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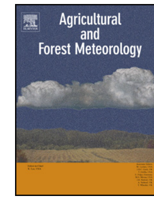

Analyzing the hydrological impact of afforestation and tree species in two catchments with contrasting soil properties using the spatially distributed model MIKE SHE SWET

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ABSTRACT

Groundwater depletion occurs at a global scale but requires regional strategies for sustainable management of freshwater resources. In Denmark the groundwater quantity and quality is under pressure, and forested areas are considered to protect groundwater reservoirs. However, little is known on how afforestation or forest conversion impacts the water resource at the catchment scale. We hypothesize that the groundwater formation and streamflow is increased when water consuming conifers are replaced with the less consumptive broadleaf tree species. To test this a distributed hydrological model with an energy-based description of evaporation and transpiration processes (MIKE SHE SWET) was used. Large scale hydrological models were established for two geologically (sandy/clayey) contrasting catchments in Denmark; Skjern and Lejre catchments. Land use scenarios were defined with forest vegetation (conifer/broadleaf) and agricultural crops (grass, maize, wheat and barley) in different areal combinations. Initially, the SWET component was calibrated against plot scale field data from two forest sites to obtain vegetation parameter estimates for conifers and broadleaves. Subsequently, the catchment models were run for 10 years with predefined land use scenarios. MIKE SHE SWET simulated canopy interception and throughfall for conifers and broadleaf forests satisfactorily. The catchment simulations showed that replacing current conifer forests with broadleaves, resulted in a significant increase in groundwater recharge and groundwater level, especially in the Skjern catchment with predominantly sandy soils. Also, doubling the forest area, as intended by national legislations, using only broadleaves did not negatively affect the groundwater generation or minimum stream discharge compared to current conditions at Skjern. However, because the shallow geology in the Lejre catchment are dominated by clayey glacial moraine deposits with low hydraulic conductivity, increased net precipitation in areas covered by broadleaf forests would primarily discharge as overland flow or drainage flow rather than contributing to groundwater formation.

1. Introduction

Groundwater depletion is a global problem (Aescherbach-Hertig and Gleeson, 2012) and the extent of depletion varies by region and thus calls for regional strategies for sustainable use and management of freshwater resources. As such there is a need to identify means to increase the water resource in order to sustain quantity and quality of water for ecological functions and societal consumption. Land-use is an important factor influencing the catchment water balance and changes in land-use will directly impact the available water resource (Elfert and Bormann 2010; Gustard and Wesselink 1993; Scanlon et al., 2005). In Denmark and many parts of Europe, the forest area is expanding by replacing agricultural areas and represents an important land use change (Fuchs et al., 2013) impacting biodiversity, climate change mitigation goals and water resources. Increased forest area and altered tree species composition may affect the hydrological cycle of catchments because of higher water use of forests compared to

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agriculture (Ladekarl et al., 2005; van der Salm et al, 2006; Verstraeten et al., 2005).

Early studies identified increased water loss associated with afforestation practices in catchments in the UK (Law 1956). Later, Bosch and Hewlett (1982) and Bell et al. (1990) showed for paired catchments that the change in water yield following afforestation or felling was proportional to the change in forest area. Conversion to coniferous forests decreased water yield relative to the original broadleaf forest and hence it was inferred that the conversion of coniferous to deciduous forest could be used to increase water yield (Komatsu et al., 2008). Plot modeling of forest water balance has also shown that recharge below broadleaf forests was higher compared to that of conifers because of higher evaporation of conifers (Christiansen et al., 2009; Rosenqvist et al., 2010; Salazar et al., 2013; Ladekarl et al., 2005; van der Salm et al., 2006), provided the stand ages are comparable (Müller, 2009).

However, paired catchment studies and plot scale studies do not operate on scales relevant to water management practices. Hence, hydrological models have been used to explore the hydrological implications of different land uses on larger scales. Gustard and Wesselink (1993) found that afforestation with coniferous forest shifted the flow duration curves down, decreased the annual minimum discharge, and increased the minimum storage to maintain a given water yield in the Balquhidder catchment in the UK. Zhang and Hiscock (2010), using MODFLOW coupled with the FAO-EA recharge model, estimated a reduction in recharge of up to 45% in simulations of four land-use scenarios with increasing forest area. Niehoff et al. (2002) and Elfert and Bormann (2010) used the physically based and distributed WaSiM-ETH model to quantify the impact of land use on flooding and river discharge. However, so far the importance of conversion from coniferous to broadleaf-dominated forests have not been evaluated in a model context because most distributed hydrological models lack proper tree species specific parameterization. Since canopy interception from forests is significant, it is very important for models to simulate evaporation satisfactorily such that different types of vegetation, including tree species, are parameterized correctly.

