Research paper

Water and carbon balances in a hemi-boreal forest

Emílio Graciliano Ferreira Mercuri[1,2]*, Toomas Tamm[2] and Steffen Manfred Noe[2]

Mercuri, E.G.F., Tamm, T., Noe, S.M. 2023. Water and carbon balances in a hemi-boreal forest. – Forestry Studies | Metsanduslikud Uurimused 78, 72–90, ISSN 1406-9954. Journal homepage: http://mi.emu.ee/forestry.studies

Abstract. The carbon and water fluxes and their inter-relations are key aspects of ecosystem dynamics. In this study, regionalization was used in transferring parameters from the GR4J-Cemaneige model calibrated in Reola hydrographic basin to predict daily flows in Kalli basin; both watersheds are located in the southeast of Estonia. Evapotranspiration data was collected from the MODIS sensor of the Terra satellite and from the Station for Measuring Ecosystem-Atmosphere Relations (SMEAR Estonia). Precipitation data was collected from Tartu–Tõravere and SMEAR Estonia stations and river flow from Reola hydrometric station. The year 2011 was used for model warm-up, model calibration was done in 2012–2017 and the 2018–2020 period was used for validation. The GR4J-Cemaneige model was calibrated at Reola Basin, with a Nash-Sutcliffe Efficiency index of 0.73. The 6 constants of Reola subbasin were transferred to Kalli subbasin for river flow simulation. Net ecosystem exchange (NEE) was measured at the 70 m SMEAR tower with the eddy covariance technique. The balances indicate that the ecosystem at Kalli watershed is slowly becoming a source of carbon and less water is available at the catchment reservoir. NEE has increased from -1.23 µmol m^{-2} s^{-1} in 2015 to -0.62 µmol m^{-2} s^{-1} in 2020, while the delta water storage decreased from 0.24 mm in 2015 to -0.05 mm in 2020. This behavior may increase soil drying and oxidation, and it will probably release more carbon in the future. This research allows a better understanding of the Järvselja hemi-boreal forest water-carbon dynamics.

Key words: SMEAR Estonia, eddy covariance method, GR4J-Cemaneige model.

Authors' addresses: [1]Department of Environmental Engineering, Federal University of Parana (UFPR), Centro Politécnico, Curitiba 81530-000, Brazil; [2]Institute of Forestry and Engineering, Estonian University of Life Sciences, Fr. R. Kreutzwaldi 5, Tartu 51006, Estonia; *e-mail: emilio@ufpr.br

Introduction

This study represents an investigation of hydrological and carbon balances at a watershed located in the southeastern part of Estonia. This region is part of Narva watershed, which extends from the Russian Federation to Estonia and has its mouth in the Gulf of Finland (Georgievsky & Mamaeva, 2020). Ahja, Reola and Kalli watersheds are tributaries of the Emajõgi River, part of Narva watershed, and are covered with forests more than 50%. The hydrology of these forests is connected with its productivity and its biological responses, hence a feedback interaction between the energy and water balances must be

DOI: 10.2478/fsmu-2023-0006



© 2023 by the authors. Licensee Estonian University of Life Sciences, Tartu, Estonia. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

linked to understand the biosphere processes (Wei *et al.*, 2021). Terrestrial water storage and evapotranspiration (ET) have strong dependence on the vegetation type at the catchment scale, and they also play an important role in forest management and carbon exchange. Kalli watershed is located in the Lake Peipsi depression (Arold, 2005) and bordered by wetland areas with strong groundwater influence. It has a high groundwater table due to the vicinity to Lake Peipsi and the low altitudes of forest grounds (Noe *et al.*, 2011).

Baltic paleosol, located in northwest Russia, Estonia, Latvia, and Lithuania (Liivamägi *et al.*, 2014), was formed due to weathered succession, since the Cryogenian–Ediacaran age, when glaciations were deposited in western Baltica (Kumpulainen & Greiling, 2011). Fine-grained soil originated during the retreat of the continental Fennoscandian ice sheet during late Weichselian (Di Buò *et al.*, 2019; Woronko *et al.*, 2022). The soil formation process in Estonia at the calcareous glacial till (Are *et al.*, 2020) may have significantly influenced the groundwater movement at the watershed scale.

Several studies have questioned the appropriateness of water-balance closure assumptions, when not all components of the hydrological cycle are available (Flerchinger & Cooley, 2000; Mazur *et al.*, 2011; Pan *et al.*, 2017; Scott & Biederman, 2019; Safeeq *et al.*, 2021). The simplification that changes in storage with respect to time are zero at annual and smaller timescales is known to be wrong (Istanbulluoglu *et al.*, 2012; Wang *et al.*, 2014; Wang *et al.*, 2015; Rice & Emanuel, 2019). The Gravity Recovery and Climate Experiment (GRACE) satellite mission can provide the water storage change at the catchment scale, but it is limited to regional studies, due to the spatial resolution of the data (Richey *et al.*, 2015a; Richey *et al.*, 2015b; Vishwakarma *et al.*, 2021). Furthermore, hydrological models, such as the Soil and Water Assessment Tool (SWAT) have groundwater exchange related constants available for calibration (Tamm *et al.*, 2018; Carneiro *et al.*, 2020), which reinforce the importance of a better understanding of the closure of the water balance.

The aim of this study is to quantify the water and carbon balance at Kalli watershed. We analyze the similarity and relations between the net ecosystem exchange of carbon and the water availability in the soil reservoir. The overview of hydrological fluxes is presented for Reola and Kalli watersheds in daily, monthly and yearly sums, showing the temporal variation of precipitation, evapotranspiration, streamflow and delta storage. Hydrological modelling and regionalization were used for assuming the hydrological similarity for the flow response of the basins which have consonant relief, forests, soils and land use.

The upper part of the land use of Kalli basin is formed by the Järvselja experimental forest, which contains the dominant tree species in the hemiboreal zone: Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) H. Karst.), silver birch (*Betula pendula* Roth), downy birch (*Betula pubescens* Ehrh.), European aspen (*Populus tremula* L.), common alder (*Alnus glutinosa* (L.) Gaertn.) and grey alder (*Alnus incana* (L.) Moench) (Noe *et al.*, 2015). Estimates of evapotranspiration can vary from different tree species and depend on specific characteristics and processes of the forest, such as the Leaf Area Index (LAI), average age of the forest, species distribution, and human influences like clear cuts and forest management. As other hemi-boreal forests in the Baltic region, the Kalli basin forest is drained for forest management purposes, Figure 1 shows a ditch located in Järvselja Forest. Drainage ditches function as first-order streams, thus providing the input of particles and chemical substances into the fluvial system; also they are among the most favored habitats for beavers resulting in flooded stands, reduced tree growth and economical losses (Kalvīte *et al.*, 2021). In terms of the glob-

al warming potential, the contribution of CO_2 emissions to the total budget of greenhouse gas (GHG) emissions from drainage ditches can exceed the CH_4 contribution (Vanags-Duka *et al.*, 2022).



