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Water balance evaluation in Denmark using remote sensing-driven land surface modelling and spatially distributed hydrological modelling

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Abstract This study evaluates the water balance of the island of Sjælland (7330 km^2) in Denmark using two different types of physically-based model approaches. The DaisyGIS model is an advanced 1-D land surface model which is parameterized at the plot-scale and upscaled using remote sensing and GIS (Geographical Information System) data to represent land cover and soil characteristics. In comparison, the DK-model constitutes a 3-D integrated hydrological model setup (based on the MIKE SHE code) which uses a comprehensive geological data set and is calibrated to obtain global model parameters representing all catchments at Sjælland. A good agreement was found between annual net precipitation (precipitation minus evapotranspiration) estimated by the two model systems, but seasonal differences in evapotranspiration occurred which could be related to the use of the remote sensing for evapotranspiration calculation in Daisy or caused by dissimilar soil properties. Despite these differences, the DK-model simulated streamflows efficiently for both agricultural and forest catchments. In contrast, Daisy simulations suggest that a more advanced distributed land surface parameterization can contribute to improving water balance simulations of urbanized surface-water dominated catchments. The integrated annual water balance of Sjælland was found to be nearly in balance but large spatial variations occurred among the 30 studied catchments. Overall, the results indicate a need for further studies on model sensitivity and uncertainties related to net precipitation quantification in spatially distributed hydrological modelling.

Key words water balance modelling; large-scale; land surface model; 3-D hydrological model; Denmark

INTRODUCTION

In Denmark, 99% of the water supply is based on groundwater. In some areas, an excessive use of groundwater results in very low streamflows during summers, with adverse impacts on stream ecology. In order to improve water management, it is important to have an accurate overview of the water balance components at the larger scale and, in particular, to know the rate of groundwater recharge and interactions between stream and groundwater flows.

In this paper, two physically-based model systems (DaisyGIS and DK-model) are used for large-scale water balance evaluation in Denmark. The objective is to examine the reliability of water balance simulations using physically-based process modelling and spatially distributed model parameterization. While DaisyGIS emphasizes evapotranspiration and unsaturated water flow modelling using plot-scale model parameterization, the DK-model emphasizes predictions of saturated water flows based on meso-scale (all Sjælland) model parameterization. The reliability of water balance simulations is addressed by comparing estimates of net precipitation from the two models at the intermediate catchment scale. Furthermore, model efficiency of water flow simulations from Daisy and the DK-model are evaluated using stream discharge data, and the integrated net precipitation and water balance of Sjælland is assessed.

STUDY AREA

Sjælland (55.5°N, 12.1°E) is the major island of Denmark upon which Copenhagen is also located. It has an area of 7330 km^2, which corresponds to 17% of the area of Denmark. The topography is dominated by clayey moraines which is responsible for a gently undulating landscape located at –7 m to 120 m above sea level. Glacial deposits with a thickness of 2–150 m overlay limestone and marls. Approximately 70% of the land area is cultivated, 14% is occupied by forests and 10% of the region is covered by urban settlements. Due to the prevalence of clayey soils, the agricultural regions are typically pipe-drained.

MODEL DESCRIPTIONS AND SETUP

An overview of major differences in the DaisyGIS and the DK-model in terms of data inputs, model parameterization and model structure is summarized in Table 1.

The DaisyGIS model

DaisyGIS is a 1-D physically based hydrological modelling tool which simulates water and nitrogen balances (Abrahamsen & Hansen, 2001) in a Geographical Information System (GIS) for different soil columns. It simulates leaf area development, or assimilates leaf area index from remote sensing data (Boegh *et al.*, 2004), and represents soil–vegetation–atmosphere interactions for calculating evapotranspiration (van der Keur *et al.*, 2001). Soil water percolation in the unsaturated zone is based on the Richards equation. The 1-D water balance of a soil column is given by:

$$P_p = E_p + R_p + D_p + M_p + \Delta S_p \tag{1}$$

where P is precipitation, E is evapotranspiration, R is surface runoff, D is pipe drain flow, M is soil matrix percolation and ΔS is change in soil water storage. The subscript p denotes plot scale.

