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Applying profile- and catchment-based mathematical models for evaluating the run-off from a Nordic catchment

Csilla Farkas*, Sigrun H. Kværnø, Alexander Engebretsen, Robert Barneveld, Johannes Deelstra

NIBIO, Norwegian Institute of Bioeconomy Research, Frederik A. Dahls vei 20, 1430 Ås, Norway.
* Corresponding author. E-mail: csilla.farkas@nibio.no

Abstract: Knowledge of hydrological processes and water balance elements are important for climate adaptive water management as well as for introducing mitigation measures aiming to improve surface water quality. Mathematical models have the potential to estimate changes in hydrological processes under changing climatic or land use conditions. These models, indeed, need careful calibration and testing before being applied in decision making. The aim of this study was to compare the capability of five different hydrological models to predict the runoff and the soil water balance elements of a small catchment in Norway. The models were harmonised and calibrated against the same data set. In overall, a good agreement between the measured and simulated runoff was obtained for the different models when integrating the results over a week or longer periods. Model simulations indicate that forest appears to be very important for the water balance in the catchment, and that there is a lack of information on land use specific water balance elements. We concluded that joint application of hydrological models serves as a good background for ensemble modelling of water transport processes within a catchment and can highlight the uncertainty of models forecast.

Keywords: Runoff; SWAT; COUP; DRAINMOD; HBV; INCA; Model harmonization; Model comparison.

INTRODUCTION

Agriculture is one of the main contributors of nutrient loads to open water courses, being to a large degree responsible for the eutrophication of inland and coastal waters (Bodí et al., 2012; Cerdà et al., 2009; Debolini et al., 2015; Walraevens et al., 2015). Water is the transport mechanism for nutrients and soil particles to open water courses and groundwater. Therefore, a good understanding of the surface and subsurface hydrological processes is important in selecting the right mitigation measures to improve soil and water quality (Bisantino et al., 2015; Gessesse et al., 2015; Keesstra et al., 2016; Prosdocimi et al., 2016; Tian et al., 2016; Zema et al., 2016). In a study carried out in the Baltic and Nordic countries, Vagstad et al. (2004) found that the hydrology played an important role in explaining the differences in nutrient losses between catchments. Catchments having a large contribution of groundwater runoff in the total runoff, in general had lower nitrogen losses. The proportion of the locally detached nutrient load that is transported out of the catchment depends on the magnitude of the local losses, precipitation and antecedent moisture conditions (Giménez et al., 2012), and the degree to which the catchment facilitates water and sediment transport (Heathwaite et al., 2005). The latter term, hydrological connectivity, is itself dependent on structural system components such as terrain, soil physical characteristics and land management, and the system functions that govern drainage and overland flow (Bracken and Croke, 2007). While functional connectivity expresses flows and fluxes in time, structural connectivity is a (pseudo)static catchment characteristic, at least for the duration of a rainstorm.

Borselli et al. (2008) express structural connectivity as a spatial index that combines a characterisation of a point's contributing area with its downstream pathway to a sink area, e.g. the stream network. Expressed in this way, connectivity is also a function of intra-annual variations, such as crop cover characteristics as an index for resistance to overland flow. While overland flow and the resultant sediment fluxes relate to horizontal connectivity, vertical connectivity is a key system property to understand catchment responses.

In the other hand, artificial drainage of agricultural land is an important hydrological path way and can lead to an increase in nitrate-nitrogen runoff, its magnitude however influenced by soil type, drain spacing and drain depth (Skaggs et al., 1980). Tiemeyer et al. (2006) made similar observations and showed in addition that measurement scale can essentially influence the calculated nutrient losses. At the same time, subsurface drainage systems reduce the overland flow and the risk for surface runoff induced erosion and phosphorus loss (Turtola and Paajanen, 1995). Deelstra et al. (2007), when characterizing the hydrology in agricultural dominated catchments, showed that large diurnal variation in discharge could occur, often caused by a combination of scale, soil type, subsurface drainage intensity and topography. Especially in the Nordic countries, hydrological flow paths can be influenced during the winter season with below zero temperatures affecting nutrient loss and soil erosion (Deelstra et al., 2009). Understanding of these flow processes is important with respect to 1) their impact on nutrient and soil loss processes in catchments, 2) the choice and implementation of suitable mitigation measures to abate present and future pollution problems, 3) the design of hydro-technical implementations and 4) the effects of replacing traditional land use and soil management systems by new, sustainable climate-adaptive ones, that contribute to reduction of soil erosion and nutrient losses to surface water bodies.

