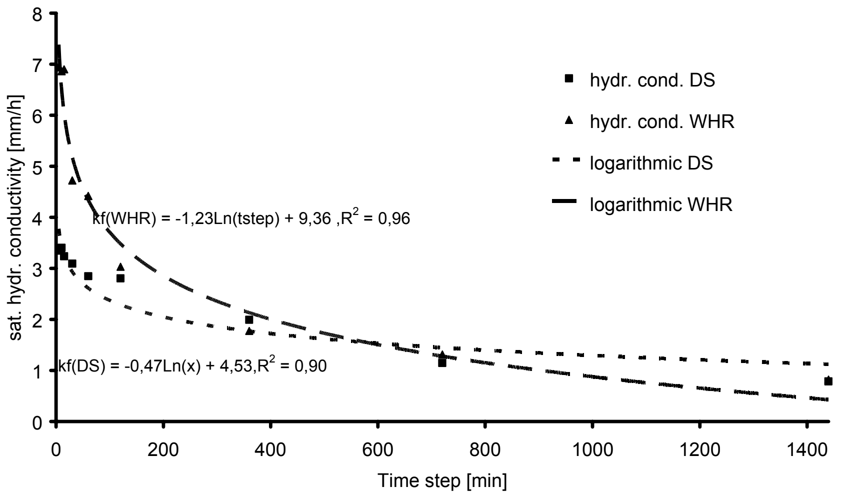

Figure 17: Optimum time step dependent hydraulic conductivity values k_f = f(tstep) for two basins

If we assume that the parameter values for a 1 minute time step might potentially be close to physical values, we get 9.36 mm/h for gage WHR and 4.53 mm/h as extrapolated values from the empirical function for gage DS. These values are close to the published values according to the German soil texture classification system. Although the coefficients of determination are high, one should note visually some sort of inconsistency between 60 and 360 minutes.

The time step depency function are also given for maximum infiltration Inf_m in Figure 18 for the two basins.

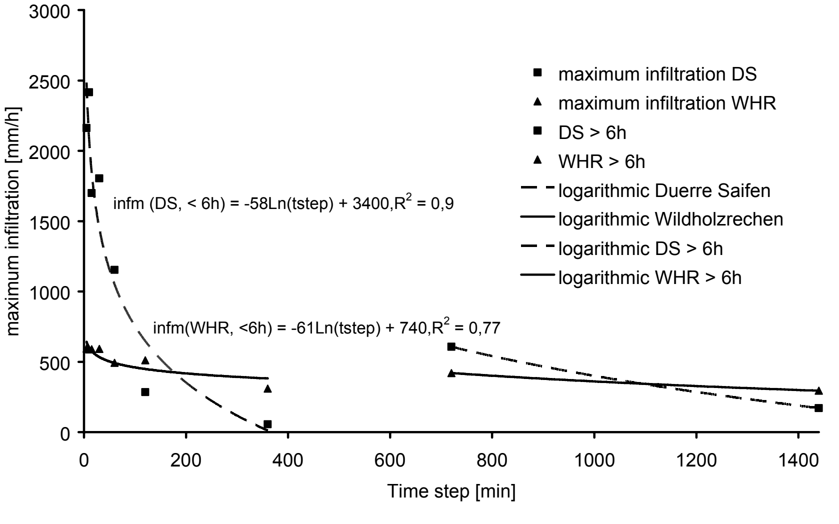

Figure 18: Maximum infiltration rates inf_m = f(tstep) for gages WHR and DS

It becomes again evident that there exists an inconsistency for the relationship between 360 and 720 minutes, in particular for the DS catchment. This might be related to the sensitivity analysis results in Figure 12 b where a second minimum for k_f was identified for MBE but not for 1-NSC.

The analysis results for the retention constants starts with direct runoff. In Figure 19 the retention constants are summarised. According to coefficients of determination they again follow acceptably well a logarithmic function with the exception of the fast constant for WHR which shows the only unsystematic behaviour in the total analysis, which cannot yet be interpreted.