The DaisyGIS model is set up for Sjælland using a soil map which was constructed by combining soil textural data in depths 0–20 cm (n = 5750) and 35–55 cm (n = 770) with a geological map (depth 100 cm) to represent three soil horizons. Retention curves and hydraulic conductivity functions are defined for each horizon of the specified soil types using pedotransfer and hydraulic functions. A remote sensing based land-cover map representing eight major land surface types (winter sown grain crops, spring sown grain crops, beets, bushes, grass/meadows, young forest, deciduous forest, coniferous forest and urban regions) were used, and remote sensing (EOS/MODIS) based time series of leaf area index (LAI) in 500-m grids were assimilated every 16th day. Four classes of lower boundary conditions were defined by overlaying maps of wetlands (25-m grid; groundwater depth set to 0.4 m), soil types and land use (facilitates mapping of pipe-drained regions) on a lower resolution (1 km) map representing the 10-year average groundwater levels at Sjælland (simulated by the DK-model). Drainage model parameters were decided for different soil types using "rules of thumb" developed from field investigations of pipe drain flows which were conducted as part of a national drainage survey.

Climate forcing consists of daily precipitation, global radiation, air temperature, air humidity and wind speed in 10 km meteorological grids. Evapotranspiration is modelled using the Penman-Monteith equation for agriculture/open land. For forests, the semi-empirical FAO Penman-Monteith method was used with the empirical K_c factor scaled between its minimum (0.5 for bare soil) and maximum (1.2 for full vegetation cover) estimates using remote sensing data. For urban regions, an initial loss (representing intercepted water and its evaporation) of 0.5 mm day^{-1} was used for paved areas. The fraction of paved area was evaluated using remote sensing data for all urban grids to facilitate calculation of urban surface runoff. The non-paved fractions of urban grids were simulated as grass.

In order to keep computational speed at a reasonable level, the spatial inputs were grouped into a number of computational classes each representing a unique composition of climate condition, land cover, soil type and lower boundary condition. For Sjælland, this means that simulations are done deterministically in 4489 vertical columns and then transferred to profiles having the same characteristics.

The DK-model

The *National Water Resource Model* (DK-model) is a 3-D integrated groundwater/-surface water model setup for all Denmark (43 000 km^2) which has a 1-km grid resolution (Henriksen *et al.*, 2003) and is based on the MIKE SHE code. In order to reduce computational time, the complex unsaturated component in MIKE SHE (based on Richards equation) has been replaced by a relatively simple, stand-alone, root zone component (Sonnenborg *et al.*, 2003) calculating recharge to the uppermost saturated model layer. A comprehensive 3-D groundwater component then simulates the recharge to 11 geological layers composed by alternating sand, clayey till and limestone layers. The model includes a river component for streamflow routing and estimating stream–groundwater interaction. The DK-model itself determines the catchment boundaries allowing groundwater flows to cross topographical divides in places where these do not coincide with groundwater divides. The 3-D water balance at catchment scale is given by:

$$P_c = E_c + R_c + Q_I + Q_B + M_c + W + A + \Delta S_c \tag{2}$$

where Q_I is interflow (composed by pipe drain flow, D_c, and residual interflow), Q_B is baseflow, W is water abstraction, A is water flow to/from neighbouring catchments and ΔS represents change in water storage (soil, groundwater, streamwater). The subscript c denotes catchment scale.

Table 1 Overview of model structure and data representation in DaisyGIS and the DK-model.

	DaisyGIS	DK-model
Model structure	1-D advanced physically-based land surface and unsaturated zone representation	3-D integrated physically-based representation. Simple root zone, advanced geological model, aquifer/river interaction
Climate inputs	10-km climate grid data (P, S, T_a, e_a, u).	40-km climate grid data (P, T_a, EP; P scaled with topography to 1-km resolution; EP based on the Makkink equation)
Topography and depth to ground water level	No topography. Dynamic drainage or distributed depth to static groundwater level included.	Topography and distributed depth to dynamic groundwater level included.
Soil and geology	Three soil horizontal unsaturated zone; pedotransfer/hydraulic functions	1 root zone + 11 alternating geological layers; global parameterization for Sjælland using field data and model calibration
Land and vegetation cover	Eight land cover types; LAI every 16 day; 500 m grid	Three land cover types; no vegetation dynamics (fixed root zone capacity); 1000 m grid
Evapotranspiration	2-layer model (soil, vegetation) Open land: Penman/Monteith Forest: FAO-Penman/Monteith Urban: Initial loss parameterization	Empirical model as a function of soil water content in root zone Wetland: EP assumed Open land: RZC = 70 or 140 mm Forest: RZC = 150 mm
Drainage	Pipe drainage included in agricultural, grass and urban regions with clayey soils or shallow ground water; distributed parameterization	Drainage included in the whole model area. Calibrated global drainage parameters
Streamflow	Distributed surface runoff and pipe drain flows. No routing.	Streamflow routing. Stream-groundwater interaction.
Lower boundary	Dynamic aquitard in pipe drained areas, otherwise gravity drainage or static groundwater depth	Dynamic. Impermeable boundary below 11th geological layer (~ 50–150 m b.s.l.)

