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Groundwater recharge algorithm for forest management models

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ABSTRACT

Multifunctionality is a critical objective in forest management planning. Water related ecosystem services are only sparsely implemented in Forest Management Models (FMM) although water scarcity is highly relevant. This study proposes an approach to integrate groundwater recharge into a FMM. The approach is based on knowledge transfer between two different forest growth models. For site-specific simulations on the landscape level, observation-based models require functions that describe groundwater recharge in a non-mechanistic way. However, groundwater recharge is difficult to measure and strongly depends on environmental conditions. Thus, we calibrated the observation-based FMM site-specific for two different case study areas, using a process-based forest growth model and substitute empiricism. Relations between forest structure and groundwater recharge were derived with multiple linear regressions and included in a FMM. The groundwater recharge was remarkably influenced by tree species and stand structure at both sites. The approach simulates groundwater recharge plausibly depending on site conditions and stand management on landscape level. Groundwater recharge was between 30–50% of the occurring precipitation and higher within broadleaved stands. Exemplary simulation of a European beech - Norway spruce mixed forest stand reveals a trade-off between groundwater recharge and stand volume growth depending on forest management.

1. Introduction

In the face of climate change, forest development must be aligned to meet a broader range of tasks as in the past. Accordingly, modern forest management must consider a wide spectrum of ecosystem services. The Helsinki Criteria (MCPFE, 1993) implicates changes in forests that are managed with a focus on wood production and the maximization of financial gain toward more multifunctional forest ecosystems. Because of the strong paradigm shift within the past decades, it has become increasingly important to have an understanding of the manner in which sensitive ecosystem service provisions react to forest management and the possible conflicts and compatibility of various services (Biber et al., 2015). Practicing sustainable development remains a challenge today (Pandeya et al., 2016). In Germany, for example, there are efforts by several political parties to pay forest owners for the provisioning of modern ecosystem services and supportive forest management practices (DFWR, 2017).

Water is an increasingly critical economic factor in decision-making in industries such as mining, power, and tourism (WWAP, 2012). Today's global water withdrawal consists of one third of groundwater (Kundzewicz and Döll, 2009). By 2025, half of the world's population will be living in water-stressed areas (WHO, 2017). When considering the total water requirements of society and ecosystems, even more humid areas such as substantial parts of Europe, North America, South-West Australia, and South America are prone to water scarcity (Rijsberman, 2006). Water scarcity, on the one hand, is a result of increasing consumption and decreasing availability of water.

The human population and consumption of water per person are increasing (FAO, 2011). Industries, agriculture, and municipalities are the biggest consumers of water. Agriculture is the biggest consumer worldwide. Within Europe, industries have the largest demand for water (FAO, 2011). According to the Food and Agriculture Organization (FAO), freshwater is not being used efficiently. In addition to increasing water withdrawal, the second reason for water scarcity is

Abbreviations: AWF, Augsburg Western Forests; CCF, Continuous Cover Forestry; et_a, actual evapotranspiration; fc, field capacity; FMM, Forest Management Model; GSS, species-specific growing space share; GWR, groundwater recharge; h, tree height; Lnr, soil layer number; LSN, Lieberose Schlaubetal Neuzelle; MH, arithmetic mean height; n, number of trees; NFI, National Forest Inventory; PAWC, plant available water content; per, percolation; prec, precipitation; PWP, permanent wilting point; qmd, quadratic mean diameter; SDI, Stand Density Index; swc, soil water content; VH, vertical heterogeneity

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decreasing water availability. According to Natkhin et al. (2012), a decline in groundwater levels is recognizable across several regions in northeast Germany. Turral et al. (2011) stressed on the ways in which climate change influences water availability. They underpin that climate change will significantly reduce the recharge of groundwater in dry regions like South America and Africa. In Europe, climate change brings higher probability of droughts. Groundwater serves as the primary buffer for decreasing water supply. Therefore, it is highly important to be aware of the ways in which land use and landscape structures govern the availability of water.

Forests normally consume more water than cropland (Müller, 2011). During droughts, however, forests become more efficient and consume much less water (Zimmermann et al., 2008). Intensive agricultural land use is challenged with groundwater pollution. Therefore, about half of the water protection area in Germany is within forests (LfU, 2015). An upcoming issue that is often discussed is the development of a water cycle that is dependent on climate change and land cover (Peel, 2009; Oudin et al., 2008). However, only few investigations consider forest stand structure (Natkhin et al., 2012). Beside soil and climate conditions, the composition of tree species and stand structure influence groundwater recharge (Müller, 2013). Typical variables for describing the forest stand characteristics are tree species, stand density, tree height, and vertical heterogeneity. Findings in the literature concerning the magnitude of groundwater recharge differ strongly from each other. This is because of the differences between precipitation quantity and other site and stand conditions. As a benchmark, a range between 20–50% of the precipitation is a plausible quantity of groundwater recharge (Anders et al., 2004; Rust, 2009; Müller, 2011; Sutmöller and Meesenburg, 2012; Müller, 2013).