Figure 1. Ditch located in Järvselja Forest, photograph taken by the authors in September 2017.

Net ecosystem exchange (NEE) of the forest is composed of two processes: photosynthesis, which represents the carbon uptake by plants (gross primary production, GPP) and the total ecosystem respiration (R_{eco}), which consists of photorespiration, maintenance respiration, synthesis respiration of autotrophic plants and heterotrophic respiration by animals and microbes (Waring & Running, 1998). NEE signal convention is given by the equation NEE = GPP - R_{eco}. This study brings an innovative contribution as it presents the dynamics of the water and carbon cycles together at the hydrographic basin scale, in addition to discussing trends for the future.

Water balance

The water balance at the scale of a watershed can be expressed by equation 1. Figure 2 presents a scheme of the hydrologic system, with fluxes between different compartments.

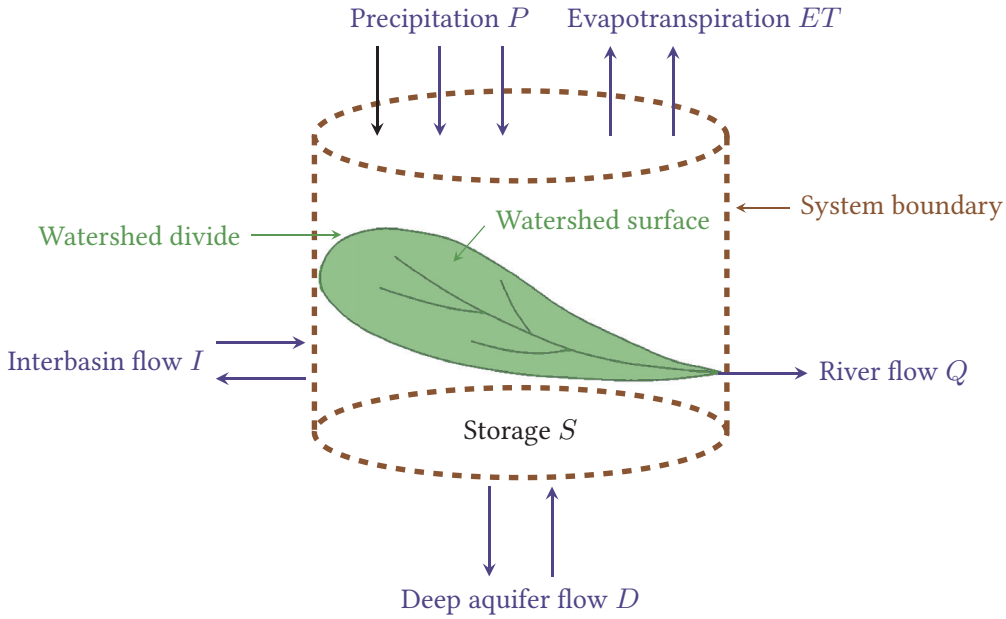


Figure 2. Scheme of a watershed showing the storage and fluxes in and out of the hydrologic system, adapted from Chow *et al.*, 1988.

$$\frac{\mathrm{d}S}{\mathrm{d}t} = P - ET - Q + (D + I) \qquad (1)$$

where S is the water volume stored per unit area in the basin, P is the areal mean rate of precipitation, ET is the evapotranspiration rate, Q is the river discharge per unit area, D is the deep aquifer flow and I is the total interbasin water exchange, as shown in Figure 2.

The terms in parentheses in equation 1 are difficult to quantify and are generally neglected from water balance (Chow *et al.*, 1988), we will follow this simplification. In equation 2 the variables from equation 1 are integrated with respect to time in the time interval Δt = 1 day, thereafter it represents the discrete water balance in each day i at the scale of the watershed.

$$\Delta \mathrm{S}_i = P_i - ET_i - Q_i \qquad (2)$$

For a large area and over a long period of time it is common to assume that positive and negative changes in catchment storage average to negligible values $(\overline{\Delta S} \approx 0)$ (Brutsaert, 2005; Reaver *et al.*, 2020). Andréassian *et al.* (2016) stated that long-term averages are characterized by at least a decade and preferentially three decades of time series data, which allows us to ignore catchment storage dynamics (both soil moisture and ground water). In this paper we are calculating the delta storage in daily, monthly, yearly, 6-year and 10-year intervals, so that our hypothesis is that for short time periods $\overline{\Delta S} \neq 0$. The bar over the symbols in equation 3 represents the short-term average over time, i.e. for less than 10 years.

$$\overline{\Delta S} = \bar{P} - \overline{ET} - \bar{Q} \qquad (3)$$

Applying the sum in equation 2 for N days of the analysis we get the accumulated water balance equation, described in equation 4.

$$\sum_{i=1}^{N} \Delta \mathrm{S}_i = \sum_{i=1}^{N} (P_i - ET_i - Q_i) \qquad (4)$$

Considering the classical approach of neglecting the long-term average storage (Brutsaert, 2005), we get equation 5. This equation is also called the Water Balance Method (WBM), as it relates the inputs of the hydrological system on the left hand side and the outputs on the right hand side.

$$\sum_{i=1}^{N} P_i = \sum_{i=1}^{N} (ET_i + Q_i) \qquad (5)$$

Several studies point out that the use of rain gauges can generate errors in undermeasurement of precipitation, both for snow (solid precipitation) and rain (liquid precipitation), mainly due to the effect of wind (Larson & Peck, 1974; Legates & DeLiberty, 1993; Groisman & Legates, 1994; Duchon & Essenberg, 2001; Hoeltgebaum, 2021). The WBM or double-mass curves can be used to correct the precipitation data (Searcy & Hardison, 1960).

The term ΔS_i represents the change in terrestrial water storage and has a great variability and uncertainty, but it is the key factor in relating terrestrial water to groundwater (Dias & Kan, 1999; Mohajerani *et al.*, 2021). It can be subdivided in different compartments of surface water storage, as shown in equation 6.

$$\Delta \mathrm{S}_i = \Delta \mathrm{GW}_i + \Delta \mathrm{SM}_i + \Delta \mathrm{SWE}_i + \Delta \mathrm{SW}_i \qquad (6)$$

The term ΔS_i was decomposed into 4 compartments: ΔGW_i or the change in groundwater storage, ΔSM_i the change in soil moisture, ΔSWE_i the change in snow water equivalent and ΔSW_i the change in surface water storage. The last term includes the effects of interception and surface reservoirs like lakes and rivers.