S: global radiation, T_a : air temperature, e_a: air humidity, u: wind speed, EP: potential evapotranspiration, RZC: root zone capacity.

Regional parameterization of the DK-Model for Sjælland (Henriksen *et al.*, 2003) was conducted by making maximum use of geological data and other available data sources. Each geological layer is characterized by unique model parameters for all of Sjælland. Based on a sensitivity analysis, the most sensitive parameters (~10 parameters) were selected and subsequently estimated through calibration using a combination of inverse steady-state groundwater modelling and manual trial-and-error dynamic groundwater/surface water modelling. Observed hydraulic head data from 4439 wells and stream discharges from 28 gauging stations were used as calibration targets.

Climate forcing of the DK-model is represented by 40-km grids of daily precipitation, potential evapotranspiration and air temperature, which are distributed in 1-km grids according to variations in topography thus allowing higher altitude regions to receive relatively more precipitation. For calculation of E_c, distinction is made between three different land uses; wetland, forest and open land (incl. agriculture). In wetlands, E is assumed at its potential rate every day. In other areas, an empirical relation between actual and potential E is estimated as a function of soil water content in the root zone. The model includes a snow storage (when the temperature is below 0°C), and snow melting is calculated using a temperature degree day factor. The E_c model was verified at plot-scale but when applied to catchment water balance simulations, it was found that the regional $(P_c - E_c)$ was too high and responsible for water balance errors (Henriksen *et al.*, 2003). In order to obtain a reasonable water balance at the discharge stations, a correction factor of 0.77 is suggested to reduce $(P_c - E_c)$. The need for this correction factor is explained by uncertainty in P_c inputs and E_c calculations (Henriksen *et al.*, 2003).

METHODOLOGY

Water balance simulations conducted by the DaisyGIS and DK-models were extracted for the period 2001–2003. Three sets of outputs were produced:

- daily water balance of three different catchments characterized by extensive forest (43%), urban (24%) and agricultural (90%) land covers, respectively. The corresponding catchment areas are 62 km^2, 45 km^2 and 261 km^2.
- annual water balance of 30 catchments larger than 20 km^2 and not containing lakes
- integrated annual water balance of Sjælland.

To assess the water balance models' reliability, the calculation of net precipitation (which equals the unsaturated zone drainage in the bucket model type calculation of the DK-model) by the DK-model is compared to Daisy net precipitation $(P_c - E_c)$ and Daisy soil drainage $(M_c + D_c)$ which is extracted at depth 1.5 m. Liquid water flows from the two model systems but is not directly comparable because Daisy does not consider streamflow–groundwater interaction (i.e. baseflow). Instead, the DK-model simulations of streamflow $(R_c + Q_I + Q_B)$ are evaluated using stream discharge (Q) data, and Daisy simulations of surface runoff and pipe drainage $(R_c + D_c)$ are evaluated using stream discharge data which were corrected for baseflow $(Q - Q_B)$ using a simple baseflow separation technique (Gustard *et al.*, 1987).

Model efficiency is quantified in terms of the Nash-Sutcliffe Efficiency (NSE):

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{N}(o_i - c_i)^2}{\sum_{i=1}^{N}(o_i - \bar{o})^2} \tag{3}$$

where o and c are the observed and calculated fluxes at timestep i, and N is the total number of discharge observations. Furthermore the dimensionless root mean square error (RMS*) is calculated:

$$RMS^* = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(o_i - c_i)^2}}{\frac{1}{N}\sum_{i=1}^{N}o_i} \tag{4}$$

and the squared linear correlation coefficient (r^2) is calculated to quantify the degree of variability which is explained by the models.

In order to evaluate Daisy water flows in the forest catchment (where Daisy $(R_c + D_c) \approx 0$), it is assumed that the total soil matrix percolation below the root zone contributes to interflow. Accordingly, $(M_c + D_c + R_c)$ is compared to Q measurements in the forest catchment. Because interflow components other than pipe drainage will become more important during wintertime (i.e. macropore flow, soil matrix flow and rapid fluctuations in groundwater), the Daisy water flow model efficiency is quantified in the period 1 April to 1 October only. For the surface water dominated urban catchment, model efficiency is evaluated separately for the whole year and for the period 1 April–1 October.