This becomes even more important when considering the influence of climate change on hydrological flow paths, nutrient and soil loss. In this respect, mathematical models can be indispensable tools to facilitate decision making relative to the implementation of mitigation measures to improve water quality with the objective to achieve good ecological status, as embodied in the EU - Water Framework Directive. Different models can be used to predict nutrient and soil loss from agricultural dominated catchments; however a prerequisite is that the dominating hydrological flow processes are represented. When applying process-based mathematical models for describing the hydrological processes, occurring in a catchment under present and changing conditions (Bisantino et al., 2015; Galdino et al., 2016; Gessesse et al., 2014; Keesstra et al., 2009), it is important to analyse whether these models are able to simulate the hydrological processes and the water balance elements for various land use types - ranging from agricultural crops to different types of forest - and for different soil types.

The aim of this study was to test the applicability of different soil profile and catchment scale hydrological models for predicting the surface runoff and the soil water balance elements. Five different models (SWAT, DRAINMOD, COUP, HBV, INCA) were applied to the agricultural dominated Skuterud catchment with a land use covering agriculture, forest, bog and urban area.

MATERIALS AND METHODS

Catchment description

The Skuterud catchment, located in south eastern Norway was chosen as the pilot area for model comparison studies. The Skuterud catchment is a part of the Norwegian Agricultural Environmental Monitoring Programme (JOVA) since 1993. The catchment is located approximately 35 km south of Oslo. The total are of the catchment is 450 ha, with arable land constituting 61%, forest covering 29% while the rest is urban area (8%) and bog (2%). A large database containing detailed information about runoff, nutrient and soil loss is available in addition to data on farming practices, soil physical and chemical properties and meteorological data. (Deelstra et al., 2005). The long term mean annual temperature for Skuterud is 5.3°C. The mean annual temperature for 1993–2007 was 6.2°C, varying from 4.6–7.2°C (Table 1).

Table 1. Yearly temperature, precipitation, evapotranspiration, runoff, nitrogen and soil loss at the Skuterud catchment for 1993–2007.

	Average	Maximum	Minimum
Temperature (°C)	6.2	7.2	4.6
Precipitation (mm)	857	1200	651
PET (mm)	535	691	463
Runoff (mm)	528	919	278
Nitrogen loss (kg ha^{-1})	30	45	17
Soil loss (kg ha^{-1})	779	2009	170

The highest temperatures occur during the growing season from May to August. Below-zero temperatures can already occur in November but in general the winter starts in December and can last until March, with significant variation over the years. The average yearly potential evapotranspiration (PET) is 535 mm and varies from 463–691 mm. The long-term average annual precipitation is 785 mm. The average precipitation during the observation period was 857 mm, varying from 651 to 1200 mm. In general, the highest precipitation amounts occur after the growing season during the period from October to December. The meteorological data was obtained from the climatological station at IMT/Norwegian University of Life Sciences (1961–1990) at Ås, located approximately 4 km south-west from the Skuterud catchment.

The highest runoff and nutrient losses occur during the off-season from September–March. The average yearly runoff is 528 mm. There is a large variation in the yearly runoff for the period 1993–2007 (Table 1). Similar variations in the nitrogen and soil loss are observed. There is a strong seasonality in runoff generation. On average only 13% of the yearly runoff is generated during the summer season from May–August while 90% of the yearly runoff is discharged in less than 150 days. Surface runoff can occur during the autumn due to excessive precipitation over longer period. However, more often surface runoff is generated due to precipitation/snowmelt in combination with frozen soils which can occur both during autumn but more frequent during snowmelt at the end of the winter season.

