Hydrol. Earth Syst. Sci. Discuss., 9, 3607–3655, 2012
www.hydrol-earth-syst-sci-discuss.net/9/3607/2012/
doi:10.5194/hessd-9-3607-2012

Hydrology and Earth System Sciences Discussions

On the importance of appropriate rain-gauge catch correction for hydrological modelling at mid to high latitudes

S. Stisen, A. L. Højberg, L. Troldborg, J. C. Refsgaard, B. S. B. Christensen, M. Olsen, and H. J. Henriksen

Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, 1350 Copenhagen K, Denmark

Received: 2 March 2012 – Accepted: 8 March 2012 – Published: 16 March 2012

Correspondence to: S. Stisen (sst@geus.dk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

An existing rain gauge catch correction method addressing solid and liquid precipitation was applied both as monthly mean correction factors based on a 30 yr climatology (standard correction) and as daily correction factors based on daily observations of wind speed and temperature (dynamic correction). The two methods resulted in different winter precipitation rates for the period 1990–2010. The resulting precipitation data sets were evaluated through the comprehensive Danish National Water Resources model (DK-Model) revealing major differences in both model performance and optimized model parameter sets. Simulated stream discharge is improved significantly when introducing a dynamic precipitation correction, whereas the simulated hydraulic heads and multi-annual water balances performed similarly due to recalibration adjusting model parameters to compensate for input biases. The resulting optimized model parameters are much more physically plausible for the model based on dynamic correction of precipitation. A proxy-basin test where calibrated DK-Model parameters were transferred to another region without site specific calibration showed better performance for parameter values based on the dynamic correction. Similarly, the performances of the dynamic correction method were superior when considering two single years with a much dryer and a much wetter winter, respectively, as compared to the winters in the calibration period (differential split-sample tests). We conclude that dynamic precipitation correction should be carried out for studies requiring a sound dynamic description of hydrological processes and it is of particular importance when using hydrological models to make predictions for future climates when the snow/rain composition will differ from the past climate. This conclusion is expected to be applicable for mid to high latitudes especially in coastal climates where winter precipitation type (solid/liquid) fluctuate significantly causing climatological mean correction factors to be inadequate.

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

1 Introduction

Precipitation is inevitably a crucial variable in any water resources assessment. Without accurate measurements or estimates of precipitation, water balance studies and modelling becomes meaningless (Larson and Peck, 1974). Errors in spatial representation of precipitation can originate from too sparse rain gauge network or suboptimal location of gauges with respect to e.g. gradients and topography. For the individual rain gauge, however, systematic biases can be caused by catch deficiencies, mainly the wind-induced undercatch of solid precipitation (Adam and Lettenmaier, 2003). At mid to high latitudes (45–65°) systematic biases in solid (winter) precipitation will have a significant effect on the assessment of water balances at all temporal and spatial scales, even when biases are relatively small, because most groundwater recharge occurs in winter when evapotranspiration rates are low.

Detailed catch correction methods exists (Allerup et al., 1997; Goodison et al., 1998; Groisman and Legates, 1995) and they have been applied in several studies (Forland and Hanssen-Bauer, 2000; Fortin et al., 2008; Yang et al., 2005) revealing large differences between the correction of solid and liquid precipitation. Comprehensive studies of precipitation undercatch have been conducted at the global scale on gridded dataset of 0.5 to 2.5° based on mean monthly correction factors (Adam and Lettenmaier, 2003; Huffman et al., 1997; Legates, 1995). Other studies have examined the effect of catch correction on continental scale runoff using coarse modelling schemes (Adam et al., 2007; Berezovskaya et al., 2004; Fekete et al., 2004; Tian et al., 2007; Voisin et al., 2008). Few detailed water balance studies at the catchment to national scale are specific about the rain gauge catch correction method applied, see Bowling et al. (2003) and Stisen et al. (2011a) for exceptions. This is the case even for applications in regions where solid precipitation is significant and where precipitation biases can easily amount to 20–40 % during winter months. Unfortunately, the lacking focus on catch correction is probably mainly due to the fact that many hydrological models are evaluated against discharge data only and that model parameter optimization can compensate for precipitation biases and not because such biases are negligible.

The issue of appropriate rain gauge catch correction is especially relevant in transitional climates and seasons where both solid and liquid precipitation occur (Adam and Lettenmaier, 2003). These transitional climates are common at mid to high latitudes (45–65°) and in coastal climate zones where winter temperatures and thereby precipitation types vary considerably both from day to day and year to year. Under such conditions a standard climatology of mean monthly correction factors is not ideal for describing the bias caused by wind-induced undercatch of solid precipitation. Instead a dynamic rain gauge catch correction has to be applied taking into account the actual wind speed and precipitation type during each observation.

Evaluation of different precipitation data set and bias correction methods can be done through hydrological modelling. However this requires a physically based approach where both model performance and optimized parameters are considered. Ideally, the model should be evaluated against runoff, groundwater levels and actual evapotranspiration; however accurate actual evapotranspiration estimates are generally not available at a regional to national scale. Many simple rainfall runoff models will not be suitable for evaluating climate input biases since they are only constrained to stream discharge and typically contain parameters with little physical meaning.

The current study compares two different applications of the same catch corrections method (Allerup et al., 1997) to a national gridded rain gauge based dataset for Denmark: (i) standard correction (based on mean monthly correction factors 1961–1990) and (ii) dynamic correction (daily estimates based on current local wind speed and temperature). Subsequently, the national Danish water resources model, a comprehensive coupled surface-subsurface model, is calibrated separately with both precipitation dataset. Finally, the two correction methods are compared in terms of calibration and validation performances and evaluation of model parameters and state variables not included in the calibration. Precipitation correction has previously been evaluated in Denmark (Stisen et al., 2011b), however that study concerned a single catchment only, leaving a national assessment unresolved.

2 Rain gauge catch-correction

The Danish rain gauge network has up until 2010 consisted mainly of manual stations equipped with the Hellmann rain gauge. The placement of the gauge at 1.5 m above ground is the primary cause of wind-induced undercatch due to the turbulence around the opening of the gauge. Wetting losses and evaporation from the gauge contributes to the underestimation of precipitation, but by far the most important error source is the wind-induced undercatch, especially for solid precipitation.

This means that underestimation of precipitation is mainly a function of precipitation type, wind speed and shielding conditions (Larson and Peck, 1974). In 1972 a study on precipitation correction was initiated in Denmark, which resulted in a correction method for liquid precipitation (Allerup and Madsen, 1980). Based on a WMO initiative from 1985 (Goodison et al., 1998) "The Solid Precipitation Intercomparison Project" was carried out during the period 1987–1998. The project included several countries who established national and regional test fields equipped with the Double Fence International Reference (DFIR) for solid precipitation. The goal of the project was to determine systematic biases in measurements of solid precipitation, derive methods for correction of solid precipitation and to introduce a reference method for solid precipitation measurement. The Nordic test facility was established in Jokionen, Finland (1987–1993). Based on data from the Finnish test site, the correction method for liquid precipitation (Allerup and Madsen, 1980) was extended to include mixed and solid precipitation (Allerup et al., 1997). The elegancy of the method is its ability to handle all precipitation types in one expression through the unifying snow fraction parameter α.

$$\mathrm{CF}(\alpha) = \alpha \cdot \mathrm{CF}_{\mathrm{solid}}(V,T) + (1-\alpha)\cdot \mathrm{CF}_{\mathrm{liquid}}(V,I) \tag{1}$$

$\mathrm{CF}(\alpha)$ is the combined correction factor for any combination of solid and liquid precipitation. Correction for liquid precipitation is a function of wind speed and rainfall intensity while wind speed and temperature are used in the correction of solid precipitation.

$$\mathrm{CF}_{\mathrm{liquid}} = \exp\{0.007697 + 0.034331\lambda_{\mathrm{liquid}}u + (-0.00101\ln(I)) + (-0.012177\lambda_{\mathrm{liquid}}u\ln(I))\} \tag{2}$$

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

$$CF_{solid} = \exp\{0.04587 + 0.23677\lambda_{solid}u + 0.017979T + (-0.015407\lambda_{solid}uT)\} \quad (3)$$

Where CF is the correction factor (–), λ is the wind correction factor (–), u is the wind speed at reference height (ms^{-1}), I is rainfall intensity (–) and T is air temperature (°C). The empirical constants only apply to the unshielded Danish Hellmann rain gauge.

Since the method has not been validated at extreme wind speeds a threshold of $15\,ms^{-1}$ and $7\,ms^{-1}$ is applied for liquid and solid precipitation, respectively. In case of observed wind speeds above these values wind speed is set to the threshold value.

2.1 Standard mean monthly correction factors 1961–1990

The Allerup model is applied by the Danish Meteorological Institute (DMI) to calculate mean monthly standard correction factors for each 30 yr climatology period. The current correction factors are based on the period 1961–1990, and are national average factors for three shelter categories, A, B and C (Allerup et al., 1998). These factors are estimated using data from a relatively sparse network of 12 stations nationwide where all required input are available. As indicated above this includes wind speed, temperature, precipitation type and intensity during rainfall, and measured at the same location as the rain gauge. Until recently the Danish recommendations for hydrological applications were to use the mean monthly standard correction factors (Plauborg et al., 2002), either for individual rain gauges with known shelter category or applied to the national 10 km grid data set (Scharling, 1998) using the average shelter category B, as done in this study.

2.2 Dynamic correction factors

As an alternative to the mean monthly standard correction factors the Allerup model has been applied in a dynamic mode using daily wind speed and temperature data to estimate individual correction factors for each grid for each day. In order to perform such a rain gauge catch correction a number of simplifications have to be made since the required input for the correction model are not available at the optimal temporal and

HESSD
9, 3607–3655, 2012

spatial resolution. The correction applied here is performed on the national 10 km grid dataset, below the different simplifications are summarized.

- The corrections are estimated and applied to daily mean precipitation amounts not accounting for the actual conditions during precipitation.
- Precipitation intensity and wetting loss are assigned as mean monthly values (Vejen, 2005).
- Wind speed and temperature are mean daily values taken from the national 20 km grid (Scharling, 1999)
- Wind speed is downscaled to rain gauge measurement height assuming a logarithmic wind profile and a uniform surface roughness of 0.25 m.
- No consideration is made to actual station shelter conditions, average conditions are assumed resulting in $\lambda_{\text{liquid}} = 0.78$ and $\lambda_{\text{solid}} = 0.70$.
- Discrimination between liquid and solid precipitation is performed based on temperature. Liquid $> 2\,^{\circ}$C ($\alpha = 0$), solid $< 0\,^{\circ}$C ($\alpha = 1$), mixed precipitation between 0 and $2\,^{\circ}$C ($\alpha = 1 - 0.5T$).