Water in the soil (ΔSM_i) can be also subdivided into saturated and unsaturated zones, part of it can be calculated by satellite information calibrated with ground truth measurements of soil moisture. According to Noe *et al.* (2011) the soil in Kalli watershed, near the SMEAR tower, was of high clay content, therefore the soil hydraulic conductivity is low, which implies that the soils will stay wet longer after snowmelt in spring. The soil around the flux tower has a humus horizon with a thickness of 24 cm, and the underlying sediment material was characterized by blue gleyic spots (Noe *et al.*, 2011).

Material and Methods

The map with the region of interest located in the southeast of Estonia, near the Russian border, is presented in Figure 2. There, three watersheds (Reola, Ahja and Kalli) drain into the Emajõgi River which drains to Lake Peipsi. The map shows the location of the Järvselja Forest and the watershed delineation with a thicker continuous black line, a subbasin of Reola watershed is depicted in green and a subbasin of Ahja watershed in yellow, which from now on will be called Reola and Ahja catchments. Their outlets were defined based on the location of the hydrometric stations. Kalli basin contains the Station for Measuring Ecosystem-Atmosphere Relations (SMEAR Estonia), part of the Järvselja Forest and ends after the confluence of Kalli and Apna rivers (Noe *et al.*, 2015). Figure 3 also shows the position of two meteorological stations (Tartu–Tõravere and Võru), two hydrometric stations (Reola and Ahja) and the SMEAR Estonia footprint area of influence.

The footprint area was calculated using the simple two-dimensional parameterization for Flux Footprint Prediction (FFP) (Kljun *et al.*, 2015). Footprint perimeter

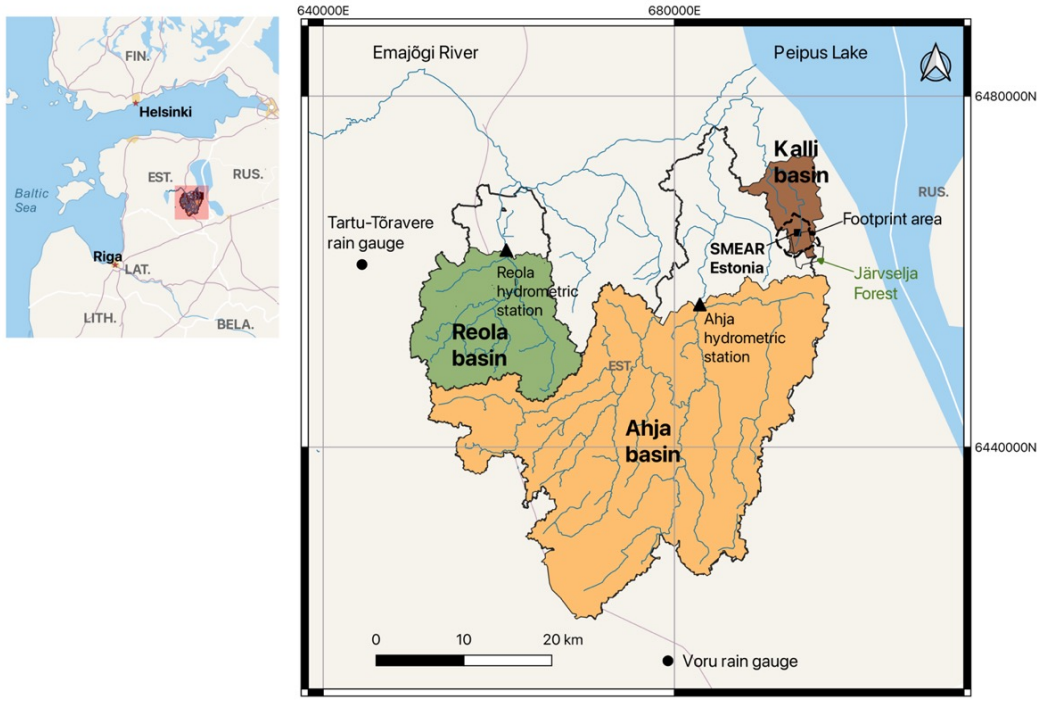


Figure 3. Study area, meteorological and hydrometric measuring stations, Reola, Ahja and Kalli subbasins, location of Järvselja Forest and footprint area.

represents the 90% source area and was determined using all 2020-year data from the 70 m tower of SMEAR. The perimeter represents the footprint climatology, an aggregation of footprints over several time steps. The 30-minute time step was adopted and the variables used in calculation were the Obukhov length, the boundary layer height, the standard deviation of lateral velocity fluctuations, the friction velocity and the wind direction.

The watershed delineation was made using the 25-meter resolution Digital Elevation Model (DEM) from the Estonian Topographic Database. The DEM raster data and the river drainage shapefile were downloaded from the Geoportal of the Republic of Estonia. The DEM was processed in QGIS using the *r.watershed* and *r.water.outlet* tools. The land use/land cover (LULC) classification was obtained from the European Spatial Agency (ESA) Sentinel-2 imagery with 10 m resolution; the data is from the year 2017. Table 1 shows the areas of the basins calculated in QGIS and the percentages of LULC. Rangelands consist of grasslands, shrublands, woodlands, wetlands, and deserts that are grazed by domestic livestock or wild animals. The built-up area is smaller than 1.5% in all basins.

Data inventory consists of hydrological and micro-meteorological records from different sources. The daily river flow rate (m^3/s) between 1970 and 2021 from Reola and Ahja hydrometric stations were downloaded from the Estonian Environmental Agency. Streamflow data was converted from m^3/s to mm/d after dividing by the watershed area and converting seconds to days. Daily precipitation data, daily temperature (minimum, maximum and average) between 2004 and 2021 at Tartu–Tõravere and Võru rain gauges were obtained from the Estonian Environmental Agency (EEA). EEA uses the OTT Pluvio² L weighing rain gauge, which is capable of measuring rain, snow, and hail. SMEAR Estonia provided precipitation measured by the Vaisala WX520 weather transmitter located at an open area 2 m high near the station and evapotranspiration calculated with the eddy covariance method using wind and water vapor concentration data measured at the 70-meter tower with 10 Hz frequency and compiled into a 30-minute time series that extends from 2015 until 2022. Evapotranspiration (*ET*) and Potential Evapotranspiration (*PET*) at the scale of the three subbasins from 2000 to 2022 were obtained by the MOD16 product from Moderate-Resolution Imaging Spectroradiometer (MODIS), a satellite-based sensor from the National Aeronautics and Space Administration (NASA). Satellite data of *ET* and *PET*, spatial resolution of 500 m × 500 m, comes originally as an 8-day composite data and it was converted to daily data. The consistency of the data was achieved by using double-mass curves (Searcy & Hardison, 1960).

