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Modelling the effects of land use and climate change on the water resources in the eastern Baltic Sea region using the SWAT model

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ABSTRACT

Combined and separate impact of climate and land use change on the future river runoff was assessed in the eastern Baltic Sea region by using the SWAT (The Soil and Water Assessment Tool) hydrological model. SWAT was applied to assess how plausible changes in climate and land use may affect the river hydrology by the end of the century. The model was calibrated and validated for a period from 1970 to 2010 (41 years) using daily river runoff data. Statistical and visual analysis of the achieved model presented adequate fit to the observed data allowing the reproduction of the current hydrological conditions of the basins for future analysis. The following conclusions from the study were made: 1) a strong linear correlation between forest cover change and annual river flow change was found; 2) the impact of land use change on runoff is important on an annual scale; 3) the scale of a basin is not important on the hydrological response to forest cover change; 4) the combined effect of land use and climate change was found to be non-additive. Findings of this study would help policy makers, to improve land and water management decisions and in formulating strategies to harness the positive impacts of possible overall increase in river runoff in the north-eastern Baltic Sea region.

1. Introduction

The statistical distribution of weather patterns is changing. Changes in air temperature and precipitation influence the hydrologic cycle and, moreover, the water resources. Climate change is caused by a possible combination of natural processes and human activity, although the extent of anthropogenic activities is uncertain. According to the intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, the global linear trend (1906–2005) for the annual near surface mean temperature is an increase of 0.74 °C per decade (IPCC, 2007). Furthermore, according to Tietäväinen et al. (2010) the rate of warming has tripled during the last 50 year (up to 0.30C per decade) in the Northern part of the Baltic Sea (Finland). The quality of the data for trend analysis in the first part of the 20-th century is considered low, and the credibility of the data in the second half can be considered as medium (Hartmann et al., 2013). This uncertainty is carried to future predictions, since this data is used as base to drive climate models.

The trends in runoff are influenced by changes in precipitation and temperature, where latter seems to have a stronger impact (The BACC II Author Team, 2015). Jaagus (2006) analyzed trends in the time series of air temperature and precipitation in Estonia during 1951–2000. There has been a statistically significant increase in air temperature during the cold period. In precipitation, increasing trends are present from October until March, and also in June. The duration of snow cover has decreased in Estonia 17–20 and 21–36 days, on the inland and coast, respectively. An increase in winter discharge has been detected in the Baltic Sea sub-basins. This is due to the higher temperatures, causing earlier snowmelt (BACC Author Team, 2008). It is evident from the above that in the eastern Baltic Sea region, the climate is changing.

Hydrological models are one of the tools to assess the possible changes in the future hydrology and water resources. Some of the widely used in the Baltic Sea region are the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2005), HBV (Bergström and Forsman, 1973; Lindström et al., 1997), Hydrological Predictions for the Environment (HYPE) (Lindström et al., 2010) and Hydrological Simulation Program Fortran (HSPF) (Bicknell et al., 1997). Hydrological models in these studies take into account the climate change impact on water quantity (Kjellström and Lind, 2009; Kriaučiūnienė et al., 2008; Latkovska et al., 2012; Øygarden et al., 2014; Tamm et al., 2015) or quality (Arheimer et al., 2012; Donnelly et al., 2011; Rankinen et al., 2016). However, there are no regional studies about the sole impact of land use change nor combined impact of climate and land-use change on future water resources in the eastern Baltic Sea region. The closest study in this topic has been carried out in the Narew basin, located in the North-East of Poland (Piniewski et al., 2014).

General Circulation Models (GCMs) are one of the basis of future

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climate studies, however, they have a coarse resolution (Flato et al., 2013). Stone (2003) found that in climate change impact studies, the resolution of the climate model plays an important role in estimating water yields in a basin. To overcome this limitation, one of the solutions is to use finer scale regional climate models (RCMs) which are forced by boundary and initial conditions generated by a CGM (Giorgi et al., 1990; Wang et al., 2004). Prein et al. (2016) demonstrated how RCMs clearly added value by improving the representation of spatial precipitation patterns. However, a study by Di Luca et al. (2013) suggests that RCMs may add relatively low additional value to surface temperature. However, they found that the largest potential for added value appears in coastline regions due to different warming of land and water surfaces.

Besides climate change, changes in land use may have a significant effect on hydrology (Wang et al., 2006), and thus, on water resources. At least one-third of the land surface has been modified by humans (Ellis, 2011). This tendency is likely to continue in the future to cope with the growing demand for resources (MEA, 2005). Global forest area has declined over 3% in the period from 1990 to 2015. The conversion of forest land to agricultural use has been the most significant driver for this tendency (Smith et al., 2016). However, in the Baltics, the recent land use change trend has been the opposite. After the Baltic States regained independence from the Soviet Union in 1991, the decrease in the agricultural land use started. This trend can largely be explained by the natural expansion of forest on abandoned agricultural lands and by afforestation, where less fertile lands were planted with trees (Palang et al., 1998). According to FAO (2010) 52% of the total area of Estonia is covered by forest, whereas around 23% is agricultural land. Besides changes in forest and agricultural land, urban land use increase in Estonia has been significant (Roose et al., 2013). Thus the main drivers for land use changes in the Baltics have been both political and economical.