Following these simplifications the dynamic correction is performed on each of the 609 grids for each day during 1990–2010. Similar simplifications have been applied by Vejen (2005) to a small island of Denmark and have previously been justified by Allerup et. al. (2000) where precipitation correction based on off-site weather information was investigated. They concluded that reliable corrections could be achieved if information from no longer than 50 km away from the rain gauge was used. In a recent study by Refsgaard et al. (2011), an attempt was made to evaluate the dynamic correction against the standard correction for a common reference period, although based on sparse data, this analysis indicated no sign of a systematic bias when applying the simplifications of the dynamic correction method.

HESSD
9, 3607–3655, 2012

2.3 Differences between standard and dynamic

The main advantage of the mean monthly standard correction factors is the ease of use, especially for operational large scale applications. Also they are assumed more robust as national average factors for the period they cover (1961–1990) since they are based on data that fulfil all assumptions of the Allerup model. However there are several limitations, such as the lack of spatial information, inability to differentiate warm and cold winters and short term variability in precipitation type. In addition, they are not particularly suited to applications outside the period 1961–1990, since even longer term climate trends are neglected. It is e.g. known that the winters in the recent period 1990–2010 have been significantly warmer than the reference period 1961–1990, resulting in fewer solid precipitation events and therefore lower correction factors (Refsgaard et al., 2011).

Figure 1 illustrates the spatial distribution of mean precipitation over Denmark for the period 1990–2010 when applying the standard and dynamic correction methods to the 10 km grid dataset. Even though the annual differences are relatively small, on the order of 3–6 %, the difference has a seasonal bias that changes the seasonal pattern of precipitation between summer and winter. As indicated in Fig. 1 (bottom) the difference between the two correction methods is almost exclusively found in the winter months (December, January and February), where differences of up to 14 % are found, whereas the annual differences are lower with maximum values of around 7 %. As expected the dynamic correction generally has lower precipitation amounts, due to the on average warmer winters of the period 1990–2010 compared to the period 1961–1990, resulting in lower winter correction factors.

3 The coupled surface-subsurface model

The groundwater-surface water modelling presented here, is based on the National Water Resources Model (the DK-model) developed at the Geological Survey of

HESSD
9, 3607–3655, 2012

Denmark and Greenland. The national model was initiated in 1996 and the first version was released in 2001 (Henriksen et al., 2003). During the period 2005–2009 the model went through a major update including a new enhanced interpretation of the national hydrogeological model based on new groundwater mapping data from geophysical mapping and subsequent modelling at smaller scale, providing local and regional geological model updates of the first DK- model geology (in a 100 × 100 m resolution for the geological model). In addition, the hydrological model resolution was reduced from 1000 m to 500 m, and the unsaturated zone module was dynamically coupled to both the irrigation module and the saturated zone modules (Højberg et al., 2012).

The national water resources model is split into seven regional models (Højberg et al., 2012) for reasons of computational efficiency. For the domains not consisting of islands (domain 4, 5 and 6, Fig. 2) the land phase boundary conditions are delineated from the topography. Of the seven model domains six are included in this study (Fig. 2), excluding the Island of Bornholm (590 km^2) in the Baltic Sea. The six model domains cover 42 087 km^2 or approximately 98 % of Denmark.

3.1 Model code

The MIKE SHE modelling system is the hydrological modelling tool of the National Water Resources Model. MIKE SHE is a physically-based, and distributed modelling system covering the entire land phase of the hydrological cycle (Abbott et al., 1986; Graham and Butts, 2005). This code was selected due the comprehensive description of groundwater surface water interactions and the ability to include various unsaturated zone and evapotranspiration formulations. The current model setup is based on a full 3-D finite difference groundwater module coupled with a simplified Two-Layer unsaturated zone module (Yan and Smith, 1994). The river routing is done using the MIKE 11 code, integrated into MIKE SHE, applying the kinematic routing method.

The MIKE SHE/MIKE 11 modelling system can be considered a coupled surface subsurface model. In contrast to the more sophisticated truly integrated models such as ParFlow (Kollet and Maxwell, 2006) and HydroGeoSphere (Therrien et al., 2005)

HESSD
9, 3607–3655, 2012

which solve the subsurface variably saturated equations by applying a 3-D Richards equation, MIKE SHE solves the saturated, unsaturated and river flow in separate modules that are coupled two-ways in every time step. The coupled models are computationally much more efficient, which enables comprehensive inverse modelling even for large model setups like the one applied in the current study.

3.2 Model input and climate forcing data

3.2.1 Climate data

Precipitation data are based on the daily national 10 km grid data set provided by the DMI. The precipitation has been corrected for undercatch according to the two methods described above, Standard and Dynamic. Regarding reference evapotranspiration (ET_{ref}) and temperature data, the daily 20 km national grid data set produced by the DMI is used. ET_{ref} is calculated using the Makkink equation adjusted for conditions in East Denmark (Scharling, 1999). According to current recommendations (Refsgaard et al., 2011), the ET_{ref} has been reduced to 95 % of the original values for West Denmark (Model domains 3, 4, 5 and 6, Fig. 2). This is done to compensate for a documented overestimation of the Makkink equation compares to the Penman-Montieth equation for West Denmark (Detlefsen and Plauborg, 2001). All meteorological time series are available for the period 1990–2010. As indicated in Fig. 3, precipitation in Denmark is fairly evenly distributed over the year. In contract, reference ET has a strong seasonal cycle with very low values in winter, resulting in a distinct seasonal pattern in groundwater recharge rates with low values in summer and high in winter.

3.2.2 Geological models and soil data

The geological model was developed during the recent update of the National Water Resources Model (Højberg et al., 2012) and can roughly be divided into two geographical regions. One covering the peninsula of Jylland (Model domains 4, 5 and 6 in Fig. 2)

HESSD
9, 3607–3655, 2012

and one covering the Islands of Fyn, Sjælland, Falster and Lolland in addition to some smaller Islands (Model domains 1, 2 and 3 in Fig. 2). The conceptual hydrogeological models for model domain 1, 2 and 3, includes a Quaternary sequence conceptualised as moraine clay with sand lenses embedded in three and four vertical levels for sub-model 3 and sub-models 1 and 2, respectively. Surface near geology was adopted from the Danish soil map (http://www.geus.dk) and assumed to represent the geology to a depth of three meter below the surface. The pre-Quaternary deposits are predominantly Danien limestone, but also include Paleocene marl with low permeability in sub-model 3 and the western part of sub-models 1 and 2 (Højbjerg et al., 2012). The geological model for Jylland (model domains 4, 5 and 6) consists of a pixel based geological model overlaid by a number of geological lenses. Five different hydro-facies are used to describe the subsurface. The Quaternary is divided into a binary system of sand and clay, whereas three pre-Quaternary units are used; quartz sand, Miocene mica sand and clay. The geological lenses correspond to the division of the computational layers used in the numerical groundwater model. Depending on the complexity of the regional geology, each model domain thus have different number of computational layers (Højberg et al., 2012).

Soil data, are distributed according to the Danish soil type classification consisting of 11 classes in three horizons (A–C). The classes named JB1–JB10 range from coarse sand to compact clay, while the last soil class JB11 represents organic soils. For each class and model domain average values for field capacity, wilting point and saturated water content are estimated from gridded soil property maps containing the soil physical attributes in 500 m resolution (Børgesen and Schaap, 2005; Greve et al., 2007). Since the two-layer unsaturated zone model in MIKE SHE only considers average root zone conditions soil physical properties from horizon B are used.

3.2.3 Land use and vegetation data

Land use is divided into the 21 classes listed in Table 1. Agricultural farmland is, in addition to the crop types, subdivided according to soil type. This is done because maximum rooting depth for agricultural crops, which is an important water balance parameter, is largely controlled by soil type. Forest is divided into deciduous and coniferous forests, with the first dominating in East Denmark and the latter in West Denmark. Remaining land cover types such as urban and sparsely vegetated areas are included but considered of minimal importance for the national water balance. All land cover types are assigned annual leaf areas index (LAI) and root depth (RD) cycles that are repeated every year implying that crop rotation is not considered. However, the distribution of each crop type is done in accordance with 2005 statistics for each regional county.

3.2.4 Sinks and sources

Within the coupled model a large number of abstractions and wastewater point sources are specified. In total 40 397 groundwater abstraction wells are included, 18 551 for domestic and industrial use and 21 846 for irrigation. The groundwater abstractions for domestic and industrial use are specified by their location and filter depth as well as their annual abstraction. For the irrigation wells an irrigation demand area surrounding each well is defined. The demand area prescribed for each well is a function of the density of wells and the fraction of land defined as agriculture within a buffer zone around each well. The actual irrigation amount is calculated internally in MIKE SHE from a demand function described by the root zone soil water deficit, and therefore varies according to climate, root depth and soil type. Since root depth is a calibration parameter affecting the total irrigation amount, the irrigation is simulated separately before the automatic calibration and applied as additional precipitation. Volumes corresponding to the irrigation amount are extracted from the irrigation well beneath the irrigated grid cell. The decoupled procedure insures that the irrigation applied is identical for all model simulations independent of precipitation correction method and model parameter combination. The domestic abstractions are treated as an external sink which is removed from the model calculations. However, most of this is captured in the 1120 waste water point sources. These external point sources are registered outlets

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
HESSD
9, 3607–3655, 2012
Rain-gauge catch correction for hydrological modelling
S. Stisen et al.

from wastewater treatment plants corrected for rainwater contribution and are specified as discharge into the stream system.

3.3 Calibration scheme

The calibration framework is built around the PEST optimization tool (Doherty, 2004), based on the Gauss-Marquardt-Levenberg local search method. PEST is a non-linear estimator commonly used for optimization of surface-groundwater models (Keating et al., 2003). The gradient based search methods are best suited for optimizations where the initial parameter set is relatively close to the optimal solution. This is assumed to be the case for the current version of the national water resources model, since it is a physically based model where parameters have a physical meaning and can be estimated by other means than calibration. In addition there is vast experience from previous calibrations of the national model forming a good background for defining sound initial parameter values (Henriksen et al., 2003, 2008)

The model is run for the period 1990–2007 while simulations are evaluated for a calibration period (2000–2003) and a validation period (2004–2007). This ensures a ten year warm up period which is regarded as appropriate for the modelled hydrological system, since initial conditions from the end of a previous model run are assigned. The winter precipitation (DJF), which mainly controls the discharge dynamics of individual years, is displayed in Fig. 4 for the calibration and validation periods. The figure reveals that the average winter precipitation is similar between the two periods, whereas the intra annual variability is largest in the validation period.

Five of the six model domains included in this study are calibrated separately but following the same calibration protocol. The geology in model domain 1 and 2 are comparable, and model domain 2 has not been subject to calibration, but used in a proxy-basin test where optimised parameters are transferred from model domain 1. A proxy-basin test can be used to test the robustness of the model conceptualisation. Where an acceptable performance of domain 2 will indicate a sound model concept.