NEE was determined using eddy covariance (EC) at SMEAR Estonia at the 70-meter tower from 2015 to 2022. The fluxes follow the atmospheric community sign convention, where the negative value denotes the direction of the flux from the atmosphere to the ecosystem, while the positive flux is the opposite (Krasnova, 2022). The eddy covariance fluxes were calculated as a covariance of the gas mixing ratio (CO_2 and H_2O) and vertical wind speed and averaged over 30-minute periods using the EddyPro software (LI-COR, Lincoln, NE, USA).

Table 1. Areas of the watersheds and percentages of land use.

Watershed	Area (km^2)	Forest (%)	Crops (%)	Rangelands (%)	Other (%)
Ahja	920.1	55.3%	33.9%	8.7%	2.1%
Reola	236.4	54.8%	30.3%	13.1%	1.8%
Kalli	55.6	74.9%	0.0%	24.6%	0.5%

Data corrections

Ten years of good quality hydrologic data was chosen for the water balance analysis, simultaneous data was collected from 2011 to 2020. Figure 4 shows an overview extract of available river flow and precipitation data, from 2015 to 2020, for visualization purposes. Due to its piezoelectric measurement detection principle, the impact of individual raindrops on a steel cover, the rain sensor at SMEAR underestimates solid precipitation (Vaisala, 2012), especially in winter, which can be seen in Figure 3. A correction of SMEAR precipitation data was made by looking at the mean average air temperature T_{air} at the station: when $T_{air} < 1^{o}C$ the nearby Tartu–Tõravere rain data was used to fill the gaps of spurious precipitation data.

Daily average MODIS evapotranspiration from Reola, Ahja and Kalli subbasins was compared to measurements at

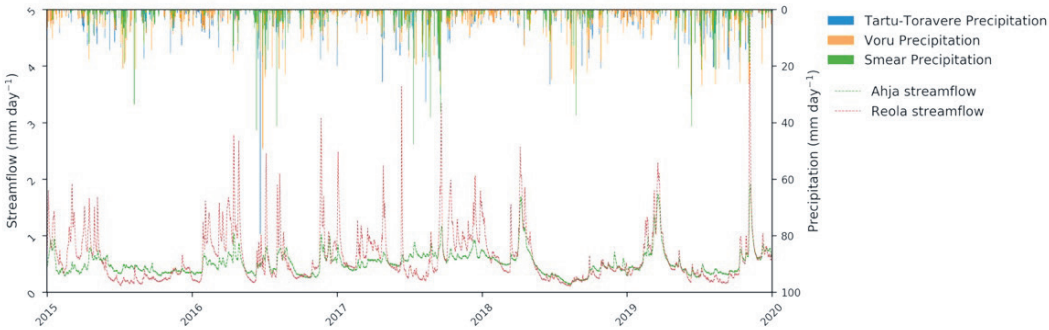
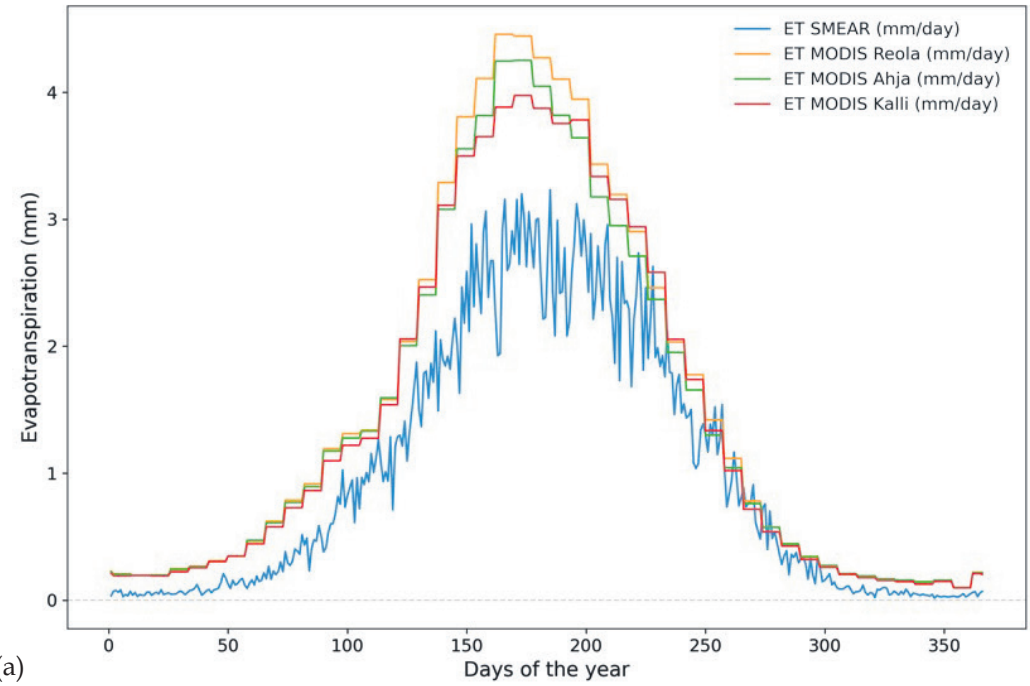
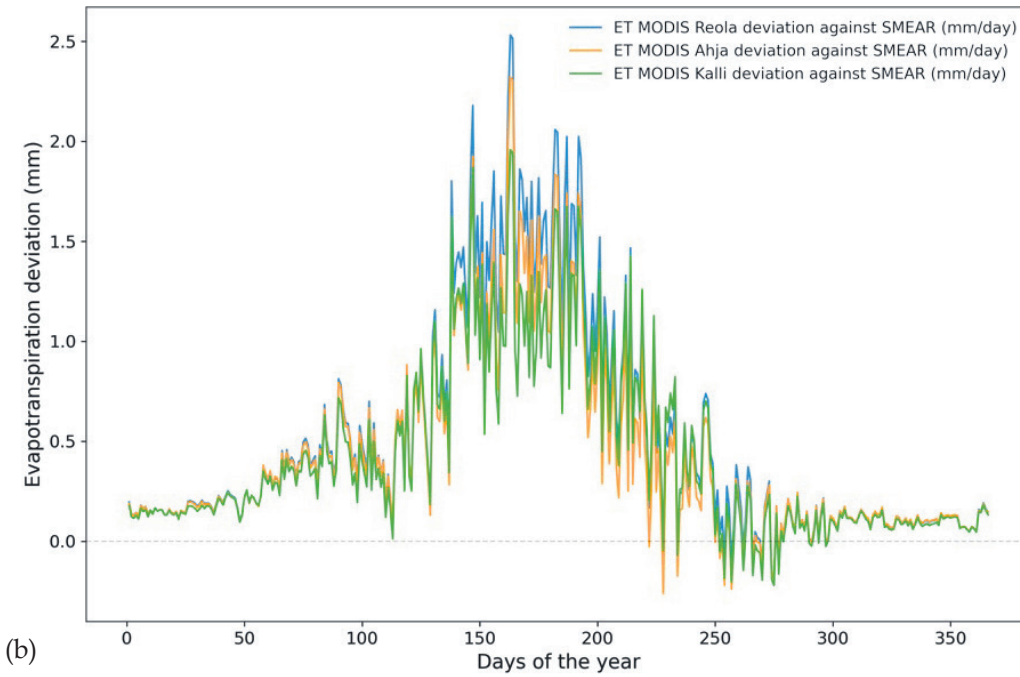


