University of Sopron
Faculty of Forestry

Theses of doctoral (PhD) dissertation

The impact of vegetation on water balance in context of the climate change

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Background and objectives

The current and ongoing climate change can be characterized by a global temperature rise (an increase of 3.7 °C to 4.8 °C until 2100 relative to the period 1850-1900, according to the baseline scenarios – those without additional mitigation) (*IPCC*, 2014). The most significant effect of climate change is its impact on the water cycle through altering precipitation patterns and the evapotranspiration processes at multiple scales (*Sun* et al., 2011, *Szilágyi and Józsa*, 2008). The supposed changes in the distribution and amount of precipitation with the continuously increasing temperature may induce a higher rate in water consumption of the plants. In addition, this higher rate will generate changes in soil moisture, ground water and after all in the water cycle.

Globally circa 62% of the precipitation that falls on the continents is evapotranspired and nevertheless, evapotranspiration exceeds runoff on all continents except for Antarctica (*Dingman*, 2002). In the Carpathian Basin 90% of the precipitation is evapotranspired, while the remaining 10% is the runoff (*Kovács*, 2011). Therefore, evapotranspiration plays an important role in the availability of water on the surface of land, thereby controlling the large scale distribution of plants and primary production (*Vörösmarty* et al., 1998). Evapotranspiration also plays a key role in runoff and water availability in agriculture. Furthermore, most of the world's food supply is grown on irrigated land; thus, efficient irrigation requires knowledge of transpiration (*Dingman*, 2002).

Although evapotranspiration is a major component of hydrologic water balance, it is not well understood (*Wilson and Brown*, 1992). Accordingly, the necessity of modeling and attaining a quantitative understanding of the evapotranspiration process is unquestionable, particularly in context of climate change projections. Consequently, further studies are required, especially in regional scale.

The overall objective of my dissertation is: revealing the impacts of climate change on water-cycle, considering the Carpathian Basin's special climatic attributes in case of the agrarian and forestry sectors during the 21st century. To achieve this purpose, the main tasks are the following:

- A robust monthly step water balance model has to be established.

- The base model has to be calibrated and validated with measured actual evapotranspiration data for the 3 chosen study areas, which represent three different surface covers in the northwestern part of the Carpathian Basin.
- Based on the calibrated and validated models, projections for the actual evapotranspiration as well as for the soil moisture have to be done for the 21st century with the help of 4 bias corrected regional climate model datasets.
- Different kinds of water stress indexes have to be determined to quantify the impacts of climate change onto the vegetation.
- Impact of the extended rooting depth has to be determined

Data and methods

Three study areas in the Western part of Carpathian Basin were selected, namely: forested area (near Sopron), mixed parcel (near Mosonmagyaróvár) and agricultural field (the so-called Marchfeld near Vienna).

Model establishment

Thornthwaite-type, monthly step water balance model was established using the “R” statistical software (*R Core Team*, 2012). The available time series for forested area as well as for mixed parcel range from 2000 to 2008, while in the case of agricultural field from 2004 to 2011. The input values are monthly precipitation (PM) [mm] and temperature (TM) [°C].

The first main step in setting up the model was the calculation of a temperature-based potential evapotranspiration (PET) approach, after *Hamon* (1963).

$$PET_H = 29{,}8 \cdot D \frac{e_m^*}{T_m + 273{,}2} \qquad (1)$$

Where: D: day length [hr]; T_m: the average monthly temperature [°C]; e_m*: saturation vapor pressure [kPa].

The next step was a condition:

$$\text{If } P_M \geq PET_M \qquad (2)$$

$$\text{then: } ET_M = PET_M \text{ and } SOIL_M = \min\{[(P_M - ET_M) + SOIL_{M-1}], SOIL_{MAX}\} \qquad (3)$$

Where: PET_M is the calibrated monthly potential evapotranspiration [mm]. The determination of PET_M is part of the calibration. ET_M [mm] is the monthly actual evapotranspiration, and $SOIL_M$ [mm] is the monthly soil moisture, representing the amount of soil water that is available for the vegetation (not the total amount of soil water). Both ET_M and $SOIL_M$ denote the key output components of this dissertation.

The first $SOIL_{M-1}$ value was set to a maximum value that corresponded with the soil-water storage capacity ($SOIL_{MAX}$). The basic assumption was that soil water storage is saturated before the vegetative period starts. $SOIL_{MAX}$ was introduced using unsaturated hydraulic parameters of the soil types at the study areas with a standard setting of rooting depth (1 m):

$$\mathrm{SOIL_{MAX}} = \left(\theta_{\mathrm{fc}} - \theta_{\mathrm{pwp}}\right) * \mathrm{z_{rz}} \qquad (4)$$

Where: θ_{fc}: water content at field capacity [dimensionless]; θ_{pwp}: water content at permanent wilting point [dimensionless]; z_{rz}: rooting depth (vertical extent of root zone [mm].