HESSD
9, 3607–3655, 2012

3.3.1 Calibration parameters

The model parameters included in the calibration process are selected based on sensitivity analyses, combined with consideration to parameter correlation. The calibration is performed separately for the five model domains, and the parameters selected vary slightly between the models due to differences in the dominating hydrogeological elements. The overall parameter groups are however identical, and cover hydrological properties of the subsurface, stream-aquifer interactions, drainage and the available water content for evapotranspiration. The stream-aquifer interaction and the drainage are represented by a single controlling parameter each, namely the leakage coefficient (ms^{-1}) and the drainage time constant (s^{-1}). Based on a principle of parsimony, these two parameters are applied in a spatially uniform fashion. The available water content which is the main control for the simulated actual evapotranspiration for a given potential ET, is a combination of several model parameters, such as the water content at field capacity and wilting point, the root depth and the reduction function for plant water uptake at soil moisture contents below field capacity. The strategy for selecting the best optimization parameter for controlling the simulated actual evapotranspiration has been to identify a parameter with large uncertainty but a high degree of physical meaning and to fix the other controlling parameters at physically acceptable values centrally in their uncertainty span. Since soil physical properties are well described by distributed soil maps (Greve et al., 2007) these are fixed at their estimated values. The reduction of simulated evapotranspiration as a function of soil moisture content is controlled by a threshold value below which ET is reduced linearly with soil moisture reaching zero at the wilting point. The threshold is defined as a fraction of the field capacity indicating that full evapotranspiration occurs at moisture contents close to and above field capacity. Threshold values between 0.5 and 0.9 are physically realistic and consequently a value of 0.75 (Kristensen and Jensen, 1975) was selected after a sensitivity analysis indicating that this was a good value for average conditions. Similarly the crop coefficients, which multiplied with ET_{ref} generates the ET_{pot}, are also well defined with a relatively narrow acceptable range of uncertainty. Therefore fixed values typically between 1.05–1.15 for summer conditions are applied for most vegetation types (Plauborg et al., 2002). Thereby, the rooting depth is the only free parameter controlling the simulated actual evapotranspiration in the calibration, implying that some of the uncertainty associated with other model parameters may be transferred to the root depth.

Regarding the saturated zone parameters these are selected as the directional hydraulic conductivities of the main 4–5 hydrogeological units of each model domain. Generally, horizontal conductivities (K_h) are selected for calibration in the aquifer units, whereas the vertical conductivities (K_v) are selected for the aquitard units. The anisotropy factor (K_h/K_v) for the hydrological units is based on previous experiences in calibration of the national model and is generally 10, which is not subject to calibration. The specific yield and specific storage of each hydrogeological unit are not included in the calibration, because experience has shown that with only limited detailed time series of hydraulic head fluctuations physically realistic values of these parameters could not be obtained through automatic multi-objective calibration.

Typically, seven to eight free parameters are selected for each model domain, with several parameters tied to these free parameters. For the root depth, only the summer maximum root depth is subject to calibration because the winter root depth is very small for most land cover types and do not contribute to evapotranspiration because of the very low reference ET in winter. The maximum root depths for the 21 land use classes (Table 1) are all tied to a single root depth (arbitrarily chosen to be winter wheat for JB1). This means that based on the initial values in Table 1, the relation between all root depths are maintained through the calibration, and only one free root depth parameter is selected. The different parameter groups are listed in Table 2 along with their expected valid ranges. No parameter bounds have been put on any of the parameters during calibration based on the philosophy that in case unrealistic parameter values are estimated this is a valuable indication of conceptual model errors since only the most sensitive parameters are selected for calibration.

The initial model parameters are based on previous model optimizations except for the root depths in Table 1 which are based on Danish literature values (Refsgaard et al., 2011).

3.3.2 Objective functions

The model is designed for multiple purposes, which should reflect the calibration and validation process and the choice of objective functions (Højberg et al., 2012). Although the available calibration data are limited to stream discharge and hydraulic head observations a multi objective calibration is pursued in order to increase the constraint on the model and evaluate it for different purposes. This means that in addition to the Nash Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) mainly describing the discharge dynamics, both the overall water balance error (WBE) and the water balance error in the low flow summer months (WBE_{summer}) are included as separate objective functions, because both the total water budget and the summer minimum flows are important for water managers. In order to exploit the data fully and constrain the model in accordance with the main modelling purposes a set of objective functions are designed (Table 3). Observations of hydraulic head from wells are divided into three groups. One group is the monitoring wells where long detailed time series are available. These observations are used to formulate the objective function ME_{HTS}, which is the mean simulation error for all observations in a given well, computed at a daily time step for the calibration period. The second group contains the wells where infrequent observations are available for the calibration period. These observations are compared to the closest simulated monthly value and represented as the mean of errors for a given well ME_H. The last group is wells where recent historic observations are available outside the calibration period only. The mean of observations for each well for the period 1990–2000 is compared to the simulated mean head for the period 2000–2003 ($ME_{H_{mean}}$). This group of observations is included because they contribute to the spatial coverage of observations and because average hydraulic heads are not expected to change dramatically over time. Figure 5 shows the spatial distribution of

HESSD
9, 3607–3655, 2012

observations of discharge and hydraulic head; note that for model domain 1 only ME_H are used because $\mathrm{ME}_{H_{\mathrm{mean}}}$ did not contribute significantly to the number of observations and coverage. In addition to the ME's of the different groups of observation wells, the ME of each model layer ($\mathrm{ME}_{\mathrm{layer}}$ and $\mathrm{ME}_{\mathrm{layer\ mean}}$) is added to the objective functions. This is done in order to have some control of the model performance in different geological units.

Although different objective functions are included in the optimization, the models are still unconstrained with regard to important water balance components such as evapotranspiration. Problems related to missing constraint of other hydrological variables are not solved in the current study and will be difficult to address at the national scale. Instead an attempt is made to evaluate the physical realism of the optimized parameter set and the seasonal dynamics of recharge at a national scale. The ongoing HOBE project (Jensen and Illangasekare, 2011) investigates the issues of unconstrained models in more detailed studies including a wider range of observation data types, including flux stations, soil moisture networks and remote sensing data (Stisen et al., 2011a).

Weighting of multiple objective functions will in most cases become a somewhat subjective discipline, especially when observations vary in unit, number and uncertainty. The weighting in the calibration of the National Water Resources Model is done based on an initial model run after which each observation is assigned a group specific weight according to the relative weights in Table 3. This is necessary in order to guide the parameter optimization in the desired direction keeping the overall purpose of the model in mind. The weighting between discharge and head data is, following Table 3, 60 % on discharge and 40 % on hydraulic heads. In a recent paper, Stisen et al. (2011b), evaluated different weighting schemes and initial parameter values for a sub-model of the national model and found limited sensitivity to inter-group weighting primarily because honouring both discharge and head data does not necessarily conflict on optimal parameters. Likewise, different physically realistic initial values resulted in similar optimized parameter sets.

HESSD
9, 3607–3655, 2012

4 Results

4.1 Optimized parameters

Before evaluating the model performance on the specific objective functions the optimized parameter sets are evaluated. The optimized parameters across model domains are illustrated in Figs. 6 and 7 for the standard and dynamic correction methods, respectively. The resulting parameter values are quite similar for both methods and generally fall within the expected ranges in Table 2, except for the root depth for the standard correction method. For the hydraulic conductivities the difference in optimal parameter values for similar geological units is expected due to the spatial differences in geology. For the leakage coefficient, differences between model domains are also expected primarily due to scale issues attributed to the quite different topographical nature of the domains. In the outwash plains of Western Denmark the terrain slopes are gentler than in Eastern Denmark where the terrain was formed by ice during the last glaciation. The difference in topography will have an effect on the surface water – groundwater interaction when represented by a model based on a 500 m grid. The main difference between the parameters when the two different correction methods are applied is on the root depth, where the standard correction results in very large and physically unrealistic values in contrast to the dynamic method, which gives satisfying results. The reason for the large discrepancies between the two methods, according to our interpretation, has to be found in the precipitation input, since all other parameters are very similar. The standard corrected precipitation input has more winter precipitation than the dynamic, in the order of 10 % (Fig. 1 bottom). Combined with the very low reference ET values in Denmark in winter (Fig. 3), excess winter precipitation can only be lost through evapotranspiration during spring and summer. This forces the model to increase the root depth through calibration in order to increase spring and summer ET. For the dynamic correction, it is assumed that a better representation of winter precipitation results in a more balanced model, where the optimal parameter values are within a physical plausible range.

HESSD
9, 3607–3655, 2012

4.2 Performance on objective functions

The main model evaluation criteria are the objective functions utilized in the calibration. Among these the NSE is the criteria most influenced by seasonal changes in the precipitation dynamics as examined here through the comparison of two rain gauge catch correction methods. The NSE values for the standard and dynamic corrected models are illustrated in Fig. 8 for both the calibration and validation periods. The individual discharge stations (191 for calibration and 183 for validation) are sorted according to their performance and the result shows a clear improvement in model performance when using the dynamic correction method. This is especially the case for the validation period, although the validation results are generally worse than the calibration results. During calibration 51 % of the stations have NSE above 0.70 when standard correction is used compared to 71 % of the stations using the dynamic correction. For the validation period these numbers drop to 28 % and 46 % for the standard and dynamic methods, respectively.

The maps in Fig. 9 illustrate the spatial distribution of the NSE across the national model domains, revealing a systematically better performance in the southern parts of the country especially for the validation period almost all stations perform better using the dynamic correction.

Figure 10 shows a graph of the absolute WBE sorted according to performance. Also for the total water balance error the dynamic method yields better results, although only in the poorest performing 40–50 % of the stations, whereas the best 40–50 % performs similarly. For the standard corrected method 86 % of the stations have a WBE below 25 % during calibration whereas that is the case for 92 % of the stations when the models are calibrated on basis of the dynamic correction. During validation those numbers drop to 73 % for the standard model and 78 % for the dynamic.

In order to get an overview of the total water balance errors, only the most downstream station in each catchment has been selected to avoid redundancies in cases where one catchment has several gauging stations. The WBE for the 126 downstream

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

stations, covering approximately 55 % of the total model area, are illustrated in Fig. 11. The maps indicate very similar performance on WBE for the two precipitation correction methods for both calibration and validation periods. Even though the dynamic method performed better on WBE for the 50 % worst performing stations (Fig. 10), this seems not to be reflected in the overall water balance error because the large catchments generally perform well and outweigh the smaller catchments in the overall assessment.

The absolute water balance errors in the summer months (WBE_{summer}) are quite similar for both correction methods during both calibration and validation (Fig. 12), probably owing to the fact that the two precipitation inputs are almost identical for the summer months (Fig. 2) and that the summer discharge is largely groundwater feed.