RESULTS

Net precipitation and drainage

The calculation of ($P_c - E_c$) by the DK-model is compared to Daisy net precipitation ($P_c - E_c$) and total drainage ($M_c + D_c$) for an agricultural catchment in Fig. 1. During the non-growing season (October–April), when E_c is negligible, the comparison between catchment integrated ($P_c - E_c$) estimates indicates a rather good agreement between the two different methods applied for precipitation interpolation (Fig. 1(a)). During midsummer, Daisy ($P_c - E_c$) reaches values down to –5 mm day^{-1} (for clear days with no precipitation) while the simple bucket model type estimations of ($P_c - E_c$) in the DK-model remain close to zero throughout the summer. In contrast, there are several summer days with positive ($P_c - E_c$) in Daisy but, as for the DK-model based ($P_c - E_c$), Daisy drainage simulations also approach zero during summer (Fig. 1(b)). The temporal Daisy drainage simulations are generally smoother than in the DK-model

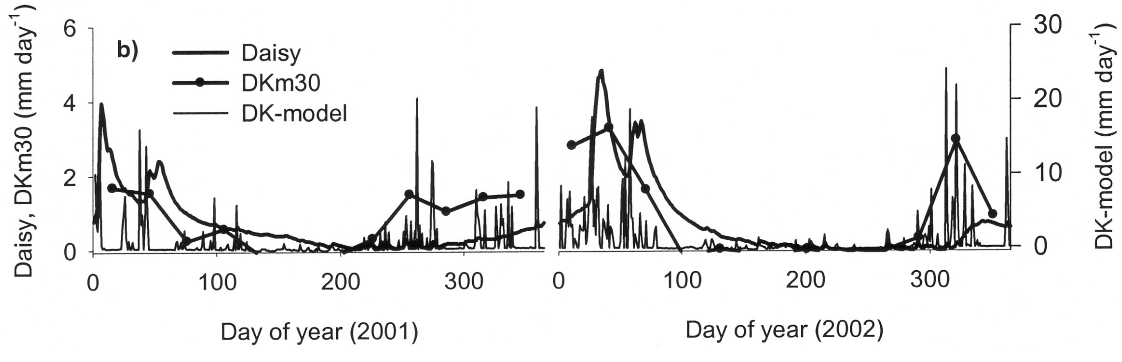

Fig. 1 (a) Daily net precipitation ($P_c - E_c$) calculated by Daisy and the DK-model (positive Daisy net precipitation rates are illustrated with larger circles to ease comparison with DK-model estimates). (b) Daily (DK-model) and monthly (DKm30) ($P_c - E_c$) estimated by the DK-model compared to daily total drainage ($M_c + D_c$) simulated by Daisy. All plots represent an agricultural catchment (basin 560005).

due to a more realistic time-delayed soil water percolation in the Daisy model. In both years, there is a clear tendency for Daisy net precipitation and drainage to exceed DK-model estimates during springtime and to be lower than the DK-model estimates during autumn. The difference could be related to the use of remote sensing for E_c calculation in Daisy since the control of leaf area development on the evaporative surface area and length of growing season is particularly important for determining E_c in spring and autumn. The lower drainage estimates simulated by Daisy during autumn are also due to the soil water storage being refilled more slowly than by the DK-model.

Annual estimates of (P_c – E_c) for three different catchments characterized by extensive areas of forest (catchment no. 500056), urban (no. 530042) and agricultural (no. 560005) land cover respectively are generally higher when calculated from the DK-model than when calculated using Daisy (Table 2).

Table 2. Annual net precipitation and total drainage for three different catchment types in 2001–2003 calculated using the DK-model and Daisy. Results are given for the periods 1 January–31 December, except the DK-model drainage which is given for the periods 28 January–27 January.

Catchment type	Catchment number	Year	Net precipitation (mm year^{-1})		Total drainage (mm year^{-1})	
			DK-model ($P_c – E_c$)	Daisy ($P_c – E_c$)	DK-model ($P_c – E_c$)	Daisy ($P_c – E_c$)
Forest	500056	2001	261	209	195	210
Forest	500056	2002	456	353	245	363
Agricultural	560005	2001	282	248	234	236
Agricultural	560005	2002	379	262	253	283
Urban	530011	2001	237	292	123	199
Urban	530011	2002	424	400	168	293

After correction of the DK-model (P_c – E_c), as discussed above and in Henriksen (2003), the annual DK-model estimates are found to be in surprisingly good agreement with Daisy estimates of (P_c – E_c) for both the agricultural and forested catchments (Fig. 2(a)). In this case, the RMS difference between the simulated (P_c – E_c) of the DK-model and Daisy reduces from 84 mm year^{-1} to 22 mm year^{-1}. In Fig. 2(b), a good agreement between DK-model simulations of annual stream flow and discharge measurements of forested, urbanized and agricultural catchments (RMS error is 37 mm year^{-1}) confirms the practical utility of empirically corrected (P_c – E_c) in the DK-model.