The soil water storage has to be considered as reservoir for evapotranspiration. If:

$$P_M < PET_M \qquad (5)$$

then: $ET_M = P_M + SOIL_{M-1} - SOIL_M = P_M + \Delta SOIL$ (6)

$$\Delta\mathrm{SOIL} = \mathrm{SOIL_{M-1}} - \mathrm{SOIL_M} = \mathrm{SOIL_{M-1}} * \left(1 - \exp\left(-\frac{\mathrm{PET_M} - \mathrm{P_M}}{\mathrm{SOIL_{MAX}}}\right)\right) \qquad (7)$$

Where: $\Delta SOIL$: decrease in soil water storage [mm].

Calibration and validation of the model

Remote sensing based (ET_{CREMAP}) (for forested area and mixed parcel) and grass-covered lysimeter (ET_{LYS}) (for agricultural field) actual evapotranspiration data served as basis for calibration and validation (*Szilágyi* et al., 2011; *Nolz* et al., 2016).

The available time series for forested area and for mixed parcel was divided into two parts. The first part is used for calibration from 2000 to 2005, whereas the second is for validation from 2006 to 2008. For agricultural field the first part is from 2004 to 2008, but the second is from 2009 to 2011.

The calibration dataset was further divided into two parts considering both potential and actual evapotranspiration.

Model performance test

Model performance was tested using the coefficient of determination (R^2) and the Nash-Sutcliffe coefficients (R_{NS}^2).

Projection procedure

Inputs for predicting future developments of ET_M, $SOIL_M$ and $SOIL_{M\_10Percentile}$ (this parameter means the average of the values below the 10. percentile of the soil moisture) were the equations of the broken line regression, the calibrated $SOIL_{MAX}$ values, and projected T_M and P_M values. The latter two originate from four grid-based, bias-corrected regional climate models (RCMs). Data were extracted from nearest pixel to the study sites' coordinates. The underlying database called "FORESEE" contains daily meteorological data (min./max. temperature, and precipitation) based on ten RCMs for 2015-2100 (IPCC SRES A1B greenhouse gas emission scenario), and observation based data for the period 1951-2009, interpolated to 1/6×1/6 degree spatial resolution grid. The bias correction of the RCMs was done by a cumulative distribution functions fitting technique (*Dobor* et al., 2014).

Water stress

Relative extractable water (REW) and soil water deficit (SWD) were used to assessing water stress (*Granier* et al., 1999). In one hand, if REW drops below 50% threshold, then water stress assumed to occur. In other hand if SWD values are positive, then water stress is assumed to occur, since it indicates deficit.

Rooting depth parameterisation of the agricultural area

Two basic conditions (runs) were distinguished with respect to the rooting zone. The first run was based on a rooting depth corresponding to the characteristics of the lysimeter (static rooting depth). The second run was based on the condition that plants are able to adapt to water stress by increasing their rooting depth in order to meet their water demand taking advantage of a larger soil water reservoir (extended rooting depth). The bottom of the sandy loam layer within the lysimeter was at 1.4 m depth. Below it is a gravel layer with low water holding capacity. Consequently, for the second run, the rooting depth was set to the 1.4 m, which then modified the water storage capacity of the soil ($SOIL_{MAX}$). In such a way, potential stress conditions were determined for both static and extended rooting depth, calculated as potential PET minus $SOIL_M$. If the deficits are positive and else exceeding soil moisture values, then water stress will occur.

Results

A Thornthwaite-type, monthly step water balance model has been developed for regional usage, as methodical development. The model allows the definition of the soil-storage capacity as well as the rooting depth and nevertheless requires only few parameters as input (monthly temperature and precipitation)

The comparison of the 3 study areas in the context of PET_H and ET_M calibration revealed that each area has significant correlation between $PET_{CREMAP/LYS}$ (measured evapotranspiration values at well watered condition) and PET_H as well as $ET_{CREMAP/LYS}$ and ET_M. Thus, the values of the R^2 and the R^2_{NS} were higher than 0.85 in each case.

Calculated ET_M using the weather data of the validation period (forested area and mixed parcel: 2006–2008; agricultural field: 2009–2011) reflected good accordance with the measured data (ET_{LYS}/ET_{CREMAP}). The R^2_{NS} values were equal or higher than 0.85, so each model was accurate.

$SOIL_{MAX}$ values after re-calibration were 502.44 mm (forested area), 276.9 mm (mixed parcel) and 142.4 mm (agricultural field), while the calculated rooting depths were 4.5 m (forested area), 2.5 m (mixed parcel), 0.9 m (agricultural field). Consequently, much higher $SOIL_{MAX}$ has been found for forested area due to the presence of trees (nearly 100% forest covered), which also mean higher rooting depth and larger soil water reservoir as well. In case of agricultural field the $SOIL_{MAX}$ value for the 2nd run (extended rooting depth) was 233.4 mm, which was calculated with the help of the maximum possible rooting depth (1.4 m).