The performances on hydraulic head levels, expressed through the RMSE for each computational model layer based on data from the calibration and validation periods, are shown in Fig. 13. This reveals a slight difference between the two correction methods in favour of the standard correction, although both perform very similar.

4.3 Alternative model evaluations

4.3.1 Proxy-basin test

The proxy basin approach applied to model domain 2 provides an additional validation of the robustness of the two correction methods. Since the model performance of model domain 2 will be highly dependant on the validity of the optimized parameter set for model domain 1. Figure 14 shows both NSE and absolute WBE for model domain 2 for the validation period (2004–2007). It is evident from the figure that stream flow dynamics and especially water balances are reproduced much better when the dynamic correction method has been applied; giving a clear indication that the parameter set obtained using this input is more robust.

4.3.2 Differential split sample test

As illustrated in Fig. 4, the validation period has an average winter precipitation rate similar to the calibration period. However, the validation period covers a much wider range of wet and dry years. Especially the winters of 2005/2006 and 2006/2007 represents dry and wet winters, respectively. Therefore an additional validation test has been performed separately for two sub-periods, namely the hydrological years 2005/2006 and 2006/2007. This test can be thought of as a simple differential split sample test (Klemes, 1986; Seibert, 2003) where the model is calibrated to one particular climate condition and validated for both drier and wetter conditions. Such tests are extremely valuable when hydrological models are calibrated for the current/historical climate and subsequently used to asses the impact on future climate conditions. The differential split sample test, shown in Figs. 15 and 16, gives another clear indication of the superior performance of the dynamic correction, since models based on this correction perform significantly better for both drier and wetter than for average conditions. It is especially interesting, that whereas the WBE for the entire validation period did not deviate significantly between the two models, the dynamic model clearly outperforms the standard model for both dry and wet conditions separately. This again speaks in favour of the dynamic model in terms of both dynamics of the precipitation input and the robustness of the optimized parameter set.

4.3.3 Optimized parameters and recharge dynamics

As expressed above the large difference in optimized root depth is expected to be caused by the imbalance between summer and winter ET dynamics combined with a winter precipitation bias in the standard corrected precipitation. Whereas Figs. 6 and 7 gave the results of optimized root depth values for winter wheat on soil type JB1, Fig. 17 illustrates the effective summer maximum root depth for each model domain. Since the root depth varies according to vegetation and soil type (Table 1), the effective average root depth will depend on the fractions of land use and soil types within each

HESSD
9, 3607–3655, 2012

domain. Figure 17 reveals an even larger difference between the models than Figs. 6 and 7, and a large spread between model domains for the standard model. Apart from being physically unrealistic, the very large root depths of the models based on standard correction of the precipitation have an effect on model variables not included in the objective functions. An example is seen in Fig. 18, where the simulated average monthly groundwater recharge for all model grids is shown for the two correction methods. Whereas the dynamic method shows a reasonable seasonal pattern comparable to the overall climate dynamics (Fig. 3), the standard correction has an unexpected seasonal recharge pattern with a net uptake in April and May compensated by a large release in July. This pattern is caused by the unrealistically large root depth which allows the model to extract large volumes of water for transpiration during April and May, which is then replenished during July when the root depths for agricultural land are reduced. From a climate input point of view (Fig. 3) there is nothing in support of recharge rates being higher in July than in August and September.

5 Concluding remarks

Appropriate rain gauge catch correction should be considered before undertaking detailed water balance studies, since even relatively small systematic biases in precipitation can have major implications on other hydrological fluxes such as evapotranspiration or recharge. In transitional climates with frequent variations in precipitation type both from day-to-day and between years, dynamic rain gauge catch correction is particularly important. This is especially the case when transient hydrological model calibration is carried out, since optimal model parameters can vary considerably depending on seasonality and variability of precipitation input.

The model results in the current study have demonstrated that a significantly better performance could be achieved on simulated stream discharge dynamics (NSE) when applying a dynamic precipitation correction. Results on multi-annual water balances were also in favour of the dynamic correction although less conclusive, mainly due to

HESSD
9, 3607–3655, 2012

the fact that models based on both methods can be calibrated to perform well for average conditions. Our study highlights the importance of unbiased precipitation data, especially when rigorous optimization is performed, because depending on the objective functions used, biases can be compensated for by tuning model parameters. This can be extremely problematic when the hydrological model is subsequently used for climate change impact assessment, because the compensating effect of the tuned model parameters will not hold true under future and different climate conditions. Therefore differential split sample testing can give additional insight into the reliability of the model under different climate conditions. Our differential split sample test revealed a significantly better performance of the model based on dynamically corrected precipitation for both drier and wetter than average years, demonstrating the superior robustness of the dynamic correction.

Regarding optimized parameter values, calibration of models based on standard corrected precipitation resulted in very unrealistic root depth values, caused by the need to compensate for a winter precipitation bias. Although the groundwater recharge rates in Fig. 18 cannot be compared directly to observations, the differences in seasonal pattern between the two models add to the conclusion that the parameterization of the dynamic model is favourable.

We believe the conclusions made here are general for mid to high latitudes, especially in coastal climates where precipitation corrections based on standard 30-yr climatologies are not suitable for detailed water balance assessments.

The interesting question remaining is whether appropriate rain gauge catch corrections are generally applied in hydrological modelling studies. Going through the literature, we have found very few examples where modellers are specific about the precipitation correction applied. This is somewhat disturbing since meteorological institutions traditionally always supply uncorrected precipitation data to users. Wagner (2009) conducted a recent survey and questionnaire among 24 research institutions across Europe, regarding common practices on the correction of precipitation in forest hydrology. The survey revealed very limited consideration to detailed precipitation correction. Of the 24 institutions, 19 reported to do no precipitation correction, of the remaining nine, three did gap filling only and only one was specific about the applied correction method.

Based on the current study, the Danish Meteorological Institute is currently preparing a new dynamically corrected gridded precipitation dataset based on spatial interpolation of rain gauges after individual dynamic correction and accounting for local shelter conditions. This will have a major impact on future water resources management in Denmark, including estimates of nitrate and pesticide leaching, climate impact assessment and implementation of the EU Water Framework Directive.

Acknowledgements. The Danish Meteorological Institute (DMI) is acknowledged for providing climate data and Flemming Vejen and Claus kern-Hansen, DMI for contributing with knowledge on the assumptions behind the precipitation correction methods in Allerup et al. (1997). The Danish Nature Agency, Ministry of Environment and the Ministry of Climate and Energy have supported the study financially. Jens Asger Andersen, Dirk-Ingmar Müller Wohlfeil, Clea Schneider and Stefán Meulengracht Sørensen, the Danish Nature Agency and Christen Duus Børgesen and Gitte Blicher-Mathiesen, Aarhus University have contributed with constructive discussions during the study.

References

Abbott, M. B., Bathurst, J. C., Cunge, J. A., Oconnell, P. E., and Rasmussen, J.: An introduction to the european hydrological system – systeme hydrologique europeen, she. 2. Structure of a physically-based, distributed modeling system, J. Hydrol., 87, 61–77, 1986.

Adam, J. C. and Lettenmaier, D. P.: Adjustment of global gridded precipitation for systematic bias, J. Geophys. Res.-Atmos., 108, 4257, doi:10.1029/2002JD002499, 2003.

Adam, J. C., Haddeland, I., Su, F., and Lettenmaier, D. P.: Simulation of reservoir influences on annual and seasonal streamflow changes for the Lena, Yenisei, and Ob' rivers, J. Geophys. Res.-Atmos., 112, D24114, doi:10.1029/2007JD008525, 2007.

Allerup, P. and Madsen, H.: Accuracy of point precipitation measurements, Nord. Hydrol., 11, 57–70, 1980.

Allerup, P., Madsen, H., and Vejen, F.: A comprehensive model for correcting point precipitation, Nordic Hydrol., 28, 1–20, 1997.

HESSD

9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

Allerup, P., Madsen, H., and Vejen, F.: Standard values for precipitation correction (1961–1990), Technical report 98–10, Danish Meteorological Institute, 1998 (in Danish).
Allerup, P., Madsen, H., and Vejen, F.: Correction of precipitation based on off-site weather information, Atmos. Res., 53, 231–250, 2000.
Berezovskaya, S., Yang, D. Q., and Kane, D. L.: Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds, Geophys. Res. Lett., 31, L21502, doi:10.1029/2004GL021277, 2004.
Børgesen, C. D. and Schaap, M. G.: Point and parameter pedotransfer functions for water retention predictions for Danish soils, Geoderma, 127, 154–167, 2005.
Bowling, L. C., Lettenmaier, D. P., Nijssen, B., Graham, L. P., Clark, D. B., El Maayar, M., Essery, R., Goers, S., Gusev, Y. M., Habets, F., van den Hurk, B., Jin, J. M., Kahan, D., Lohmann, D., Ma, X. Y., Mahanama, S., Mocko, D., Nasonova, O., Niu, G. Y., Samuelsson, P., Shmakin, A. B., Takata, K., Verseghy, D., Viterbo, P., Xia, Y. L., Xue, Y. K., and Yang, Z. L.: Simulation of high-latitude hydrological processes in the Torne-Kalix basin: PILPS phase 2(e) – 1: Experiment description and summary intercomparisons, Global Planet. Change, 38, 1–30, 2003.
Detlefsen, N. and Plauborg, F.: Reevaluation of methods for calculating reference evapotranspiration – potential evapotranspiration), The Danish Institute of Agricultural Sciences, Foulum, Denmark, 2001 (in Danish).
Doherty, J.: PEST: Model-Independent Parameter Estimation, Watermark Numerical Computing, Brisbane, 2004.
Fekete, B. M., Vorosmarty, C. J., Roads, J. O., and Willmott, C. J.: Uncertainties in precipitation and their impacts on runoff estimates, J. Climate, 17, 294–304, 2004.
Forland, E. J. and Hanssen-Bauer, I.: Increased precipitation in the Norwegian Arctic: true or false?, Clim. Change, 46, 485–509, 2000.
Fortin, V., Therrien, C., and Anctil, F.: Correcting wind-induced bias in solid precipitation measurements in case of limited and uncertain data, Hydrol. Process., 22, 3393–3402, 2008.
Goodison, B. E., Louie, P. Y. T., and Yang, D.: WMO solid precipitation measurement intercomparison, WMO/TD 872, World Meteorological Organization, Geneva, 1998.
Graham, D. N. and Butts, M. B.: Flexible, integrated watershed modelling with MIKE SHE, in: Watershed Models, edited by: Singh, V. P. and Frevert, D. K., Taylor and Francis, Boca Raton, 245–272, 2005.
Greve, M. H., Greve, M. B., Bocher, P. K., Balstrom, T., Breuning-Madsen, H., and Krogh, L.:

Generating a Danish raster-based topsoil property map combining choropleth maps and point information, Geogr. Tidsskr., 107, 1–12, 2007.
Groisman, P. Y. and Legates, D. R.: Documenting and detecting long-term precipitation trends: Where we are and what should be done, Clim. Change, 31, 601–622, 1995.
Henriksen, H. J., Troldborg, L., Nyegaard, P., Sonnenborg, T. O., Refsgaard, J. C., and Madsen, B.: Methodology for construction, calibration and validation of a national hydrological model for Denmark, J. Hydrol., 280, 52–71, 2003.
Henriksen, H. J., Troldborg, L., Højberg, A. L., and Refsgaard, J. C.: Assessment of exploitable groundwater resources of Denmark by use of ensemble resource indicators and a numerical groundwater-surface water model, J. Hydrol., 348, 224–240, 2008.
Højberg, A. L., Troldborg, L., Stisen, S., Christensen, B. S. B., and Henriksen, H. J.: Maintenance of a national water resources model as a participatory modelling task, Environ. Model. Softw., submitted, 2012.
Huffman, G. J., Adler, R. F., Arkin, P., Chang, A., Ferraro, R., Gruber, A., Janowiak, J., Mcnab, A., Rudolf, B., and Schneider, U.: The Global Precipitation Climatology Project (GPCP) combined precipitation dataset, B. Am. Meteorol. Soc., 78, 5–20, 1997.
Jensen, K. H. and Illangasekare, T. H.: HOBE: a hydrological observatory, Vadose Zone J., 10, 1–7, 2011.
Keating, E. H., Vesselinov, V. V., Kwicklis, E., and Lu, Z. M.: Coupling basin- and site-scale inverse models of the Espanola aquifer, Ground Water, 41, 200–211, 2003.
Klemes, V.: Operational testing of hydrological simulation-models, Hydrolog. Sci. J., 31, 13–24, 1986.
Kollet, S. J. and Maxwell, R. M.: Integrated surface-groundwater flow modeling: a free-surface overland flow boundary condition in a parallel groundwater flow model, Adv. Water Resour., 29, 945–958, 2006.
Kristensen, K. J. and Jensen, S. E.: A model for estimation the actual evapotranspiration from the potential one, Nord. Hydrol., 6, 170–188, 1975.
Larson, L. W. and Peck, E. L.: Accuracy of precipitation measurements for hydrologic modeling, Water Resour. Res., 10, 857–863, 1974.
Legates, D. R.: Global and terrestrial precipitation – a comparative-assessment of existing climatologies, Int. J. Climatol., 15, 237–258, 1995.
Nash, I. E. and Sutcliffe, I. V.: River flow forecasting through conceptual models, J. Hydrol., 10, 282–290, 1970.

Plauborg, F., Refsgaard, J. C., Henriksen, H. J., Blicher-Mathiasen, G., and Kern-Hansen, C.: Water Balance at Field and Catchment Scale, The Danish Institute of Agricultural Sciences, 2002 (in Danish).
Refsgaard, J. C., Stisen, S., Højberg, A. L., Olsen, M., Henriksen, H. J., Børgesen, C. D., Vejen, F., Kern-Hansen, C., and Blicher-Mathiasen, G.: Water balance in Denmark – guide to quantification of water balances based on hydrological data for the period 1990–2010), Report 2011/77, GEUS, 2011 (in Danish).
Scharling, M.: CLIMATEGRID – DENMARK, Precipitation 10 × 10km, Technical Report 98–17, Danish Meteorological Institute, Copenhagen, Denmark, 1998 (in Danish).
Scharling, M.: CLIMATEGRID – DENMARK, Precipitation, air temperature and potential evapotranspiration 20 × 20 and 40 × 40km, Technical Report 99–12, Danish Meteorological Institute, 1999 (in Danish).
Seibert, J.: Reliability of model predictions outside calibration conditions, Nord. Hydrol., 34, 477–492, 2003.
Stisen, S., McCabe, M. F., Refsgaard, C. J., Lerer, S., and Butts, M.: Model parameter analysis using remotely sensed pattern information in a multi-constraint framework, J. Hydrol., 409, 337–349, 2011a.
Stisen, S., Sonnenborg, T. O., Hojberg, A. L., Troldborg, L., and Refsgaard, J. C.: Evaluation of climate input biases and water balance issues using a coupled surface-subsurface model, Vadose Zone J., 10, 37–53, 2011b.
Therrien, R., McLaren, R. G., Sudicky, E. A., and Panday, S.: HydroGeoSphere: a three-domentional numerical model describing fully-integrated subsurface and surface flow and solute transport, Groundwater Simulations Group, University of Waterloo, Waterloo, Ontario, Canada, 2005.
Tian, X. J., Dai, A., Yang, D. Q., and Xie, Z. H.: Effects of precipitation-bias corrections on surface hydrology over northern latitudes, J. Geophys. Res.-Atmos., 112, D14101, doi:10.1029/2007JD008420, 2007.
Vejen, F.: Pilotproject: calculation of dynamic correction on Samsø, 1989–2003, Technical report 05–16, Danish Meteorological Institute, 2005 (in Danish).
Voisin, N., Wood, A. W., and Lettenmaier, D. P.: Evaluation of precipitation products for global hydrological prediction, J. Hydrometeorol., 9, 388–407, 2008.
Wagner, A.: Literature Study on the Correction of Precipitation Measurements, FutMon C1-Met-29(BY), Bavarian State Institute of Forestry, Freising, Germany, 2009.

Yan, J. S. and Smith, K. R.: Simulation of integrated surface-water and ground-water systems – model formulation, Water Resour. Bull., 30, 879–890, 1994.
Yang, D. Q., Kane, D., Zhang, Z. P., Legates, D., and Goodison, B.: Bias corrections of long-term (1973–2004) daily precipitation data over the northern regions, Geophys. Res. Lett., 32, L19501, doi:10.1029/2005GL024057, 2005.

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

Table 1. Combination of vegetation and soil types defined in the DK-model.

Land use		Maximum root zone depth (m)	Coverage (km^2)	Coverage (%)
Permanent grass		0.70	3009	7
Forest, deciduous		1.00	1855	4
Forest, coniferous		0.85	3410	8
Heath/sparse vegetation		0.30	1024	2
Urbanised		0.10	3933	9
Farmland, winter wheat	JB1	0.60	1346	3
	JB2	0.90	632	1
	JB3–JB4	1.20	2976	7
	JB5–JB10	1.50	6565	15
Farmland, spring barley	JB1	0.60	1401	3
	JB2	0.80	494	1
	JB3–JB4	1.10	2324	5
	JB5–JB10	1.40	3781	9
Farmland, grass	JB1	0.60	1328	3
	JB2	0.70	526	1
	JB3–JB4	0.80	2432	6
	JB5–JB10	0.90	3120	7
Farmland, maize	JB1	0.60	491	1
	JB2	0.90	145	0
	JB3–JB4	1.20	770	2
	JB5–JB10	1.50	1194	3

HESSD
9, 3607–3655, 2012

Table 2. Calibration parameters, expected ranges are adapted from (Henriksen et al., 2003).

Parameter	Description	Used in model domain	Unit	Expected range
Kx_Upper 3 m	Horizontal conductivity of the upper 3 m	1 and 5	ms^{-1}	1e-06–1e-04
Kx_Qsand	Horizontal conductivity of Quaternary sand	1, 3, 4, 5 and 6	ms^{-1}	1e-06–1e-02
Kz_Qclay	Vertical conductivity of Quaternary clay	1, 3, 4, 5 and 6	ms^{-1}	1e-11–1e-07
Kx_PQsand	Horizontal conductivity of Pre-Quaternary sand	4, 5 and 6	ms^{-1}	1e-06–1e-02
Kz_PQclay	Vertical conductivity of Pre-Quaternary clay	1, 3, 4, 5 and 6	ms^{-1}	1e-11–1e-07
Kz_Chalk	Vertical conductivity of Chalk aquifer	1, 3 and 5	ms^{-1}	1e-07–1e-03
Drain Time cons.	Drainage time constant	1, 3, 4, 5 and 6	s^{-1}	1e-08–1e-06
Leakage Coef.	River-aquifer leakage coefficient	1, 3, 4, 5 and 6	ms^{-1}	1e-10–1e-06
RD WW JB1	Root depth of winter wheat for soil type JB1	1, 3, 4, 5 and 6	m	0.4–0.8

HESSD
9, 3607–3655, 2012

Table 3. The eight objective functions are defined as follows.

Objective function	Stations wells	Relative weight	Mainly sensitive to
NSE: Nash-Sutcliffe model efficiency based on daily streamflow data (–)	191	4.0	Root depth, drain const., leak. coef.
WBE: the total water balance error (%)	191	4.0	Root depth
WBE_{summer}: the water balance error for the low flow months Jun, Jul and Aug (%)	191	4.0	Root depth, leak. coef.
ME_{HTS}: mean error of time series of hydraulic head (m)	521	2.0	K-values
ME_{H}: mean error of hydraulic head for a given well for the calibration period 2000–2003 (m)	8460	2.0	K-values
ME_{layers}: mean hydraulic head error for each model layer for the calibration period (m)	8460	2.0	K-values
$ME_{H_{mean}}$: mean error of mean hydraulic head for a given well for the period 1990–2000 (m)	9198	1.0	K-values
$ME_{layersmean}$: mean hydraulic head error for each model layer (m)	9198	1.0	K-values

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

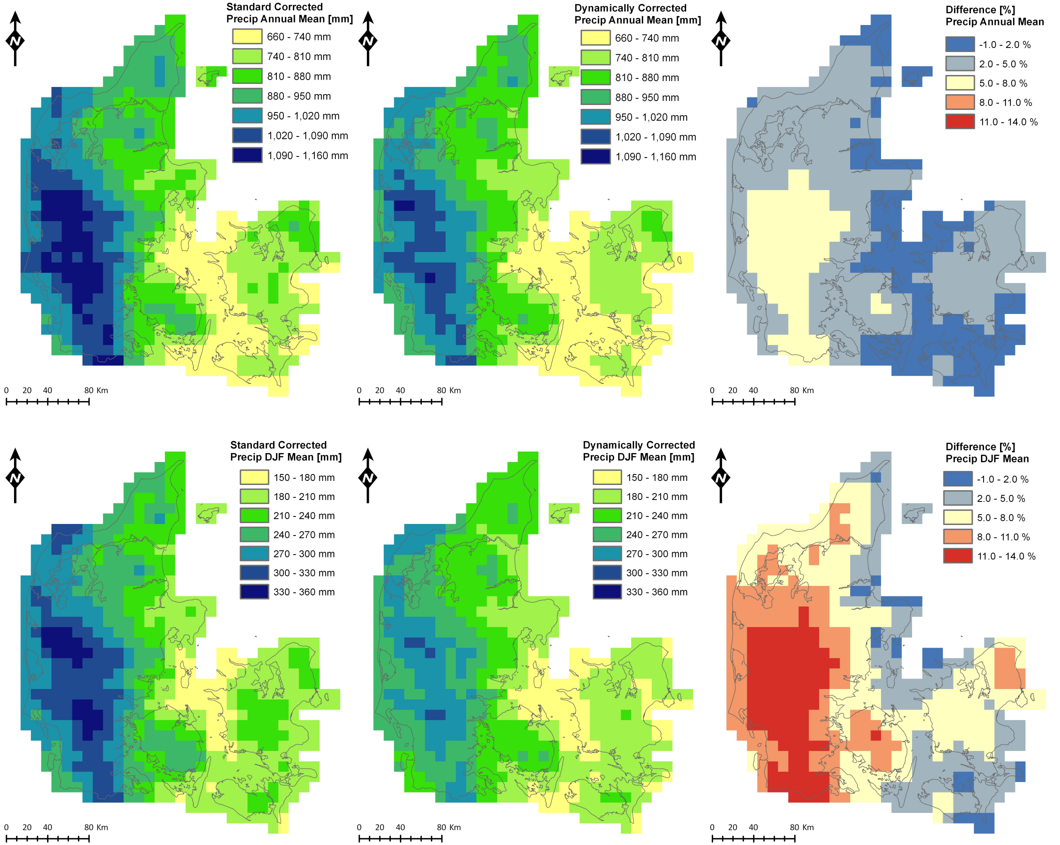

Fig. 1. Spatial distribution of mean annual precipitation (top) and winter precipitation (DJF) (bottom) for Denmark with standard and dynamic precipitation correction.