For the urban catchment, a better agreement between Daisy and the un-corrected DK-model (P_c – E_c) is observed (Fig. 2(a)). However, this is caused by relatively higher E_c simulations of the DK-model resulting from wetlands in the catchment, whereas the Daisy model simulates relatively lower E_c due to the extension of impervious areas.

Despite the rather good agreement between annual (P_c – E_c) of Daisy and the corrected DK-model estimates, larger differences are found between DK-model total drainage (M_c + Q_I) and Daisy drainage (M_c + D_c) simulations. Since the DK-model drainage estimates are based on corrected (P_c – E_c) inputs, the differences in total drainage estimates are related to dissimilar surface runoff rates, interflows and soil water storages. In Daisy, capillary rise and soil water storage change may cause the simulated drainage to exceed net precipitation rates (Table 2).

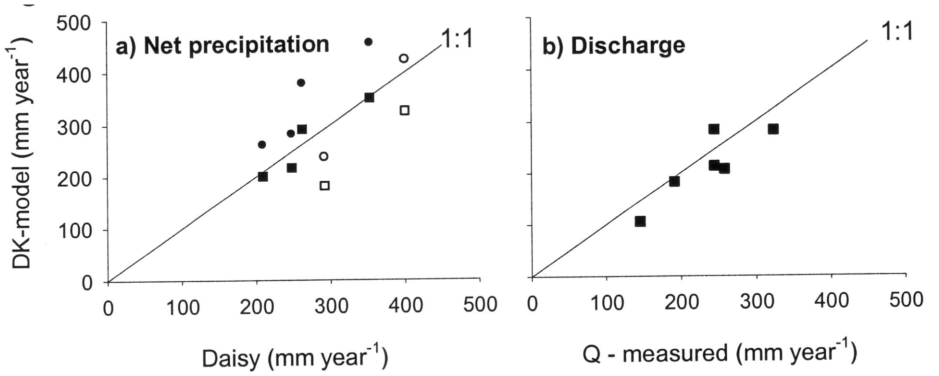

Fig. 2 (a) Annual net precipitation estimated by the DK-model and Daisy for three different catchments (forest, urban, agricultural) in 2001 and 2002. Both the modelled (circle) and empirically corrected (square) DK-model estimates are shown. Open symbols illustrate results from the urban catchment. (b) Annual discharge simulated by the DK-model compared to streamflow (*Q*) measurements.

Stream flow simulations

Considering the global model parameterization of all catchment types, streamflow (*Q*) simulations by the DK-model for the studied forested and agricultural catchments are generally in good agreement with discharge data (Fig. 3). Model efficiency is very good for the agricultural catchment (NSE = 0.79) where 83% of the variability is also explained by the model and RMS* is low (Table 3). For the forest catchment, *Q* is overestimated during winter (Fig. 3(a)). Generally, baseflow levels are well represented by the DK-model.

Model efficiency of the DK-model is lower for the urbanized catchment which is also the smallest and most disturbed catchment (Table 3). Due to long-term heavy groundwater abstraction in the area, the groundwater table is located deep below the surface. This causes baseflow to be low and streamflow to be more dependent on near-surface interflow and surface runoff from impervious areas. The model simulates the high flows during winter adequately (Fig. 3(b)) but lacks the ability to represent the quick surface flows from the impervious areas during summertime. Because the DK-model is generally found to be more reliable for larger catchments (Henriksen *et al.*, 2003), the relatively small area of the urban catchment (45 km^2) may contribute to reduce model efficiency for this catchment.

Table 3 The Nash-Sutcliffe Efficiency (NSE), the normalized Root Mean Square error (RMS*) and the squared linear correlation coefficient (r^2) based on discharge data (*Q*) and water flow simulations from the DK-model and Daisy in 2001–2003. (^{a}Evaluated using ($Q - Q_b$) instead of *Q*.)

Catchment type	Catchment number	Model	1 Jan–31 Dec. NSE	RMS*	r^2	1 Apr–30 Sep NSE	RMS*	r^2
Forest	500056	DK-model	0.28	0.76	0.70	0.55	0.80	0.25
Urban	530054	DK-model	0.25	1.25	0.40	–0.17	1.75	0.02
Agricultural	560005	DK-model	0.79	0.43	0.83	0.75	0.73	0.59
Forest	500056	Daisy: R_c+D_c+M_c	-	-	-	0.54	0.82	0.39
Urban	530054	Daisy: R_c+D_c	0.51^a	1.27^a	0.53^a	0.47^a	1.33^a	0.55^a
Agricultural	560005	Daisy: R_c+D_c	-	-	-	0.47^a	1.59^a	0.34^a