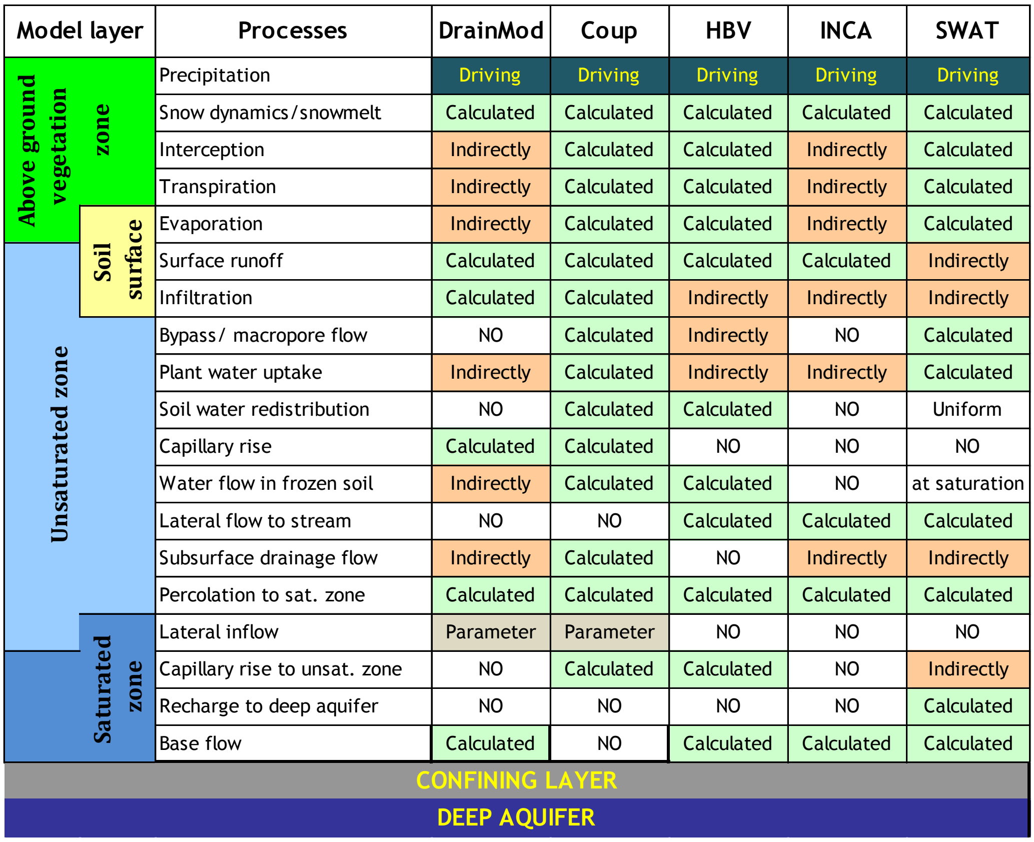
Model description

Five different dynamic mathematical models were parameterised, calibrated and compared with respect to i) spatial resolution, ii) the processes considered, iii) data and parameters required, iv) initial and boundary conditions and v) goodness of fit to the measured runoff at the catchment outlet. Two of the models – DRAINMOD (Skaggs, 1990) and COUP (Jansson and Karlberg, 2004) – are one-dimensional, profile-based models concentrating mainly on physically based representation of the hydrological processes, while the HBV (Sælthun, 1996), INCA (Butterfield et al., 2008) and SWAT (Arnold et al., 2002) are semi-distributed catchment models describing the surface and subsurface runoff generation processes in an integrated way. A short description of each model is presented below. The comparison of the main processes incorporated in the five models is given in Table 2.

The DRAINMOD model was developed to simulate the hydrology of poorly drained soils with high water table (Skaggs, 1990). Newer versions were further developed that combine the original DRAINMOD hydrology model with DRAINMOD-NII (nitrogen sub-model) and DRAINMOD-S (salinity sub-model) into a Windows based program. DRAINMOD predicts the effects of drainage and associated water management practices on water table depths, the soil water regime and crop yields. The model calculates surface runoff, changes in soil water content, subsurface drainage flow and evapotranspiration on a daily basis in response to given inputs consisting of meteorological data, measured or calculated potential evapotranspiration, soil and crop properties and drainage design parameters. Approximate methods are used to evaluate the various mechanisms of soil water movement and storage. Complex numerical methods are avoided by assuming a drained to equilibrium state for the soil water distribution above the water table. The model has been adjusted to cold conditions by incorporating the heat flow equation to predict soil temperature (Lou et al., 2000). When freezing conditions are indicated by below zero temperatures, the model calculates ice content in the soil profile and modifies soil hydraulic conductivity and infiltration rate accordingly. Snow is predicted to accumulate on the ground until air temperature rises above a snowmelt base temperature. Soil surface temperature is recalculated when snow cover exists. Daily snowmelt water is added to rainfall, which may infiltrate or run off depending on freezing conditions. Different versions of DRAINMOD have been developed, among others to simulate the hydrology of wetlands and forests (Amatya et al., 1997; Skaggs et al., 2005; Tian et al., 2010).

The coupled heat and mass transfer model for soil-plant-atmosphere systems, “COUP” (Jansson and Karlberg, 2004) is a process-based, one-dimensional model simulating vertical water, heat, carbon, nitrogen and solute transport in a soil profile. The COUP model is based on the previous SOIL + SOILN models. Water flow in unfrozen and partially frozen soil is calculated using Richards’ equation (Darcy’s law combined with the law of mass conservation). A two-domain approach can optionally be chosen to account for macropore flow. COUP calculates heat fluxes in the soil profile by the general heat flow

Table 2. Comparison of the five different models with respect to hydrological processes.