Anthropogenic land-use and land-cover change affects the hydrologic cycle through evapotranspiration and the interception of water. Climate- and land use-induced changes in precipitation and evaporation directly affect the amount of available water, which can theoretically be used for hydropower production or for other uses of water resources.

The extent of climate and land use change effects on water resources vary, being dependent on the region analyzed and scenarios considered (IPCC, 2007). These impact studies should be regionalized in order to achieve a better understanding of the future. This paper proposes to use a semi-distributed hydrological model, the SWAT model (Soil and Water Assessment Tool), to estimate potential impacts of land use (deforestation and afforestation) and climate change on water resources in the West-Estonian river basin district, located in the north-eastern Baltic Sea region. The generated information from climate and land use change scenarios can be useful for relevant policies as guidance for adaption and mitigation measures. The joint effect of climate- and land use change on regional water resources has not been explored to date in the study area.

2. Study area

This study was conducted on the north-eastern Baltic Sea region, in the West-Estonian river basin district. The Baltic Sea drainage basin is about 1,745,000 km^2, which is divided into multiple sub-basins. The Baltic Sea is almost entirely enclosed by land, only connection to the North Sea is through the narrow Straits of Denmark. West-Estonian river basin district flows either to The Gulf of Riga or to the Gulf of Finland, which is the eastern arm of the Baltic Sea.

The West-Estonian river basin district is situated in the west of Estonia and covers an area of approximately 23,500 km^2 (Fig. 1), which is around half of the whole territory of Estonia. The climatic region of the study area can be described as semi-continental (coastal) and continental (inland). The weather is often breezy and humid due to the proximity of the Baltic Sea. The average annual precipitation and actual evaporation in the study area is around 700 and 400 mm, respectively. The average annual temperature in the West-Estonian river basin district was 5.1 °C during the period from 1971 to 2000. The local topography consists of relatively flat ground, with the basin district altitude ranging from 141 m above sea level to 0 m at the coast (drains to the Baltic Sea).

Forests and other wooded areas occupy 52% of the total area of the study basins in the baseline period (Table 1), whereas around 30% is agricultural land and 18% is considered other (urban, wetlands, water bodies etc.). Land use varies in a significant way between study basins. Vihterpalu river basin can be considered highly forested, with almost 60% covered by forest, but only 14% is used for agriculture. From all of the study basins, Keila basin has the largest coverage of agricultural land (around 42%) and just below 40% is categorized as forest.

3. Methods

The procedure for estimating the impacts of possible future climate and land-use change on hydrological behavior, is as follows: (1) parametrization and calibration of the SWAT hydrological model by using current climatic inputs, land-use map and observed river flow; (2) two regional climate models (RCMs) are applied (Luhamaa et al., 2014) and bias corrected against observed climate; (3) land-use change scenarios are generated for the end of the 21th century; (4) future scenarios are generated, based on the combinations of changing climate and land use; (5) the modelling results of the current and the future period are compared with the interquartile range. In the interquartile range, the extreme values (outliers) are excluded.

3.1. Hydrological model SWAT

The hydrological model SWAT is a widely used semi-physically based and a semi-distributed model that can simulate long term runoff and water quality. SWAT has been used in various water quality and quantity studies (Easton et al., 2010; Gassman et al., 2007). In SWAT, a basin can be partitioned into subbasins, and then further into combinations of unique soil, land use and management characteristics also known as hydrological response units (HRU) which are linked to the river network. It is assumed that HRUs are non-spatially distributed. Rainfall and evaporation is calculated for each HRU. In this study, thresholds for defining HRUs were set at 10% for soil and 10% for land use. Potential evapotranspiration was estimated by using the Hargreaves method (Hargreaves and Samani, 1982), for surface runoff calculation, the modified USDA Soil Conversion Service (SCS) curve number method was used.

Observed runoff data was used to calibrate the SWAT model by the software SWAT-CUP, using the SUFI-2 (Sequential Uncertainty Fitting Procedure Version 2) algorithm (Abbaspour, 2008). River runoff from all the study basins was calibrated and validated against daily measured data from 1970 to 2010 (a 41 year continuous period). Calibration was made with observed data from 1970 to 1997 and validation with observed data from 1998 to 2010. Two-year data (1968–1969) was set as a warm-up period.

The goodness of fit was evaluated qualitatively (visually) and quantitatively with the widely used Nash-Sutcliffe coefficient of efficiency (NSE, Nash and Sutcliffe, 1970), percent bias (PBIAS) and Kling-Gupta Efficiency (KGE, Gupta et al., 2009). Using an excessively over-or underestimating hydrological model for future studies (investigating possible changes in water resources), may lead to wrong conclusions. Thus, an acceptable PBIAS value in this study was set to 10% for daily streamflow and NSE/KGE values should exceed 0.65 to be considered satisfactory.

3.2. Climate scenarios

Regional scenarios of future climate are needed in order to assess future climate change impact on water resources with a hydrological