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

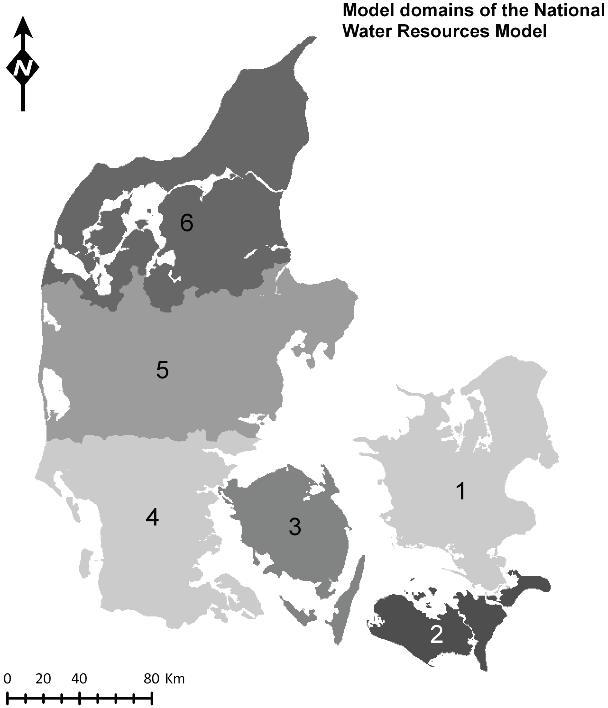

Fig. 2. Six model domains of the Danish national water resources model.

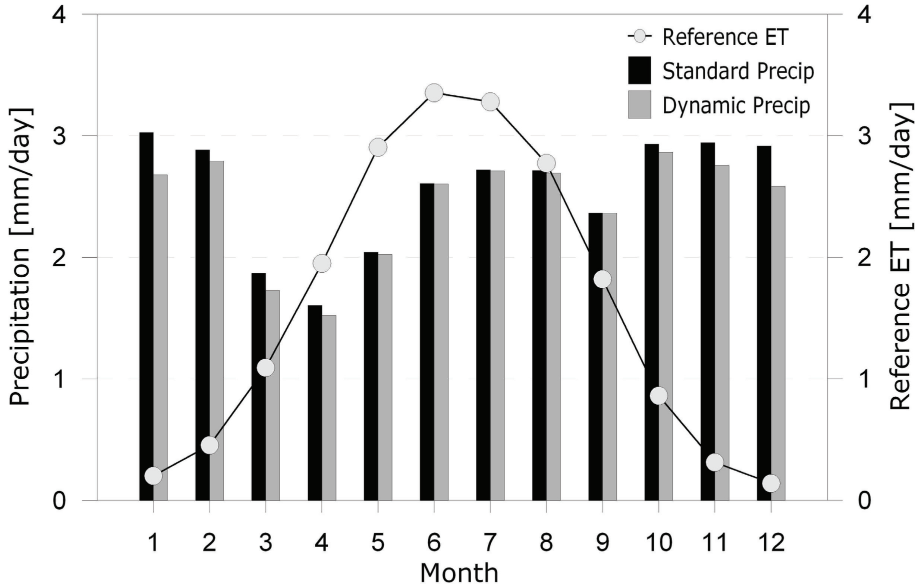

Fig. 3. Monthly average precipitation and reference ET rates for Denmark for the period 2000–2007. Precipitation rates are given for both the standard and dynamic precipitation corrected.

HESSD
9, 3607–3655, 2012

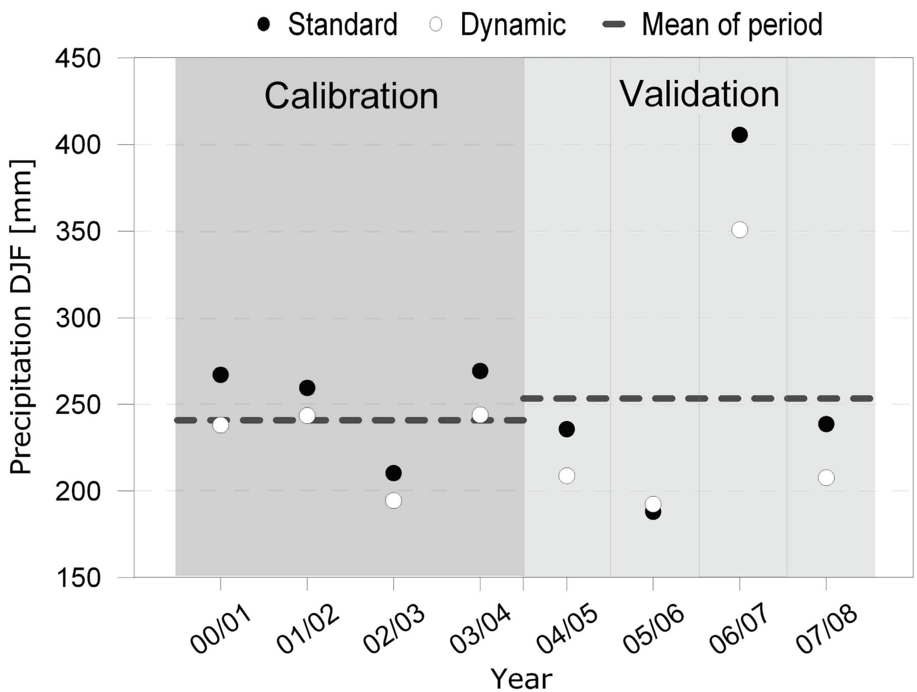

Fig. 4. Winter precipitation (DJF) for calibration and validation periods for the entire country.

HESSD
9, 3607–3655, 2012

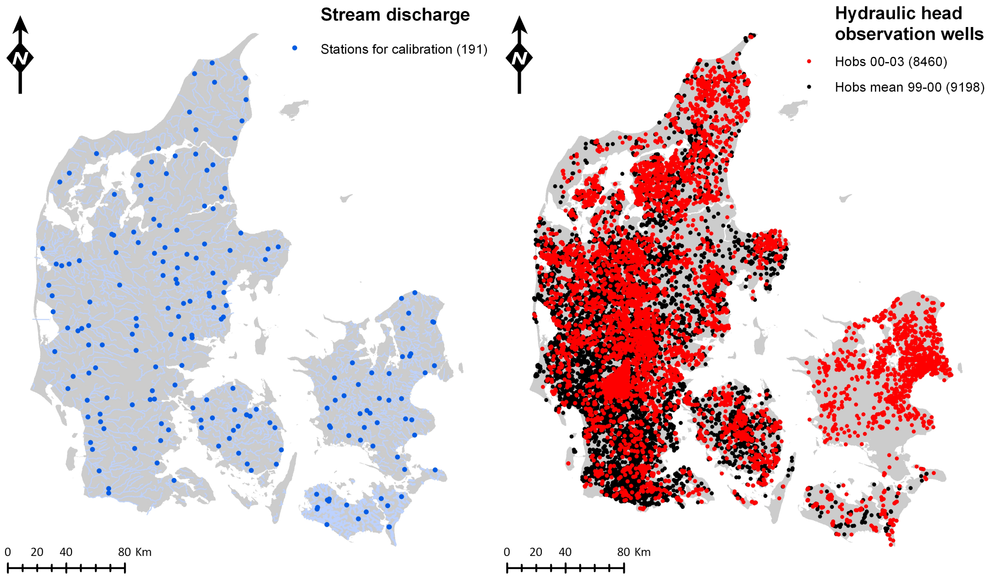

Fig. 5. All available discharge stations and observations wells for the calibration period 2000–2003.

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

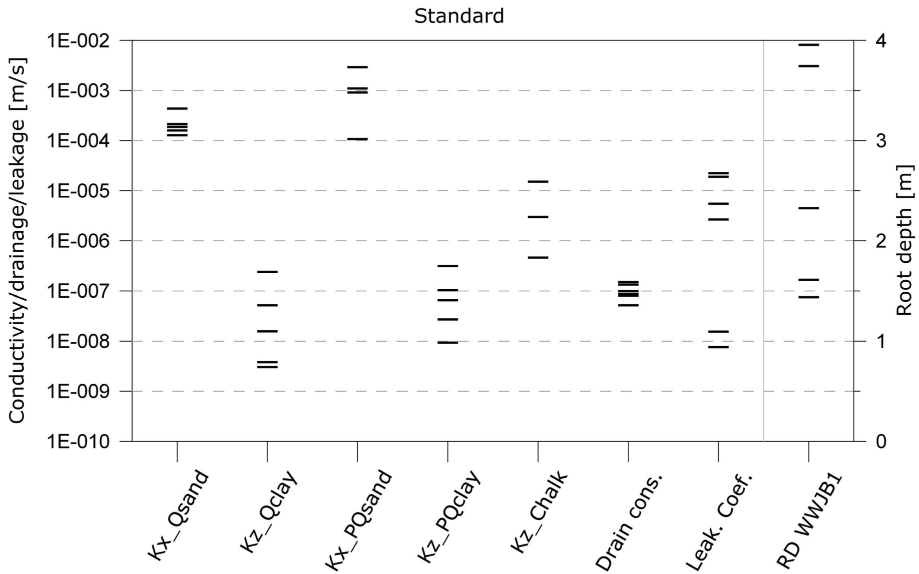

Fig. 6. Optimized parameter values for all model-domains with standard precipitation correction.