Model layer	Processes	DrainMod	Coup	HBV	INCA	SWAT
Above ground vegetation zone	Precipitation	Driving	Driving	Driving	Driving	Driving
	Snow dynamics/snowmelt	Calculated	Calculated	Calculated	Calculated	Calculated
	Interception	Indirectly	Calculated	Calculated	Indirectly	Calculated
	Transpiration	Indirectly	Calculated	Calculated	Indirectly	Calculated
Soil surface	Evaporation	Indirectly	Calculated	Calculated	Indirectly	Calculated
	Surface runoff	Calculated	Calculated	Calculated	Calculated	Indirectly
	Infiltration	Calculated	Calculated	Indirectly	Indirectly	Indirectly
Unsaturated zone	Bypass/ macropore flow	NO	Calculated	Indirectly	NO	Calculated
	Plant water uptake	Indirectly	Calculated	Indirectly	Indirectly	Calculated
	Soil water redistribution	NO	Calculated	Calculated	NO	Uniform
	Capillary rise	Calculated	Calculated	NO	NO	NO
	Water flow in frozen soil	Indirectly	Calculated	Calculated	NO	at saturation
	Lateral flow to stream	NO	NO	Calculated	Calculated	Calculated
	Subsurface drainage flow	Indirectly	Calculated	NO	Indirectly	Indirectly
	Percolation to sat. zone	Calculated	Calculated	Calculated	Calculated	Calculated
Saturated zone	Lateral inflow	Parameter	Parameter	NO	NO	NO
	Capillary rise to unsat. zone	NO	Calculated	Calculated	NO	Indirectly
	Recharge to deep aquifer	NO	NO	NO	NO	Calculated
	Base flow	Calculated	NO	Calculated	Calculated	Calculated
CONFINING LAYER						
DEEP AQUIFER						

equation in combination with the law of energy conservation, including parameters like heat capacity and thermal conductivity, both adjusted to account for the influence of soil ice content. Snow dynamics is also simulated: Precipitation falls as rain, snow or a mixture, depending on certain air temperature thresholds. Melting and refreezing of the snowpack is simulated using either an empirical function including global radiation, air temperature and soil heat flux, or an energy balance approach. Free water is released from the snow pack according to snow retention capacity. Water infiltrates into partly frozen soil through pores that are still filled with liquid water, or through large, air-filled pores. The amount of ice and liquid water in the soil change dynamically as total water content and soil temperature change, and depend on a freezing point depression function. A redistribution of liquid water may occur as infiltrating water refreezes, releasing heat which melts water in smaller, ice-filled pores. When the soil's infiltration capacity and surface water storage capacity is exceeded, surface runoff is generated by a first order rate process. Subsurface drainage can be calculated by empirical and/or physically based equations. Groundwater flow is considered as a sink term in the model. Evapotranspiration is calculated from the Penman-Monteith equation. The COUP model is able to simulate the water balance for different land uses and has among others been used for forested areas (Alavi et al., 2001; Persson, 1997)

The HBV model (Sælthun, 2006) is a semi-distributed, conceptual hydrological model that describes the essential characteristics of the precipitation-runoff process; it simulates the volumes of water stored as snow and subsurface water, and the streamflow. The model performs water balance calculations for 10 elevation bands within a watershed in order to take into account the altitude variation of the driving precipitation and temperature data. Each elevation band may be divided into a maximum of four computational elements; two land use zones with different vegetation and soil types, a lake area and a glacier area. It has components for accumulation, spatial distribution and ablation of snow, interception storage, spatial distribution of soil moisture storage, evapotranspiration, groundwater storage and runoff response, lake evaporation and glacier mass balance. Potential evapotranspiration is a function of air temperature, however, the effects of seasonally varying vegetation characteristics are considered. Water evaporates from interception storage at the potential rate, while evaporation from the soil is reduced below the potential rate when soil moisture storage is below field capacity. The algorithms of the model were described by Bergström (1995) and Sælthun (1996).

The INCA model is a processed based dynamic model describing water and mass transport in the plant/soil system and in the stream and can be used for various land use/vegetation types. In the INCA model, hydrological effective rainfall is the input to the soil water storage, driving water flow through the catchment. Hydrology within a catchment is modelled using a simple two-box approach, with key reservoirs of water in the reactive soil zone and deeper groundwater zone. Flows from the soil and groundwater zones are controlled by residence times in the reservoirs. The Base Flow Index is used to split between the volume of water stored in the soil and the groundwater (Wade et al., 2002). Calculation of river flow is based on mass balance of flow and on a multi-reach description of the river system (Whitehead et al., 1998). The model incorporates an empirical function for simulating soil temperature changes below the seasonal snow pack and a simple degree-day model to simulate the depth of the snow pack (Rankinen et al., 2004). The heat flux from the snow surface to the soil is calculated by the heat conduction equation.

The Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2005) is a continuous time, semi-distributed watershed-scale model that operates on a daily time step. SWAT is physically based and developed to quantify the impact of land management practices in large, complex watersheds. SWAT requires information about weather, soil properties, topography, vegetation, and land management practices in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modeled by SWAT using these input data. For modeling purposes, a watershed may be partitioned into a number of subwatersheds or subbasins which are spatially connected. Input information for each subbasin is grouped into hydrologic response units or HRUs. HRUs are lumped land areas comprised of unique land cover, soil, slope, and management combinations. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. SWAT calculates canopy storage (water intercepted by vegetative surfaces), infiltration, redistribution (movement of water through a soil profile after input of water), evapotranspiration (ET and PET), lateral subsurface flow, base flow and surface runoff. Surface runoff is computed using a modification of the SCS curve number method. The curve number method varies non-linearly with the moisture content of the soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as soil approaches saturation. The model increases runoff for frozen soils but still allows significant infiltration when the frozen soils are dry.

Models set up and parameterisation

The five models were run with the same driving meteorological variables and available soil and vegetation data for the Skuterud catchment. Common initial and lower boundary conditions were defined for all the models. Those parameters that were common in at least two models were set to the same value based on the available information and literature.

In case of distributed models, one simulation consisted of one model run, while the profile-based models (COUP and DRAINMOD) were run separately for representative soil profiles of agricultural and forest areas. Minor land use types in the catchment (urban and bog) were left out from the simulations and considered as forest areas. The total catchment runoff was obtained by calculating the area weighted runoff from DRAINMOD and COUP. The models were run for the period between January 1, 1993 and December 31, 2007. The year 1993 was considered as a "warming up" period to eliminate initial bias. The calibration and validation periods were defined from 1 January 1994 to 31 December 1999 and from 1 January 2000 to 31 December 2007, respectively. The models were calibrated individually by tuning on model parameters to minimise the difference between the measured and simulated runoff.

The determination coefficient (R^2) and the Nash-Sutcliffe statistics (N-S) were used for models evaluation. The model outputs were compared with the measured runoff at the catchment outlet. The water balance elements (transpiration, surface and subsurface share of the total runoff) were evaluated, using the available information from the catchment and literature data. We also compared the models results for the different seasons, focusing on winter and snow melt periods.

RESULTS AND DISCUSSION

Figure 1 presents the observed and simulated with the five different models discharge values at the catchment outlet.

Figure 2 shows the R^2- and N-S statistics, based on the simulations for the period from 1994 to 2007 comparing the measured and simulated runoff data on a daily, weekly, monthly and yearly base. The R^2- and N-S statistics were in the same order of magnitude for all the models, indicating that even one dimensional models like DRAINMOD and COUP can be used for simulating runoff dynamics at catchment level for small watersheds.

The SWAT showed the largest deviation between the daily and yearly integration. Model performances, in general, improved when integrating the results over longer time periods, indicating that the daily runoff dynamics were not simulated satisfactorily, while the weekly and monthly runoff was simulated quite well. The N-S and R^2 statistics for the models varied from approximately 0.30–0.65 to 0.70–0.90 when aggregated on daily and yearly basis, respectively. On a yearly basis, the SWAT model gave the best estimate for the total runoff at the catchment outlet, while the other four models gave more reliable estimates for daily, weekly and monthly dynamics. This is an indication, that the SWAT model needs further tuning with respect to redistribution of water between the different compartments, i.e. surface/subsurface drainage and base flow runoff and residence time of water between the root zone and the catchment outlet.