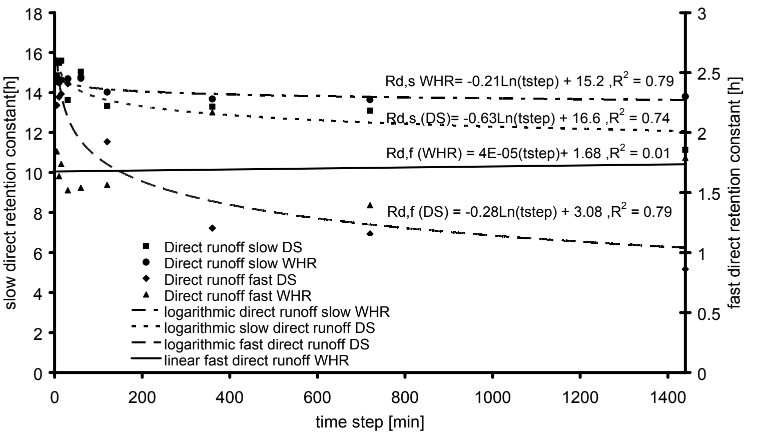

Figure 19 Fast and slow direct flow retention constants for DS and WHR

Furthermore, the retention constants for inter and base flow were analysed as given in Figure 20. While inter flow retention constants seem to be real constants independent of the time step, some linear relationships for base flow were found, however with less determination.

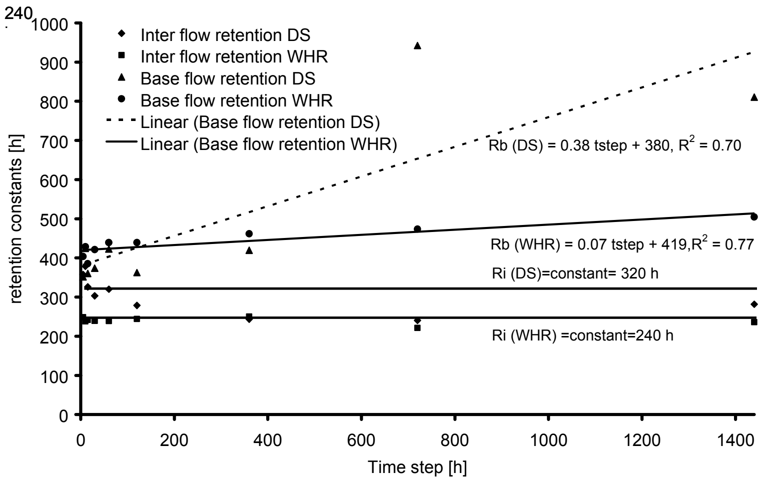

Figure 20: Inter and base flow retention constants for the DS and WHR gages.

Finally we looked at the 1-NSC and MBE as a function of time step. The results are given in Figure 21. It can be seen that the criteria improve for both criteria for increasing time steps.

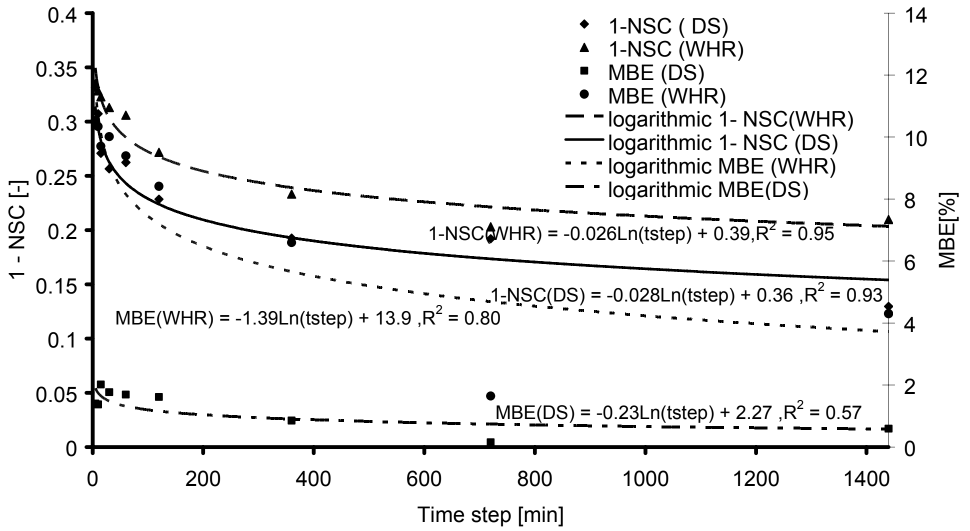

Figure 21 Evaluation criteria 1 –NSC and MBE als function of time step for gages DS and WHR

These results are not surprising as it becomes increasingly difficult to use conceptual abstraction of highly dynamic hydrological processes.