HESSD
9, 3607–3655, 2012

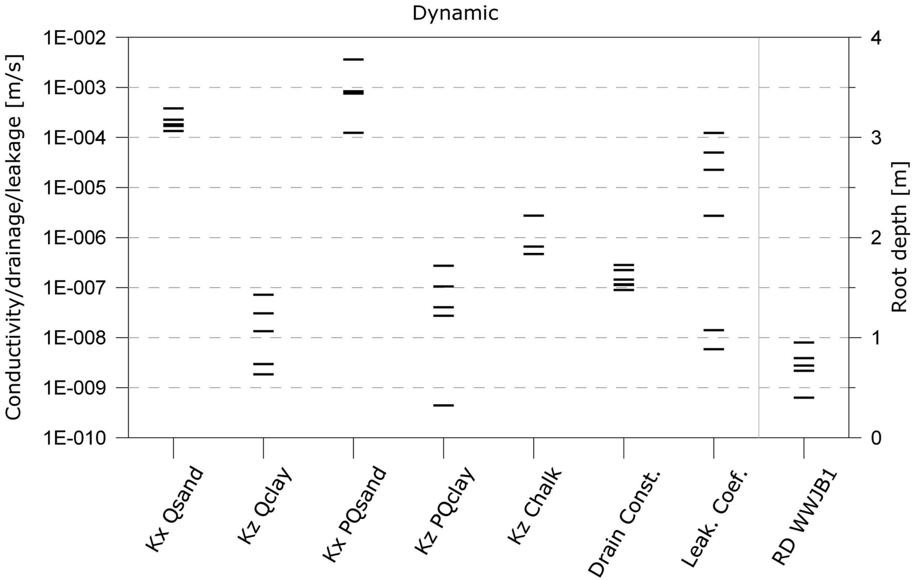

Fig. 7. Optimized parameter values for all model-domains with dynamic precipitation correction.

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

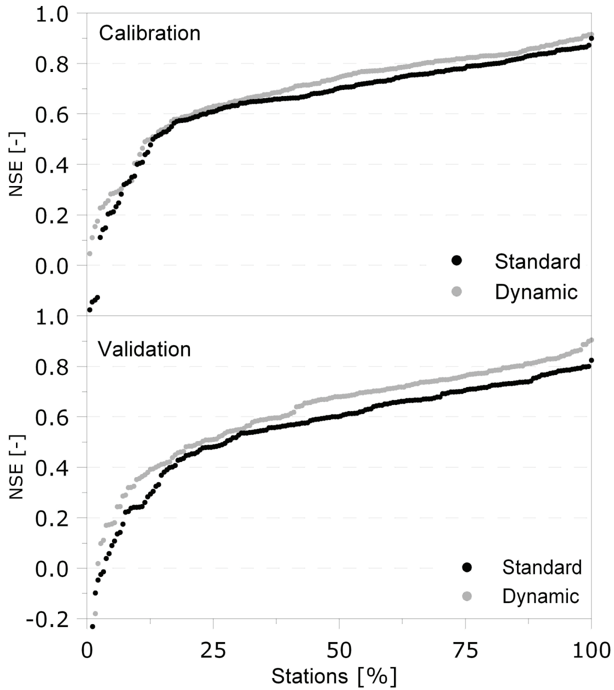

Fig. 8. Sorted model performance for NSE for both models during calibration and validation.

HESSD

9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

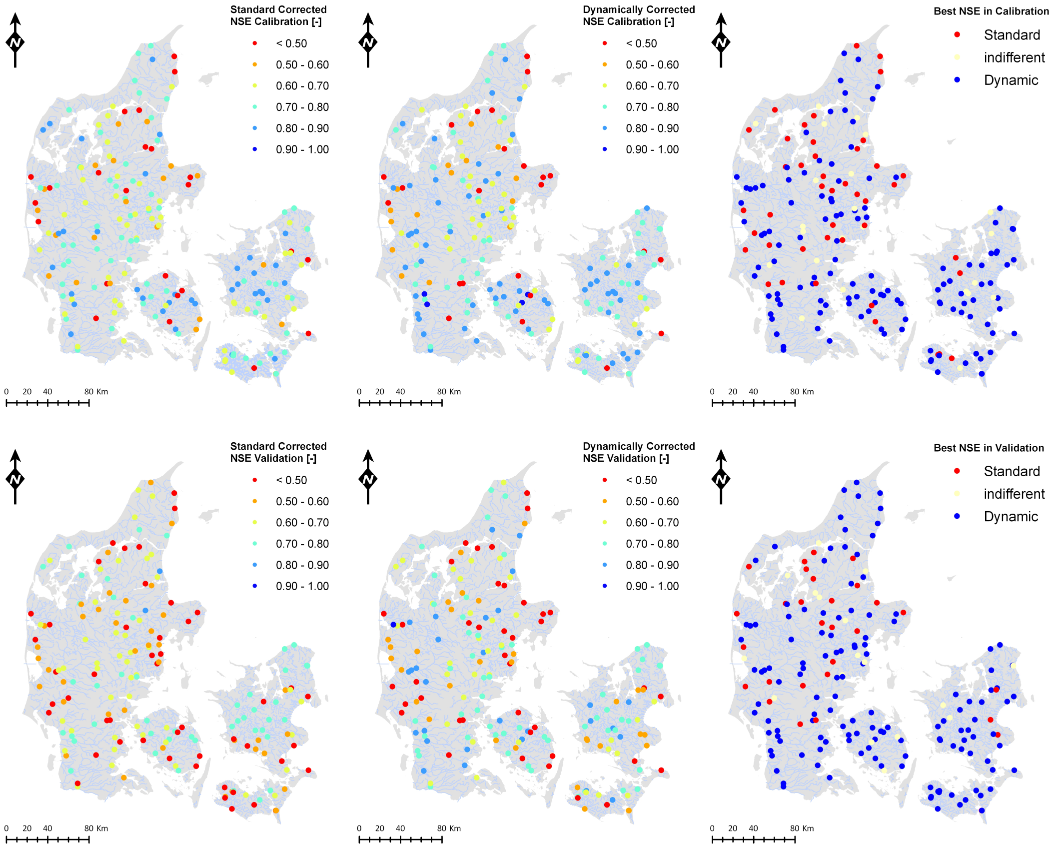

Fig. 9. Distributed map of model performance for NSE for both models during calibration and validation.

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

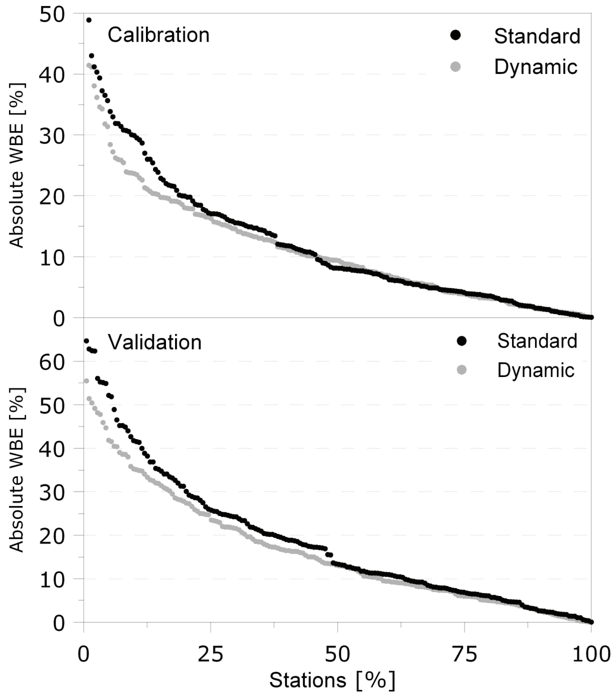

Fig. 10. Sorted model performance for absolute WBE for both models during calibration and validation.

HESSD
9, 3607–3655, 2012

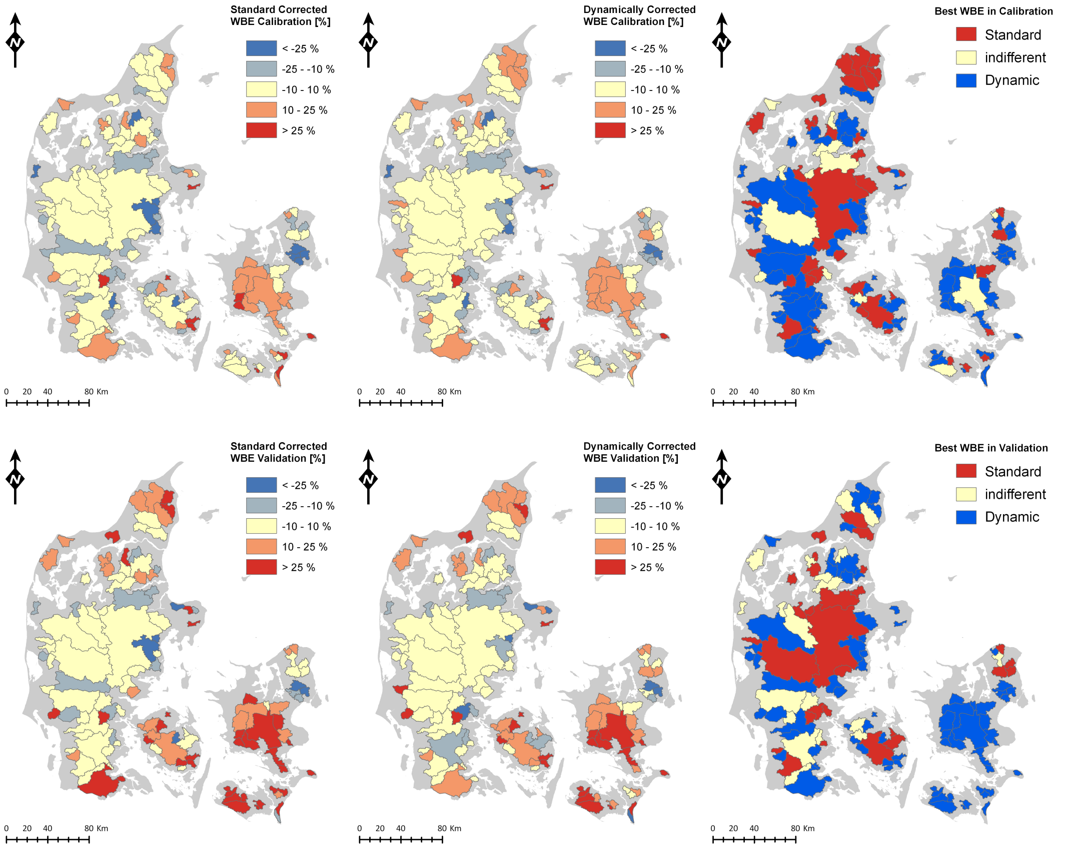

Fig. 11. Distributed map of model performance for WBE for both models during calibration and validation.