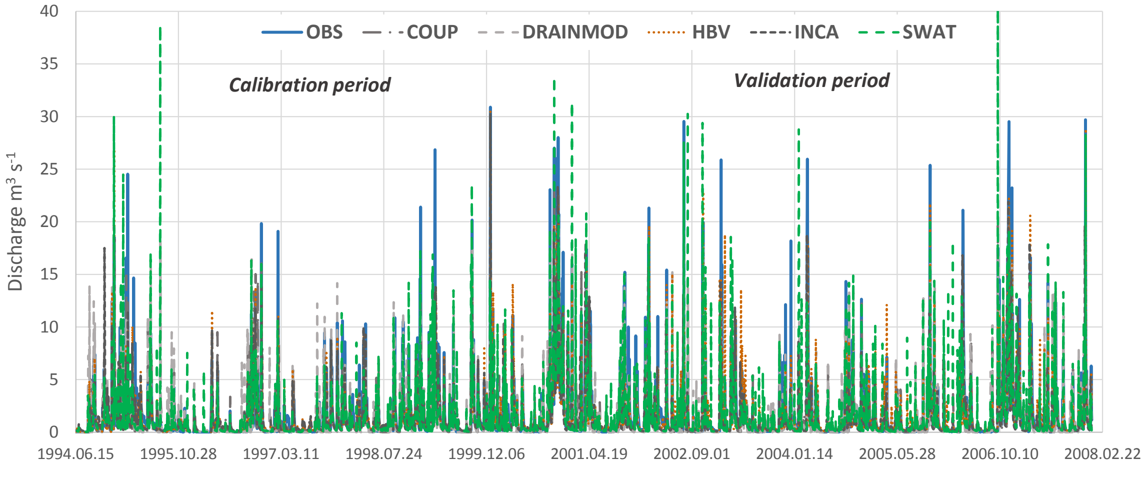


Fig. 1. Comparison of the observed (OBS) and simulated discharge for the calibration and validation periods.

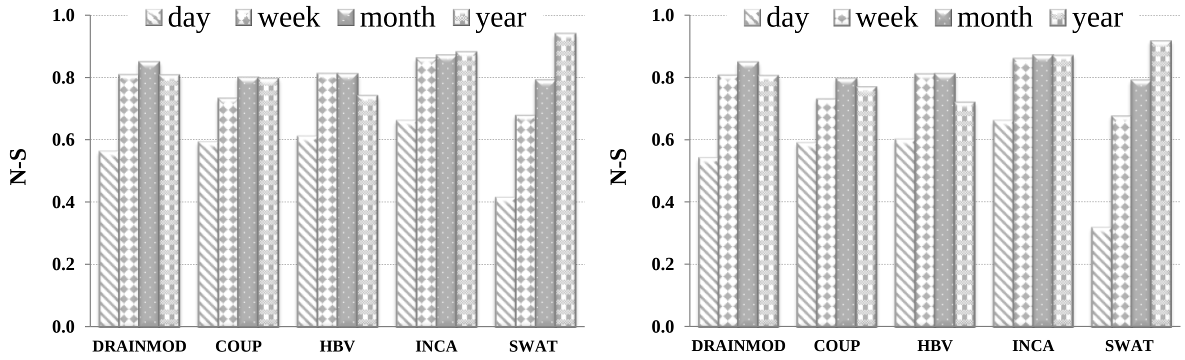


Fig. 2. Determination coefficients (R^2) and Nash-Sutcliff statistics, calculated from simulated runoff data integrated over various time periods for the five different models.

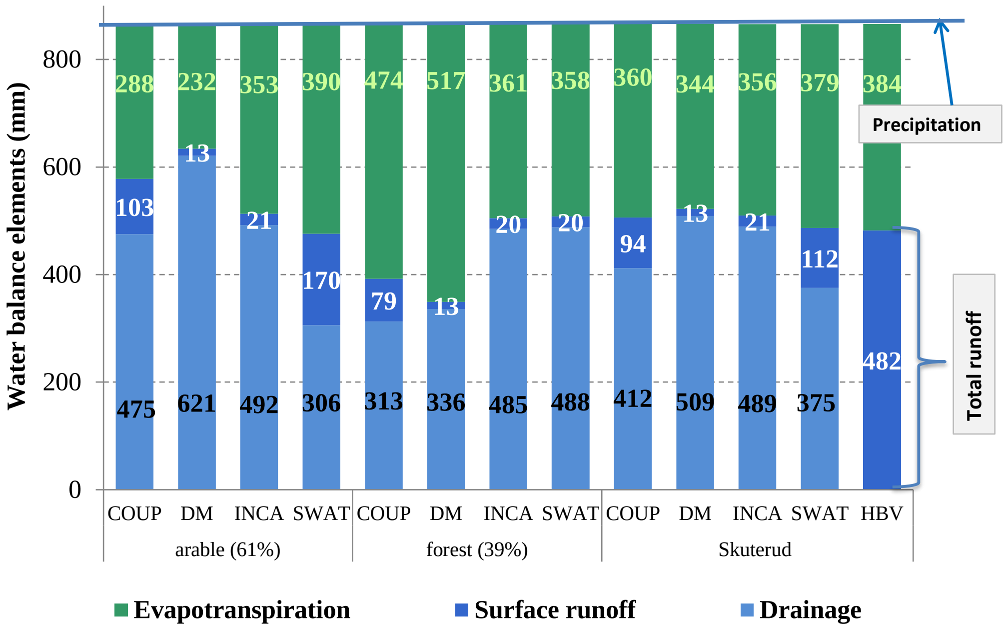


Fig. 3. Water balance elements, calculated for the arable land, forest and the whole Skuterud catchment using different models.