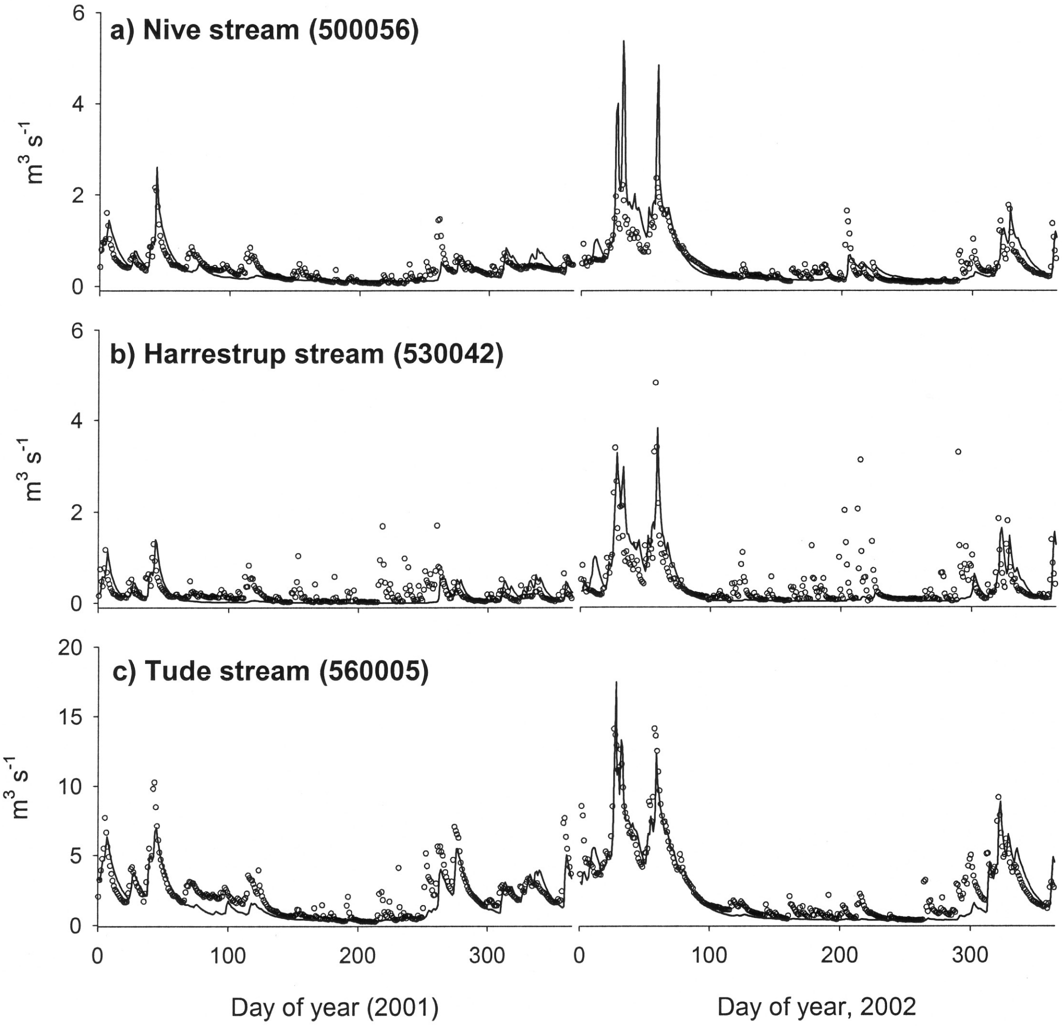

Fig. 3 Discharge data (empty circles) and stream flow simulations conducted by the DK-model (full line) for three catchments dominated by: (a) forests, (b) urban regions and (c) agricultural land. Model efficiency is quantified in Table 3.

The model efficiency of Daisy water flow is lower compared to the DK-model results for both the agricultural and forest catchments, but higher in the urbanized catchment (Table 3) where streamflow is governed mainly by quick surface flows. The higher RMS* errors of the Daisy model for the agricultural and forest catchments (Table 3) indicate a poor ability to simulate absolute water flow, which is related to the incomplete (and uncalibrated) representation of interflow in the model. For the agricultural catchment, it is likely that model efficiency could be improved by using discharge data for calibration of pipe drain parameterization. For the forest catchment, the relatively good agreement between Daisy aggregated ($R_c + D_c + M_c$) and measured Q in the forest catchment during summer confirms the contribution of M_c to interflow in this period. During winter, a larger fraction of M_c contributes to increase groundwater storage. Overall, the difference between simulated ($R_c + D_c + M_c$) and measured Q is indicative of net groundwater recharge (Fig. 4(a)).