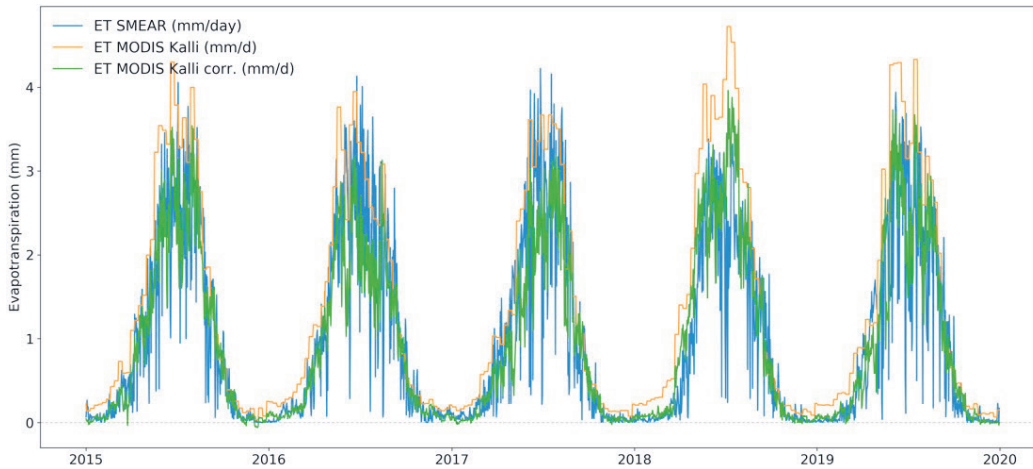
Figure 4. River flow from Reola and Ahja subbasins and precipitation measured at Tartu–Tõravere, Võru and SMEAR rain gauges.



(a)



(b)



(c)

Figure 5. (a) Daily average *ET* at Reola, Ahja and Kalli subbasins and SMEAR Estonia; (b) Daily average *ET* deviation: Reola, Ahja and Kalli minus SMEAR; (c) Comparison between uncorrected and corrected MODIS *ET* and SMEAR *ET* at Kalli subbasin.

SMEAR Estonia between 2015 and 2020. For this comparison SMEAR evapotranspiration was considered the ground truth, since it was obtained by the well-stablished eddy covariance method. The size of Kalli subbasin watershed is about one quarter of the size of the footprint area from the 70 m SMEAR tower, the footprint variable area has approximated to 14.2 km^2 occupying the head of Kalli subbasin and a part of Ahja basin. The average *ET* for days of the year are depicted in Figure 5a; it can be seen that MODIS is in general overestimating the water vapor flux from the ecosystem to the atmosphere. The daily average *ET* deviation between Reola, Ahja and Kalli with respect to SMEAR was calculated (Figure 5b) for the 3 subbasins, negative values were corrected to 0 (zero). Figure 5c reveals the comparison between uncorrected and corrected *ET* at Kalli subbasin, the SMEAR *ET* also is shown. In forests evapotranspiration is driven by solar radiation, wind intensity, water availability in the soil and water vapor gradient in the atmosphere. Days with high relative and ambient humidity and a small gradient with respect to the height above canopy creates low vapor-pressure deficit (VPD), which is the reason for low *ET*, as shown in Figure 5c.

Hydrological modelling, calibration and regionalization

The GR4J (*Génie Rural à 4 paramètres Journalier*) hydrological lumped and conceptual model (Perrin *et al.*, 2003) and the Cemaneige snow model (Valéry, 2010) were chosen to simulate the river discharge of the basins. These models have been applied to a variety of watersheds and demonstrated good accuracy (Nemri & Kinnard, 2020). The inputs of the models are daily precipitation, potential evapotranspiration, maximum, minimum and mean daily temperature and mean height of the basin, which provides the river flow at the output of the watershed. There are six constants to be calibrated in the GR4J-Cemaneige model: X_1 production store capacity (mm), X_2 intercatchment exchange coefficient (mm/d), X_3 routing store capacity (mm), X_4 unit hydrograph time constant (d), CTG weighting coefficient for the snow pack thermal state (-), K_f degree-day melt coefficient (mm/°C/d). The quality of the calibration was measured by the Nash-Sutcliffe Efficiency (NSE). Monte-Carlo-Simulation was used to perform the calibration of the GR4J-Cemaneige model constants (Piotrowski *et al.*, 2019; McIntyre *et al.*, 2002; Vrugt *et al.*, 2008).

The Nash Sutcliffe model efficiency coefficient (NSE) was used to assess the predictive skill of the GR4J-Cemaneige hydrological model. It is defined in equation 7.

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{T} (Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T} (Q_o^t - \bar{Q}_o)^2} \qquad (7)$$

In the last equation $\bar{Q}_o$ is the mean of observed river flow, Q_m is modelled river flow and Q_o^t is observed river flow at time *t* (Nash & Sutcliffe, 1970).

Since there is no record of river flow at Kalli basin, a regionalization procedure was performed to obtain streamflow in this catchment. Regionalization methods dependent on rainfall-runoff models comprise techniques for transferring calibrated parameters in instrumented basins (donor basins) to non-instrumented basins (target basins).