Selected water balance elements, calculated for the arable and forested areas as well as for the whole Skuterud catchment are given in Figure 3. When using the one-dimensional models COUP and DRAINMOD, the total simulated catchment runoff was obtained as the weighted average of the runoff obtained for forest and arable land separately. Calibration was done with emphasis on obtaining realistic values for the different water balance elements for both forested and agricultural land use. However, this was a difficult task because only the total runoff at the catchment outlet was measured. Lack of land-use specific information on hydrological and bio-geochemical processes is always an issue when calibrating catchment scale models for different purposes. An additional problem was the lack of data for water balance elements for forested land use in Norway.

The first thing considered was the difference between the measured precipitation in Ås and the measured discharge from the catchment. On average for the 15-year long simulation period this difference was 338 mm/yr, varying from 273–428 mm/yr. These values appear to be somewhat small, compared to the evapotranspiration (ET) values, estimated in Ås using other approaches. For example, in two plot studies carried out in Ås, the average difference between precipitation and discharge was 342 and 403 mm (Kværnø and Bechmann, 2010). In a lysimeter study with four different soils cropped with cereal, evapotranspiration from May to November was estimated to be around 330 mm on non-irrigated, winter-protected soil columns, and around 390 mm on irrigated, not winter-protected soil columns (Uhlen et al., 1996). According to these results, we assume that the catchment-scale simulation models gave better estimates of ET for arable land (353 mm – INCA and 390 mm – SWAT) than the profile-based models (Figure 3). The profile based models need further parameterization and calibration to improve evapotranspiration predictions.

Concerning evapotranspiration from forested areas, no overall conclusions can be drawn due to lack of measured data for soil and plant properties and runoff dynamics in Norway. In general, it is assumed that ET from forest is somewhat higher than from arable land, and since the expected ET on arable land most likely approaches or exceeds 400 mm, the overall ET from the Skuterud catchment is probably higher than the calculated precipitation-runoff difference. Possible explanations for the smaller than expected difference in Skuterud is that the measured discharge may contain uncertainties due to measurement errors originating from submerged flow condition during periods with high runoff, incorrect catchment boundaries. The incorrect inclusion of the urban areas in the modelling procedure as part of the forested land use could also lead to simulation errors. Also, there are uncertainties in the precipitation measurements, including effects of local variation (meteorological station is located some kilometres away from the catchment) and measurement errors due to the effects of wind drift on precipitation.

Knowledge about the partitioning of total runoff into surface- and subsurface runoff is of special importance with regard to the Water Framework Directive and the implementation of mitigation measures to decrease soil - and nutrient loss for improving water quality. The surface runoff from the agricultural areas generated by the COUP and SWAT models is 18 and 35% of the total runoff respectively, and is only 2 and 4% for the DRAINMOD and INCA models (see Fig. 2). For all the models, except SWAT, the total runoff generated for the forested area is less than for the agricultural area, which is in accordance with our expectations and with expert estimates.

It is hard to decide which model performed best in partitioning of total runoff into surface and subsurface runoff since very few measured data are available. For four sites on drained marine clay soils the share of measured surface runoff to the total runoff was in the range 10–30 % on average (Kværnø and Bechmann, 2010). Considering these findings, the COUP and SWAT models performed best in partitioning the total runoff from agricultural land.

Evaluation of the models on a seasonal basis showed, that the models performed well in the autumn period, having N-S values ranging from 0.53 to 0.81 and from 0.88 to 0.94 on a daily and monthly bases, respectively (Figure 4). The statistics for the winter period are also satisfactory. The summer period shows poor results, probably due to uncertainties in simulating evapotranspiration and also because at low flow amounts the relative error can be high.

The period of snow melting when the major part of soil and nutrients loss occurs is crucial in simulations. At the same time, this period gives the biggest challenge in simulations, because of the complexity of processes. Contrary to the COUP and SWAT models, INCA and the DRAINMOD showed good performance for the spring period. Differences in model performance can be due to differences in their structure, due to the complexity of the models, and also because of the need for more precise parameter tuning to capture the dynamics of the processes involved.

CONCLUSIONS

In overall, a good agreement between the measured and simulated runoff was obtained for the different models when integrating the results over a week or longer periods. However, efforts have to be made to obtain improved results also on a daily basis, especially as models are potentially useful tools in assessing the possible consequences of climate change on hydrology, nutrient and soil loss. In some cases the more simple models (DRAINMOD and HBV/INCA), gave better prediction of the catchment runoff compared to the more complex models (COUP and SWAT). This indicates that some of the processes were not yet carefully parameterised in the more complex models, and need further investigation and calibration. Model simulations indicate that i) forest appears to be very important for the water balance in the catchment, and therefore obtaining proper information about the different water balance elements for forests seems to be crucial and that ii) there is a lack of information on land use specific water balance elements.