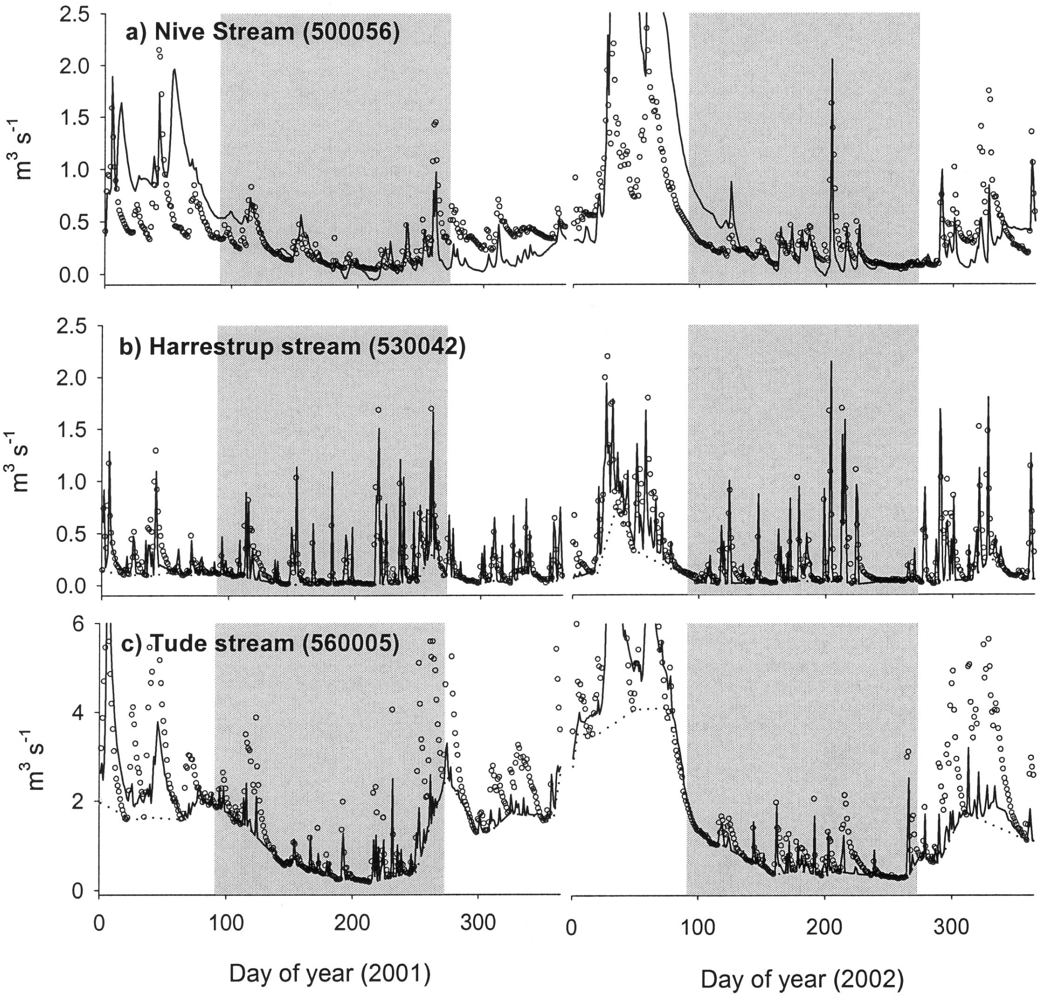

Fig. 4 Daisy water flow simulations (black line) and discharge data (empty circles) in three different catchments composed by large areas of: (a) forests, (b) urban regions and (c) agricultural land. Model efficiency is quantified in Table 3 for 1 April–1 October (shaded area in the graphs). The dotted lines in (b) and (c) show the estimated Q_b which were added to ($R_c + D_c$) to allow comparison with discharge data.

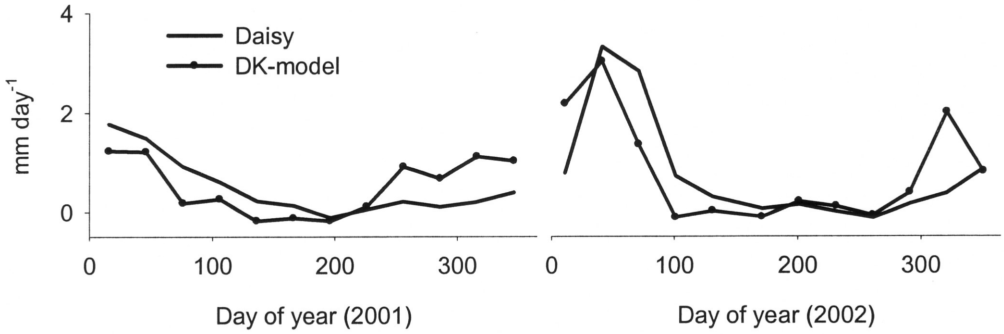

Fig. 5. Comparison of Daisy mean monthly drainage ($M_c + D_c$) and DK-model mean monthly net precipitation ($P_c - E_c$) integrated for Sjælland.