Results

After correction of input data, hydrological modelling and regionalization was used to obtain the stream flow at Kalli catchment. We have assumed that Reola, Ahja and Kalli basins have physiographic and climatic similarity, due to their proximity, similar forest types and management. The regionalization consists of transferring the 6 constants of the model from the donor basins (Reola and/or Ahja) to the target basin (Kalli).

The GR4J-Cemaneige model was applied to Reola and Ahja watersheds, using 1 year for warm-up, 6 years for calibration and 3 years for validation. For calibrating river flow at Reola subbasin the daily data series inputs are: precipitation; minimum, maximum and mean temperature; potential evapotranspiration and river flow. Meteorological and hydrological input variables were obtained from Tartu–Tõravere weather station, Reola hydrometric stations and from the application for extracting and exploring analysis ready samples (AρρEEARS) from MODIS/NASA. In Ahja subbasin the Nash-Sutcliffe Efficiency (NSE) coefficient was near 0.5, which indicates that the model did not have proper calibration, for this reason we did not use the Ahja subbasin constants for regionalization. In Reola subbasin the calibration was performed using the Monte-Carlo Method, 100k Monte-Carlo simulations were performed with random constants initialization, and results show the NSE of 0.73 for the validation period. The Reola GR4J-Cemaneige calibrated constants are CTG = 0.84, K_f = 2.66 (mm/°C/d), X_1 = 483.80 mm, X_2 = 1.26 (mm/d), X_3 = 20.01 (mm) and X_4 = 1.42 (d). Figure 6a shows the result of the GR4J-Cemaneige model calibrated and applied to Reola watershed, the image shows only the validation period. Figure 6b presents the modelled streamflow using regionalization at Kalli subbasin.

A double mass curve was constructed to check the water balance in Reola and Kalli subbasins. In equation 5, the common hydrological approach is to assume that the terms of storage and intercatchment flow vanish (Brutsaert, 2005; Reaver *et al.*, 2020), but no real proof of this statement has been showed in the literature. In Figure 7, double mass curve analysis was performed with the accumulated input (precipitation sum in the *x* axis) against the accumulated output (actual

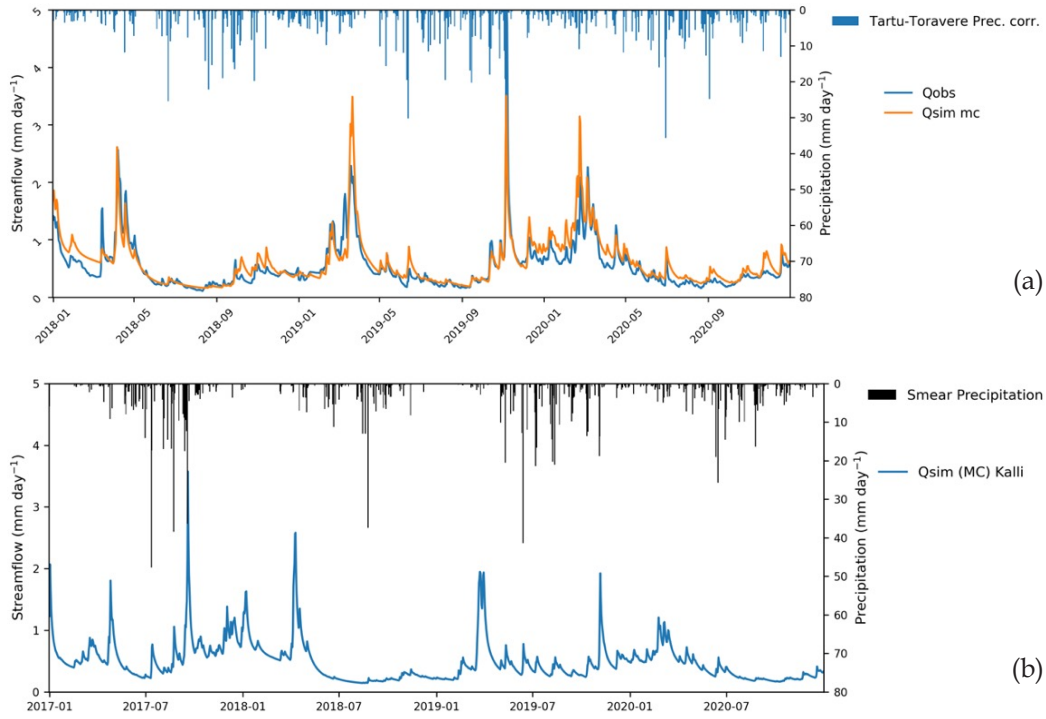


Figure 6. (a) Streamflow measured and modelled using Monte Carlo calibration at Reola subbasin; (b) Streamflow modelled using regionalization at Kalli subbasin.