The projections (using the projected database derived from 4 RCMs) revealed that the ET_M values will increase at the end of the 21st century in each study sites. The highest rate of increasing occurs in case of forested area (+9%; +4.6 mm $\cdot$ month^{-1}). However, these rates are +8% (+3.3 mm $\cdot$ month^{-1}) for the agricultural field and +6% (+2.7 mm $\cdot$ month^{-1}) for the mixed parcel. Unlike the first part of the 21st century, there is a typical increasing tendency in the second part of the 21st century at each study area.

Contrary to the tendencies of ET_M, there are greater differences amongst the study sites in context of $SOIL_M$ means, because of the larger differences in the $SOIL_{MAX}$ values. Forested area has the highest and agricultural field has the lowest soil moisture mean values. Decreases have been found for the forested area (-6%; -22.8 mm) and mixed parcel (-8%; -16.0 mm), but increases for agricultural field (+13%; 8.4 mm).

With regard to plant water uptake, the 10th percentile minimums offer key information in context of water stress. In one hand forested area has increasing values (+11%; +26.3 mm) at the end of 21st century. On the other hand, there is significant tendency of decreasing for mixed parcel (-29%; -31.8 mm) and for agricultural field (-42%; -3.6 mm). The values of agricultural field are close to 0 due to the lowest vertical extent of the root zone as well as lowest $SOIL_{MAX}$ value amongst the 3 study sites.

In context of the 30-year monthly means of ET_M, the values generally increase towards the end of 21st century, particularly in summer period. Although, considering the annual averages, the agricultural field has the highest values, but the calculation of 30-year monthly means reveals that the forested area and even the mixed parcel have higher ET_M maximums in the summer period (and greater jump of values from the starts of growing season). The maximums are the following: 115 mm · month^{-1} (forested area); 105 mm · month^{-1} (mixed parcel); 100 mm · month^{-1} (agricultural field). The reason is the higher leaf area index of the forests, which leads to higher evaporative surface.

Comparing the 3 study sites, the difference is more significant for the 30-year monthly mean of $SOIL_M$ values than for the 30-year monthly mean of ET_M values. The highest values are observed at the forested area, which has also the highest annual fluctuation, but the lowest values and smallest fluctuations are observed at agricultural field. There is a decreasing tendency for monthly values of $SOIL_M$ towards the end of the 21st century, what is particularly characteristic in the growing season.

The former facts reveal that the water stress probability will increase towards the end of the 21st century (2070/2100), so water stress analysis has to be done. There is an increasing tendency towards the end of the 21st century, when REW values of the months decrease below the 50% threshold for forested area and for mixed parcel, but the values do not approach the 50% threshold (forested area: from 83% to 78%; mixed parcel: from 78% to 71%). These rates mean 79 months with water stress at forested area, 104 months at mixed parcel from the total 360 months (30-year period). REW values of agricultural field are under the 50% threshold more frequently, but show even an increasing tendency (from 42% to 46% (194 months)). Contrary to the REW, for SWD, the higher values mean higher water stress (higher deficit). Similarly to the REW values, forested area and mixed parcel show negative tendency towards the end of 21st century. The monthly rates, wherein water stress assumed to occur, are insignificant even at the end of the 21st century (at forested area: 9% (34 months); at mixed parcel: 24% (91 months)). At the agricultural field, however there is stagnancy (at 58% (215 months)), so the values exceed the 50% threshold in each investigation period. Thus, agricultural field area is where significant water stress can occur in the future, due to the relatively small $SOIL_{MAX}$ value. The REW and SWD do not indicate seasonal periodicity of water stress, therefore further analyses are needed.

For agricultural field two basic conditions were compared regarding the rooting zone. Comparison of the first run with the second run reveals minor differences, due to the simulated availability of soil water. The latter, represented by averaged $SOIL_M$ values, followed an upward tendency, mainly because of the underlying increasing precipitations. The general trend of the $SOIL_{M\_10Percentile}$ values was downward, but with larger values (16 mm in average) for the second run. It is evident that the larger soil water storage capacity provides better conditions for plant growth. The largest values of ET_M appeared in June (95-100 mm $\cdot$ month^{-1} for basic rooting depth; 98-105 mm $\cdot$ month^{-1} for extended rooting depth). Smallest $SOIL_M$ can be found in September (12.5-25 mm for static rooting depth; 50-60 mm for extended rooting depth). The largest values of $SOIL_M$ appeared in March (115 mm and 165 mm) – at the end of the dormancy and after winter precipitation due to the low ET values.