8 Discussion and conclusion

The results obtained led to partly very close non linear statistical relationships between hydrological parameters and the time step used for discretisation. This follows the results presented Ostrowski & Wolf (1984), Littlewood & Croke (2008) and Wang et al (2009). For Δt→0 (1min) the effective hydraulic conductivity as the dominant soil parameter is close to published values in both catchments. The results also show consistency for the two basins investigated concerning the type and coefficients of empirical parameter - time step relationships. These relationships are obviously related to the averaging of the driving climatological data and of measured flow data used for parameter estimation. In addition to the observation of such non linear and partly linear relationships the authors have presented reasons for their existence. It is logical that parameters having time in their dimension depend on the time step. If they have the same dimension as rainfall intensity, this dependency should be very strong. Wang et al identified a functional relationship between saturated hydraulic conductivity and time step of the form $k_f = k_f(t_0=1 \text{ min}) * \text{tstep}^{-0.5}$. To test their hypothesis, their function was compared with the results of this study. The results is shown in Figure 22.

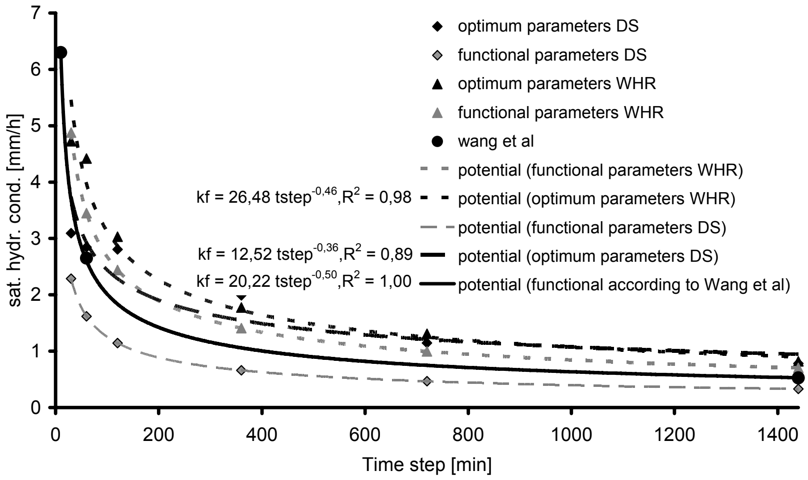

Figure 22: Timestep dependency functions fort he DS and WHR basins compared to the results of Wang et al (2009)

Their hypothesis can be confirmed at least partly. For the DS catchment the optimum function was is very close to the reciprocal square root function. For the WHR catchment, however, the power constant was – 0.35. Nevertheless, it might be very useful to further investigate the usefulness of timestep independent parameters.

However, it also became clear that despite significant empirical relationships the functions might contain inconsistencies in the range of 60 to 360 minutes. These inconsistencies seem to be caused by the internal identification of different model structures due to averaging of flow data. With the loss of information on the real dynamic behaviour of hydrological systems for increasing time steps and at the chosen spatial decomposition direct runoff can alternatively be interpreted as inter flow. This hypothesis needs further investigation, but is fostered by the conclusions of Finnerty et al (2009). In this context it should be noted that despite the small sample size which could be easily extended by looking at more models, catchments and time steps, it might be worthwhile to look at the results for small time steps separately in higher detail.

Concerning the question of physical significance it is concluded that parameters estimated with hydro-climatic data at high temporal resolution seem to be in the range of published values, still they remain spatially averaged effective parameters. With increasing time steps their physical significance further degenerates and changes to spatially and temporally averaged effective parameters.

The method applied can be easily applied to any other model and catchment provided the data is available at the required temporal resolution.

It is concluded that with this study the observation of several authors of time step dependent hydrological parameters are confirmed. In addition probable reasons for their existence were identified and presented. Possible approaches to solve the problem were indicated. The results might be a contribution to further reduce uncertainty in parameter estimation by the implementation of time step dependency functions in models for which they have been established and by improving the regionalisation of significant conceptual parameters such as effective hydraulic conductivity using historic parameter estimation results based on different time steps.

9 Acknowledgements

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