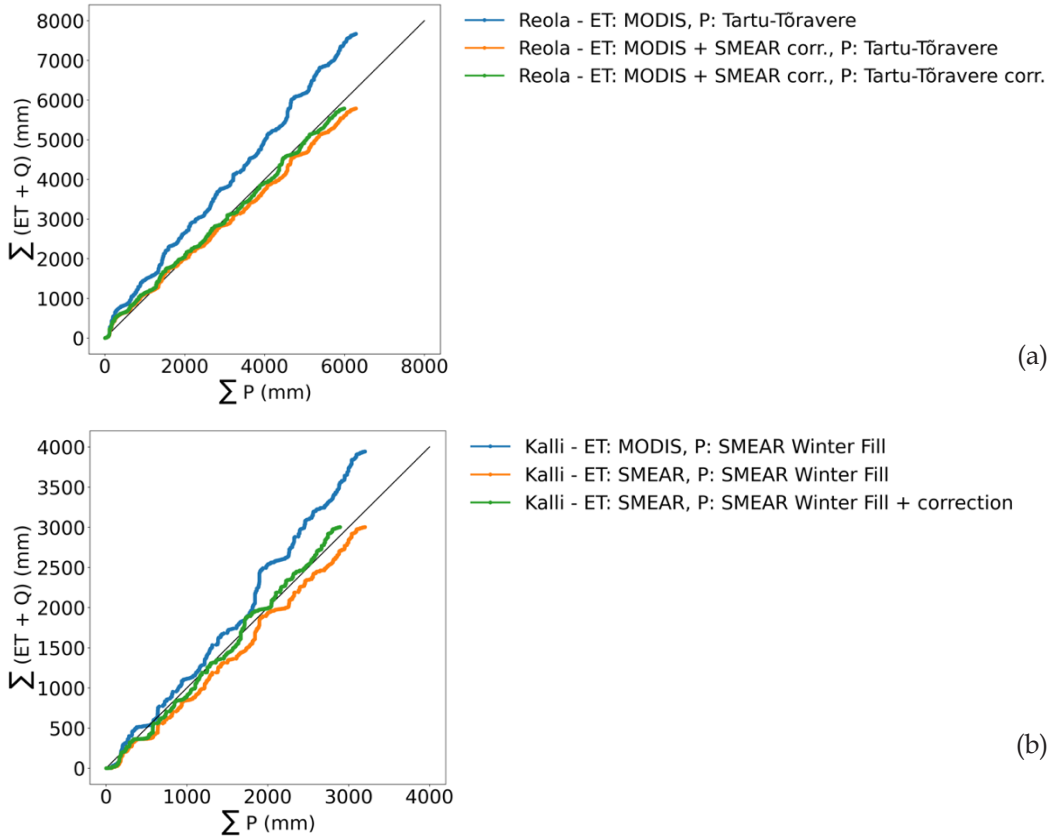


Figure 7. Accumulated input (precipitation) against the accumulated output (evapotranspiration and river flow) with different corrections for (a) Reola subbasin and (b) Kalli subbasin.

evapotranspiration and river flow sums in the *y* axis) of the two watersheds: Reola (Figure 7a) and Kalli (Figure 7b).

In Figures 7(a) and 7(b) the blue line represents the balance with evapotranspiration from MODIS without the correction mentioned before. The orange line in Figures 7(a) represents the MODIS evapotranspiration corrected by the SMEAR Estonia *ET*, and in Figure 7(b) it is the SMEAR Estonia water vapor flux measurements. In Figures 7(a) and 7(b) the green line indicates an extra correction of the precipitation series by applying the WBM. The precipitation series from Tartu–Tõravere station was multiplied by a correction factor of 0.95, while the winter filled precipitation from SMEAR was corrected by a factor of 0.90. Both WBM corrections were not used in any other analysis of this study because the time series used to make these corrections, that is, 10 and 6 years, do not represent long-term averages.

Figure 8 shows the water balance variation along the year for Reola (Figure 8a) and Kalli (Figure 8b) catchments, precipitation was positive (input) while evapotranspiration and streamflow were displayed as negatives values (outputs), ΔS was calculated according to equation 3. The Reola storage deficit period occurs from March to July while the storage recharge occurs from August to February. The Kalli storage deficit period is shorter, from May to July, and water surplus is in the same period as for Reola watershed.

Figure 9 shows the water balance variation along 10 and 6 years for Reola

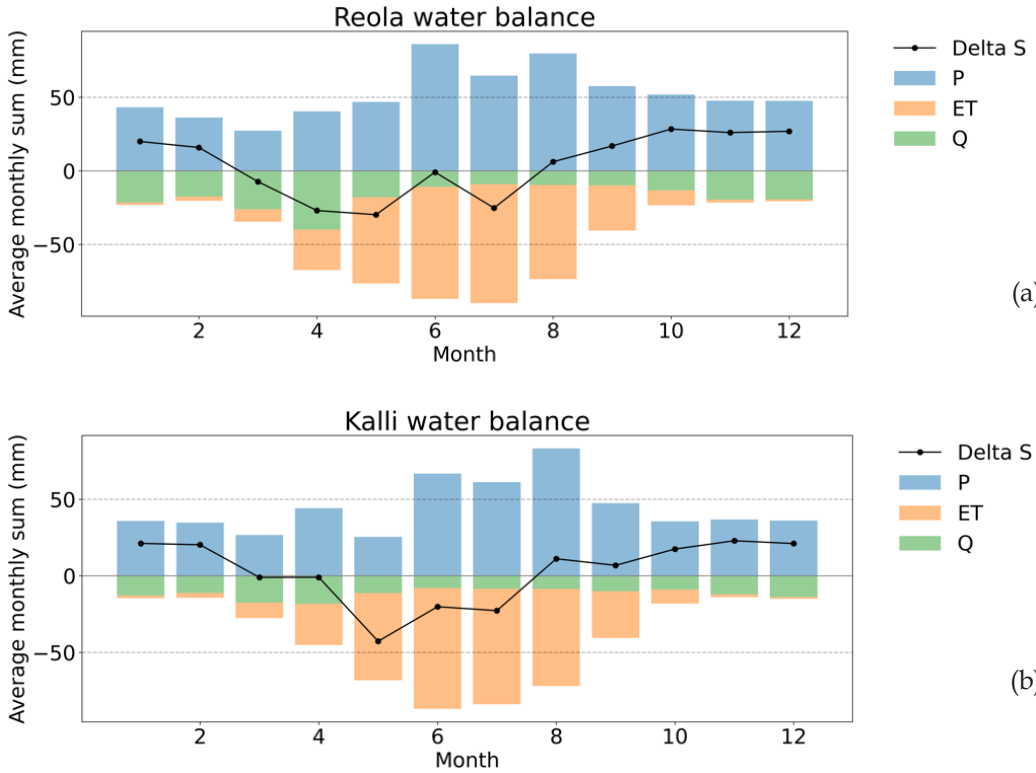


Figure 8. Water balance variation along the year for Reola and Kalli catchments, precipitation is positive (input) while evapotranspiration and streamflow are negative (outputs). (a) 6 years (2015–2020) of average monthly sums (P, ET, Q and ΔS) for Reola subbasin and (b) 10 years (2011–2020) of average monthly sums (P, ET, Q and ΔS) for Kalli subbasin.

(Figure 9a) and Kalli (Figure 9b) catchments, respectively, precipitation was positive (input) while evapotranspiration and streamflow were depicted as negative values (outputs), ΔS was calculated according to equation 3.

In Figure 10 the water storage variation ΔS_i is compared with the Net Ecosystem Exchange (NEE) for Kalli watershed, both data on a daily basis, the dashed lines represent the linear regression with respect to time *t*. The equations, fitted with the least squares method, are NEE = 0.0086 *t* – 1.2427 and ΔS = -0.0042 t + 0.2474. During photosynthesis, plants take in carbon dioxide (CO_2) and water (H_2O) from the air and soil, respectively, this connection between water and carbon cycles can be seen by the similarity of ΔS and NEE variations.