With respect to the basic rooting depth, potential water stress (calculated as PET_H - $SOIL_M$) was pronounced from June to September (largest deficit in July), when ET_M

is at maximum and $SOIL_M$ is low. Comparing the projection periods, the water stress is assumed to increase in future, about 50 mm for static rooting depth on the 2070-2100 period. Thus, periods of water stress and shortage of the available water are assumed to occur more often, although more soil water might be available in total. Water stress did not occur according to the 2nd run's projection, due to the larger $SOIL_{MAX}$.

My work is a part of a bigger ongoing project (*AgroClimate.2: VKSZ_12-1-2013-0034*), which aims a development of a robust water-balance model which needs a small number of input parameters. This research created the bedrock of the opportunity to extend the study area into a larger spatial scale (country-wide) and run projections for the future based on inputs of regional climate models.

Theses of the dissertation

1. A new simplified Thornthwaite-type monthly step water balance model has been developed for regional usage, with components of actual evapotranspiration and soil moisture as output parameters. The developed water balance model was calibrated locally, with the help of measured actual evapotranspiration data, for three different surface cover types (forested area; mixed parcel, agricultural field) **[1]**.

2. Using measured actual evapotranspiration data, the developed water balance model has been validated. The calculated actual evapotranspiration using the weather data of the validation periods reflected good accordance with the measured data (nash-sutcliffe model efficiency coefficient were 0.88 (forested area); 0.89 (mixed parcel); 0.85 (agricultural field)) **[2]**.

3. Based on the simulation results of 4 bias-corrected regional climate models (IPCC SRES A1B emission scenario), the hydrological impacts of the climate change has been evaluated during the 21st century for the three study sites. The comparison of the study areas showed that the water availability for plants is expected to be the most favorable in the forested area, whereas the most unfavorable conditions can be in the agricultural field **[2]**.

- The actual evapotranspiration mean values may increase slightly at the end of the 21st century (compared the 2070/2100 period to the 1985/2015 reference period) in each study site. The rates of increase are 6–9%.

- In case of mean soil moisture, small decreases can occur for the forested area (-6%) and mixed parcel (-8%), whereas there might be an increase for the agricultural field (+13%) at the end of 21st century.
- The 10th percentile minimums of soil moisture show an increase for forested area (+11%). Whereas significant decreasing tendency is projected for mixed parcel (-29%) and for Marchfeld (-42%) at the end of 21st century.

4. The changes of 30-year monthly means of actual evapotranspiration and of soil moisture values were analyzed during the 21st century at each study areas **[2]**.

- The 30-year monthly mean values of actual evapotranspiration is likely increasing towards the end of 21st century at each study site, but significant shift of the values (10-15 mm · month^{-1} increases, which may occur in the 2070/2100 period) can only be found in the summer period, particularly in June and July.
- Regarding to the 30-year monthly mean values of soil moistures, there might be a decrease during the growing season, but no clear tendency in the dormancy towards the end of the 21st century. The lowest soil moisture values may occur in September at each study areas. The rates of the annual soil moisture fluctuations (difference between the month with the highest and the month with the lowest soil moisture values) and soil moisture storage capacity are lowest in case of the forested area (30%) but highest at the agricultural field (63%) at the end of 21st century.

5. Based on the results of water stress analyses (with the determination of relative extractable water and soil water deficit), significant water stress can be assumed to occur only in case of the agricultural field **[2]**.

- In context of the relative extractable water (REW), the projections for the 2070/2100 period were: 78% (forested area), 71% (mixed parcel) and 46% (agricultural field) at the end of the 21st century. Therefore, the values of REW were under the 50% threshold for 79 month at forested area, for 104 months at mixed parcel, and for 194 months at Marchfeld during the 30 years (360 month) long period.
- In case of soil water deficit (SWD), where the water stress assumed to occur when the rates are over 50%, the projections for the 2070/2100 period were 9% (forested area), 24% (mixed parcel) and 58% (agricultural

field). Hence, the values of SWD were above the 50% threshold for 34 month at forested area, for 91 months at mixed parcel, and for 215 months at Marchfeld during the 30 years (360 month) long period.

6. Using potential water stress analysis, it has been pointed out that the vegetation of the agricultural field can successfully adapt to the water scarcity by growing their roots to the possibly maximum (1.4 m). Comparison of the static and extended rooting depth of the plants showed the following results:

- In case of static rooting depth, the potential water stress was occurred from June to September, and nevertheless, it is assumed that the potential water stress is likely to increase towards the end of the 21st century. The peak values of potential water stress are increased from approximately 40 mm to 60 mm, and it is shifted from August to July.
- In case of extended rooting depth, the potential water stress is not expected to occur at all during the 21st century.

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