With the ambitious afforestation plan in Denmark to double the forest area with a focus on native broadleaf species (Ministry of the Environment, 2002) the structure and type of forest and coverage are expected to change. Since water use of conifers and broadleaves differ widely, afforestation or forest type conversion can be viewed as a potential tool in water resource planning to reduce or increase water yield.

We hypothesized that the water resource can be increased on a catchment scale by replacing water use intensive coniferous trees with the less consumptive broadleaves. In landscapes with multiple land uses, such as found in Denmark, but also throughout Europe and eastern United States, we lack quantitative knowledge on how forests contribute to the catchment water balance, especially groundwater generation and stream flow. We used the SVAT implementation in MIKE SHE (referred to as MIKE SHE SWET) to obtain an energy-based description of evaporation from vegetation that enabled us to consider evaporative losses from interception, transpiration and soil for coniferous and broadleaf tree species in comparison to typical agricultural crops investigated earlier. The primary objectives were to 1) parameterize typical coniferous and broadleaf tree species in the MIKE SHE SWET model, 2) assess how much more groundwater and stream flow can be generated by changing the current coniferous forests to broadleaf in two geologically (sandy/clayey) contrasting catchments, and 3) investigate the impact on the water resources if the broadleaf or coniferous forest area is doubled in the two catchments.

2. Materials and methods

2.1. MIKE SHE SWET

MIKE SHE is a widely used distributed and integrated modeling system for simulation of all the major land based hydrological processes (Abbott et al., 1986; Graham and Butts 2005). The model is subdivided into modules that describe different hydrological processes. In the present application, the following model descriptions are used: The two-dimensional diffusive wave approximation of the Saint Venant equations for overland flow; Muskingum–Cunge routing (Chow et al., 1988) for flow in the river system; the three-dimensional Boussinesq equation for flow in the groundwater zone; the Darcy equation for the river–aquifer interaction; while the unsaturated zone is described by the one-dimensional Richards' equation. Flow to tile drains or small ditches is described as a linear reservoir where the flux is proportional to the difference between the elevation of the groundwater table and the position of the drains. More information about the MIKE SHE modeling system can be found in Refsgaard and Storm (1995) and Graham and Butts (2005).

The MIKE SHE SWET is an extension of the MIKE SHE distributed hydrological model replacing the simplified evapotranspiration (ET) module (based on potential ET) with a SWET (Shuttleworth Wallace ET) module based on the model concept by Shuttleworth and Wallace (1985). The SWET explicitly simulates the hydrological processes in the soil-surface-atmosphere continuum (Overgaard 2005) by coupling the water and energy exchange. It consists of a two layers system comprising the soil and vegetation canopy. The model simulates a single, semi-transparent canopy layer and heat and moisture are exchanged with the atmosphere through the canopy layer or by soil evaporation. The SWET model is driven by precipitation, net or global radiation, humidity, atmospheric pressure, temperature, and wind speed.

The SWET module is based on the concept of system resistances that control the transfer of energy and water between the soil, vegetation and atmosphere (Overgaard 2005). Central in this concept is the aerodynamic resistance, $r_a{}^a$ that controls the exchange between the vegetation and the atmosphere (only latent head exchange is shown here – see Overgaard (2005) for sensible heat and further derivations):

$$LE_a = \lambda \frac{e_c - e_a}{r_a^a} \tag{1}$$

where λ is the latent heat of water, e is the humidity, subscript c and a refers to mean canopy level and the atmosphere, respectively. Transpiration from the canopy is additionally controlled by the stomata resistance, $r_s{}^c$, and the leaf boundary layer resistance, $r_a{}^c$:

$$LE_c^d = \lambda \frac{e_l^d - e_c}{r_a^c + r_s^c} \tag{2}$$

where subscript l refers to leaf surface and superscript d refers to dry surface. Interception loss is controlled by the leaf boundary layer resistance, $r_a{}^c$:

$$LE_c^w = \lambda \frac{e_l^w - e_c}{r_a^c} \tag{3}$$

where superscript w indicates wet surface. Soil evaporation is a function of the soil evaporation resistance, r_g, which increases as the top soil dries out, and the soil surface – canopy resistance, $r_a{}^s$:

$$LE_s^d = \lambda \frac{e_s^d - e_c}{r_a^c + r_g} \tag{4}$$