Groundwater recharge has been proved to depend on tree species. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) recharges less groundwater than Norway spruce (*Picea abies* (L.) H.Karst.) and Scots pine (*Pinus sylvestris* L.), and these two tree species recharge less groundwater than European beech (*Fagus sylvatica* L.) (Prietzel and Bachmann, 2011). Sutmöller and Meesenburg (2012) reported a significant difference between Norway spruce and European beech in their groundwater recharge. Norway spruce stands form less groundwater than European beech stands. Groundwater recharge primarily occurs outside the vegetation period. During winter, deciduous species almost consume no water, whereas conifers transpire and consume water (Hölting and Coldewey, 2013; Rötzer et al., 2017). This is the main reason for which conifers form less groundwater than deciduous trees. Previous work have also reported that species with low growth provide higher groundwater recharge (Pöhler et al., 2013). Ilstedt et al. (2016) and Sutmöller and Meesenburg (2012) show that groundwater recharge was maximized at intermediate tree densities. Müller (2011) demonstrated that stands with small trees form more groundwater than stands with big trees, but the influence of the tree species is higher than the influence of the tree height. Delzon and Loustau (2005) show an age-related decline in stand water use. Therefore, previous work connote contrary findings about the impact of stand height on groundwater recharge.

Although the process of creating concepts for ecosystem services in science and politics has an obvious advantage, the quantitative assessment of ecosystem services is still a challenge. This is particularly true when local decision makers require local information. For that purpose, simulation techniques play an increasingly important role (Nelson et al., 2009). Projects that investigate the long-term effect of forest management on the provision of ecosystem services, like ALTERFOR (Alternative models for future forest management) (ALTERFOR, 2017), are fully based on landscape scale simulation scenarios. Therefore, management models must now provide a broad range of ecosystem service results. The simulations of silvicultural treatment, which are part of forest management models, enable the investigation of forest management with respect to all relevant ecosystem services. Simulation models that intrinsically represent the interaction between various driving forces and management are an essential tool for estimating the long-term management effects on ecosystem services. In particular, water balance and landscape development are predestined for model evaluation because they depend on the interaction of many boundary conditions and are difficult to be depicted in empirical results (Pandeya et al., 2016).

The objectives of this study, which is based on two case study areas are:

(1) to present an algorithm that integrates quantitative groundwater recharge into forest management models
(2) to analyze whether there are species-specific relations between forest stand structure and groundwater recharge
(3) to examine whether there is a trade-off between productivity and groundwater recharge

2. Material and methods

2.1. Procedure

Our approach combines a process-based forest growth model with an observation-based one (Fig. 1). Therefore, we derive multilinear

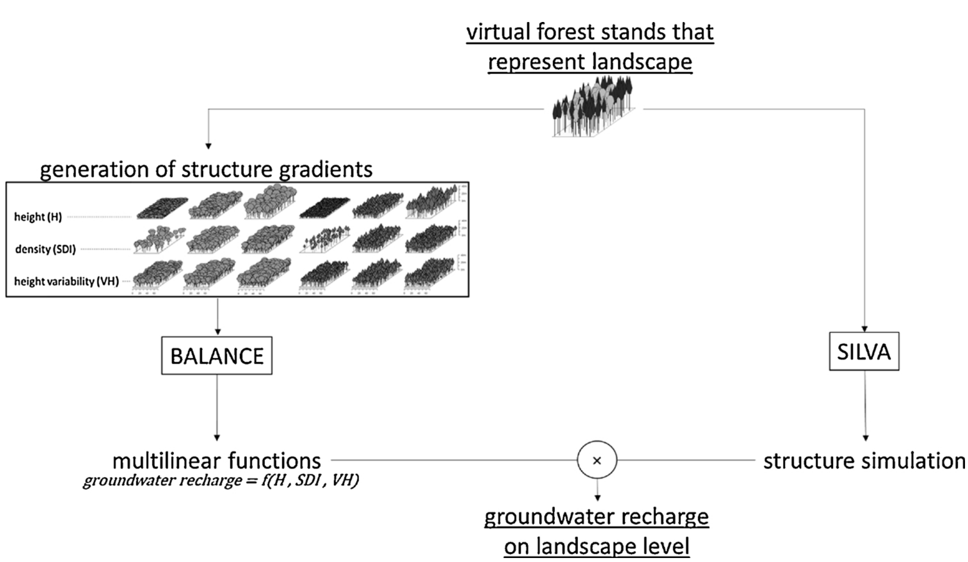

Fig. 1. Conceptual diagram of the approach for simulating groundwater recharge on the landscape level by means of an observation-based forest management model (SILVA) and a process-based forest growth model (BALANCE). Structure gradients that cover the range inside the landscape were generated. BALANCE was used to derive multilinear functions for estimating groundwater recharge as dependent on structure variables. These functions are applied to stand structures obtained from simulations using SILVA.