HESSD
9, 3607–3655, 2012

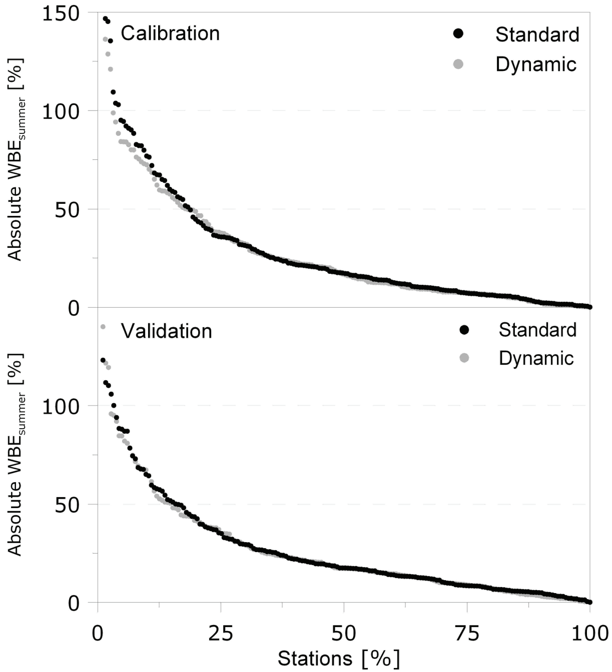

Fig. 12. Sorted model performance for absolute WBE$_{summer}$ for both models during calibration and validation.

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

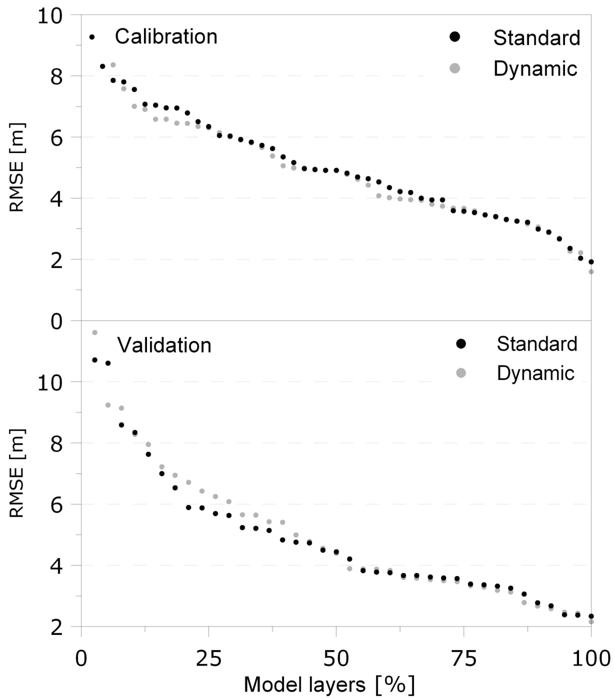

Fig. 13. Sorted model performance for RMSE of hydraulic head for both models during calibration and validation.

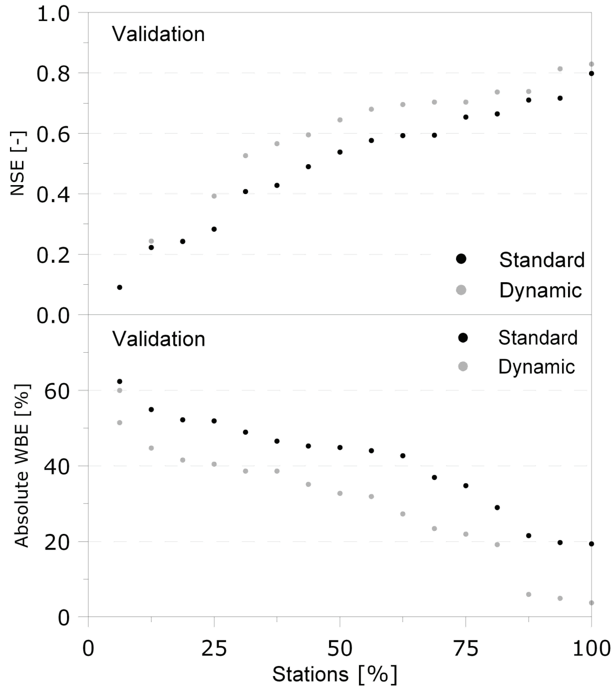

Fig. 14. Sorted model performance for NSE and absolute WBE both models for the proxy basin application to model domain 2 during the validation period.

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

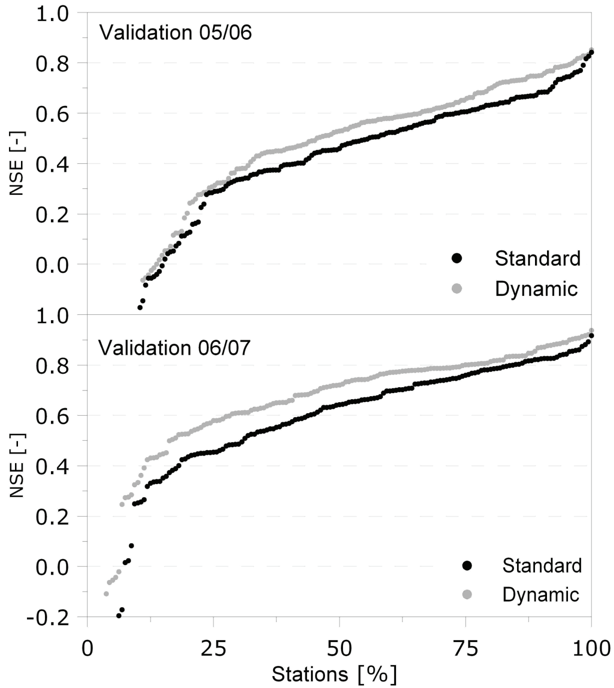

Fig. 15. Sorted model performance for NSE for both models during two additional validations periods (2005/2006 and 2006/2007).

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

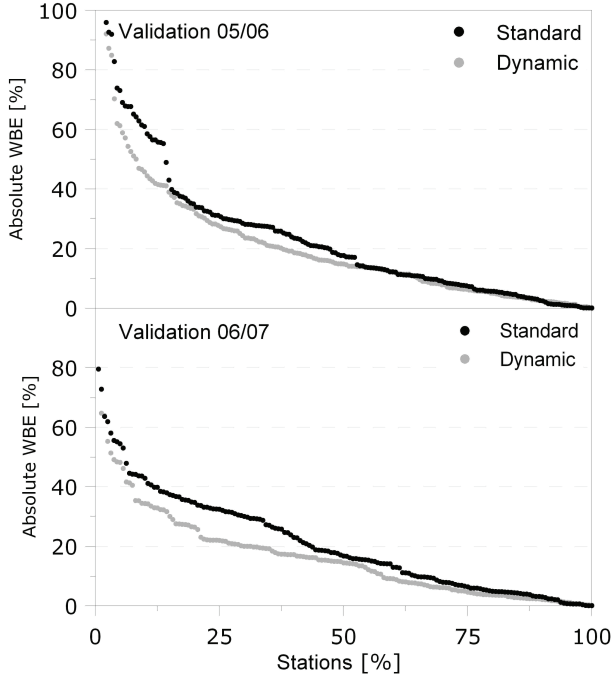

Fig. 16. Sorted model performance for absolute WBE for both models during two additional validation periods (2005/2006 and 2006/2007).

HESSD

9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.

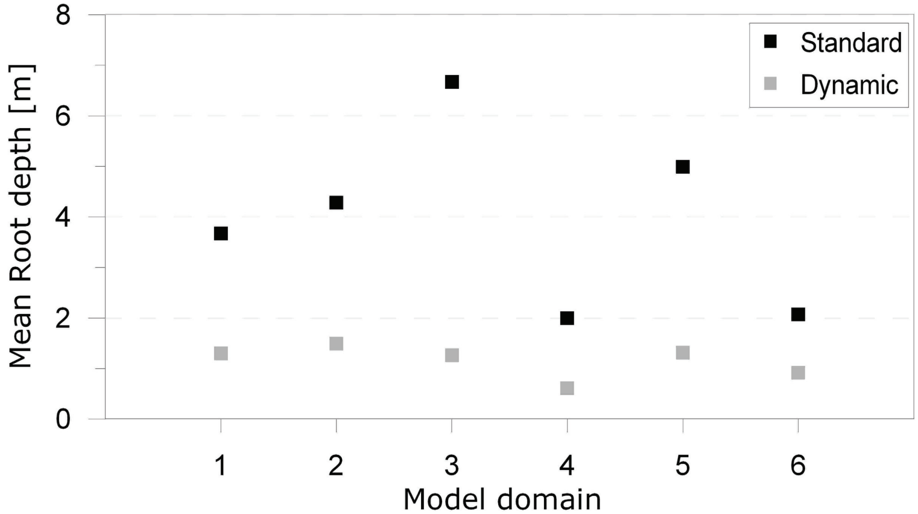

Fig. 17. Effective average summer root depths for the two optimized models for each mode domain.

HESSD
9, 3607–3655, 2012

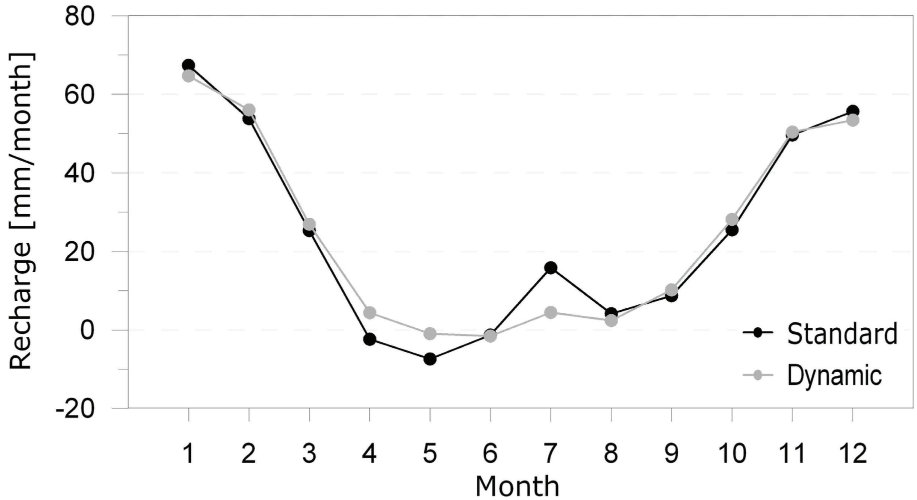

Fig. 18. Average monthly simulated groundwater recharge for all grids in the national model for the two optimized models.

HESSD
9, 3607–3655, 2012

Rain-gauge catch correction for hydrological modelling

S. Stisen et al.