Water balance evaluation of Sjælland

Comparison of Daisy ($P_c - E_c$) and the DK-model corrected ($P_c - E_c$) confirms a rather good agreement of annual estimates for Sjælland (Table 4), but overall Daisy drainage simulations exceed DK-model net precipitation estimates during spring while the opposite situation occurs during autumn (Fig. 5).

Table 4 Water balance of Sjælland (mm year^{-1}) assessed using Daisy and DK-model simulations and discharge data. Using Daisy, soil water storage changes account for –8 mm in 2001 and –13 mm in 2002.

	Daisy		DK-model	
	2001	2002	2001	2002
P_c	785	925	773	922
E_c	593	629	582	603
$P_c - E_c$	192	296	191	319
Q	194	324	194	324
ΔS (total)	–2	–28	–3	–5

Integrating the regional water balance simulations for Sjælland (ignoring water abstractions), the difference between ($P_c - E_c$) and Q can be used to assess water storage changes in soils and groundwater at Sjælland (equation 2). Using discharge measurements from 30 catchments to represent Q, the water balance of Sjælland is found to be nearly in balance in 2001 and 2002 (Table 4) but large spatial variations in ΔS are present (Fig. 6). In 2001, where the best agreement between annual ($P_c - E_c$) of the DK-model and Daisy is found, the catchment-based rates of ($P_c - E_c$) vary between 161 and 292 mm year^{-1}. Even though this period is wetter than usual, only 20 out of 30 catchments have an apparent (no water abstraction included) positive water storage change in this year (Fig. 6).

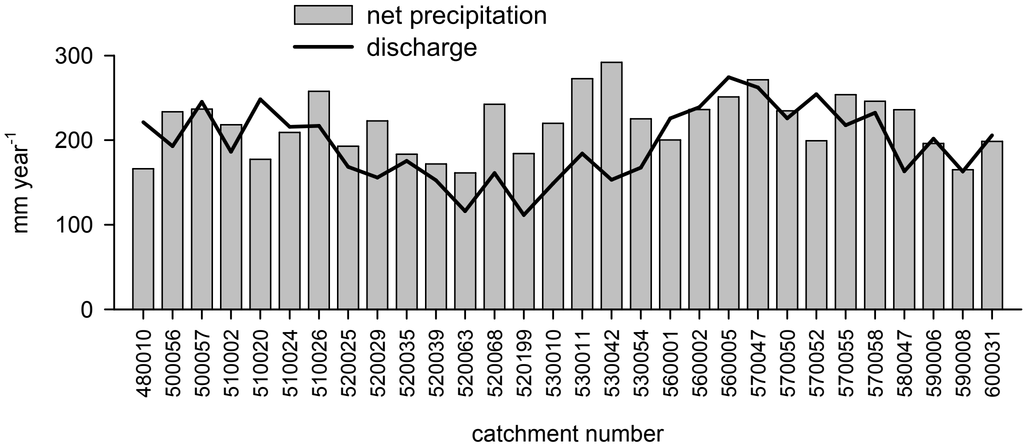

Fig. 6 Comparison of Daisy annual net precipitation and discharge measurements of 30 catchments (2001).

CONCLUSION

The empirically corrected DK-model net precipitation (Henriksen *et al*., 2003) was found to be in good agreement with Daisy annual net precipitation estimates for agricultural and forested catchments, and for all of Sjælland. Ignoring water abstraction, the water balance of Sjælland was found to be nearly in balance in 2001–2003. Despite the seasonal differences in ($P_c - E_c$) estimates, when calculated from Daisy and the DK-model, the application of the corrected DK-model net precipitation as input for streamflow simulation resulted in good annual (Fig. 2(b)) and daily (Fig. 3) discharge predictions for agricultural and forest catchments. Daisy simulations suggest that a more advanced distributed land surface parameterization can contribute to improve the water balance simulations of urbanized, surface-water-dominated catchments. Generally, differences in seasonal net precipitation estimates from Daisy and the DK-model (caused by remote sensing and/or dissimilar soil properties) suggest that model sensitivity and uncertainties related to spatially integrated net precipitation estimates should be further investigated.

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