Hydrological pathways are important in the transport of soil and nutrients. Models used in integrated water resources management should provide both surface and subsurface runoff as output. However, improved information on the relative contribution of the different runoff components at catchment scale is of utmost importance to be able to calibrate these models. The calibration of semi- or non-distributed models does not necessarily reflect proper representation of variable source areas and their contribution to fluxes at catchment level.

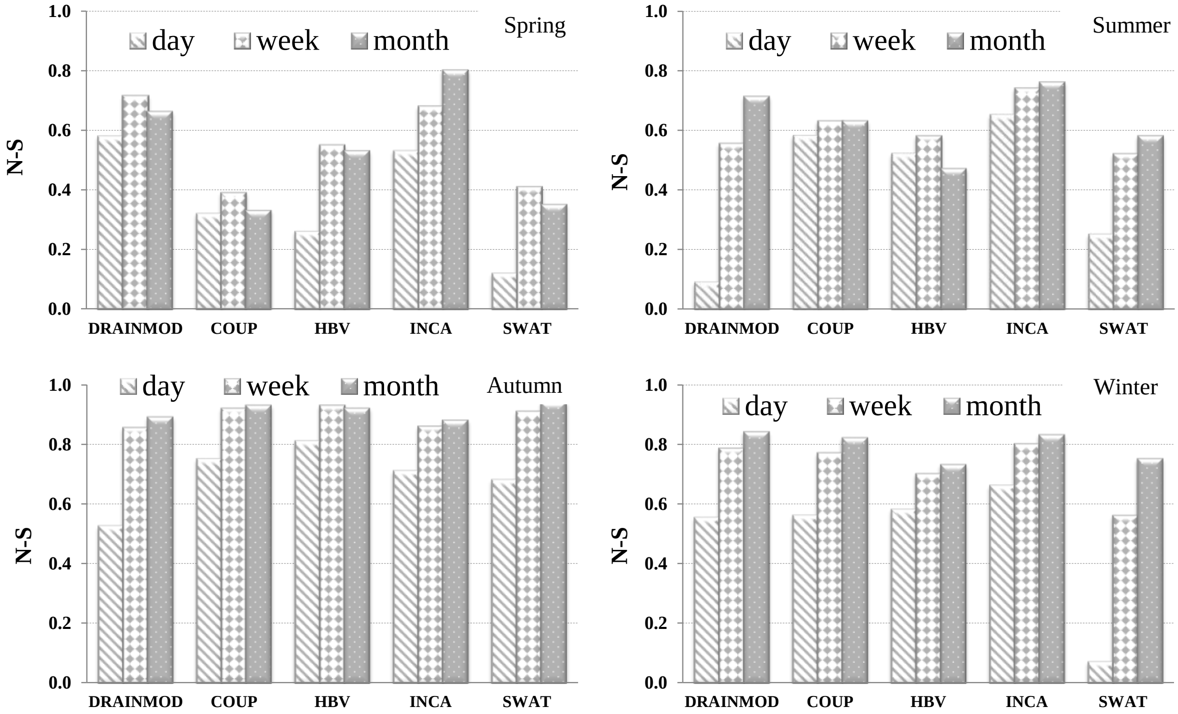


Fig. 4. Seasonal N-S statistics, calculated from simulated runoff data integrated over various time periods.

Sub-grid or HRU information about hydrological and sediment connectivity could allow models without flow routing to better represent within-catchment fluxes in space and time. Structural, or terrain based, connectivity indices could be linked to descriptive parameters of hydrological units to mimic sub-unit processes. Examples of these parameters in the INCA could be residence time for direct run-off, soil water and groundwater. We believe that further improvement of model calibration could be achieved by finding the ways on incorporating the connectivity information in the model parameters.

Our results indicate that profile based 1D models can be used for evaluating the runoff from small catchments, where the travel time from root zone to the outlet is relatively small either due to short distances or the effect of drains. In this case, models have to be calibrated separately for all the representative soil – land use combinations and modelling results need to be compared with catchment outlet measurements by integrating them according to their areal weights.

None of the models excelled with respect to all the evaluation criteria. The results showed wide variation in model behaviour with respect to the simulation of different water balance elements (i.e. evapotranspiration, surface and subsurface runoff) for various land use types. Hence, it is always important to analyse whether the modelling results are consistent with the empirical knowledge of the catchment processes and limited older data (Holko et al., 2011). We conclude that additional information is required to reduce the uncertainty of the different water balance elements and that further model calibration is needed to be able to carry out an objective-oriented model selection. Furthermore, joint, harmonised application of hydrological models serves as a good background for future ensemble modelling of water transport processes within a catchment, which can highlight the uncertainty of models forecast.

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Note: Colour version of Figures and Table 2 can be found in the web version of this article.