From Figure 10 we can see that in winters normally R_{eco} of the ecosystem exceeds the GPP, and the NEE is positive, so the ecosystem is a net carbon source. When carbon sequestration (GPP) is higher than R_{eco}, NEE is negative, and the ecosystem is a net carbon sink (around summers). Forest ecosystems commonly act as sinks of CO_2, but their sink strength varies and depends on the set of factors, including stand age and tree species composition, soil type, water availability, climatic conditions, and management practices. The data and the linear regression analysis show that Järvselja and Kalli catchment forests are slowly becoming a source of carbon while the amount of water in the soil is slowly decreasing over time. When analyzing NEE over the 2015–2022 period we see that after 2020 the

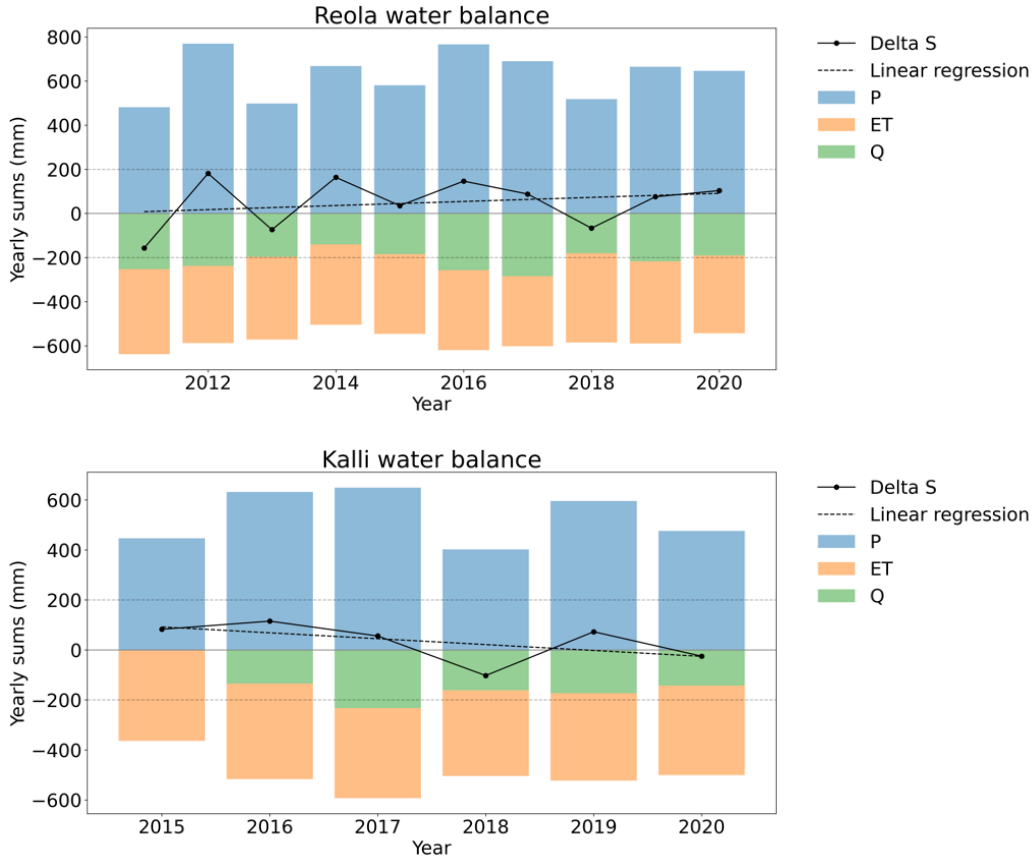


Figure 9. Water balance variation along 10 and 6 years for Reola and Kalli catchments, respectively, precipitation is positive (input) while evapotranspiration and streamflow are negative (outputs). (a) 6 years (2015–2020) of yearly sums (P, ET, Q and ΔS) for Reola subbasin and (b) 10 years (2011–2020) of yearly sums (P, ET, Q and ΔS) for Kalli subbasin.

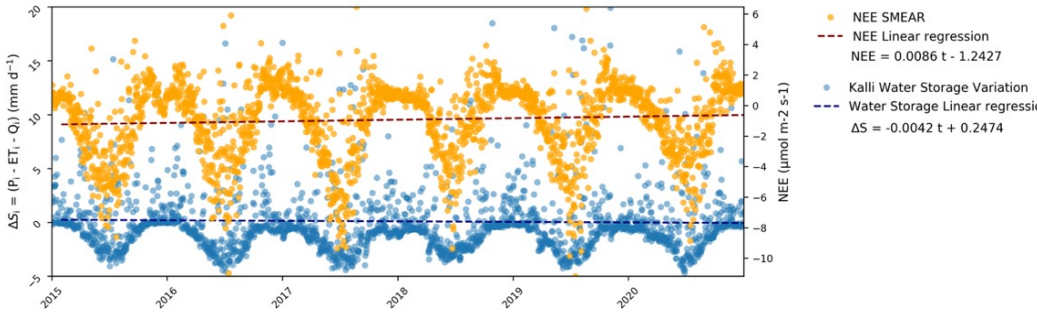


Figure 10. Daily water storage variation, ΔS_i, and daily NEE for Kalli subbasin, the dashed lines represent the linear regression.

footprint area of the SMEAR 70 m tower has already become a net source of carbon.

Discussion

In recent years the hydrological data showed that 2015 and 2018 were drier years (Figures 9a and 9b). Tartu–Tõravere rain gauge recorded 581.0 mm and 518.3 mm for yearly accumulated precipitation in 2015 and 2018, respectively, while the 2015–2020 average was 644.4 mm. In 2018 a more significant drought occurred (Krasnova *et al.*, 2019), which can be seen in the long recession curve in Figure 4, after the river flow peak due to snow melts in the first months of the year. The 2019 hydrograph also shows the influence of the previous year low baseflow in the summer period. Figure 5(c) also shows less evapotranspiration in the middle of 2018 when looking at the SMEAR data, the MODIS sensor was not able to capture the reduction in the evapotranspiration.

After comparing evapotranspiration from satellite and ground truth measurements, we observed that in general ET is overestimated by the MODIS satellite, except from the period from mid-August to the beginning of October, that is, the end of summer and beginning of autumn. We have corrected satellite data by subtracting the daily *ET* difference with SMEAR Estonia *ET*. The water balances of Figures 7a and 7b showed that the MODIS data correction was beneficial, since the error against the 1:1 line was smaller.

Figures 7(a) and 7(b) reveal the water balance at the studied catchments, the orange line in both graphs represent the data without forcing the closure of the water balance. The non-closure of the water balance may be related to the short period of time that was adopted in the two analyses: 10 years for Ahja and 6 years for Kalli. It is normally recommended to use more than 30 years for this hydrological balance (Andréassian *et al.*, 2016). However, it is also reasonable to argue that due to climate change higher temperatures generate higher evapotranspiration which might decrease soil water storage. Peat soils form altogether 10,038 km^2 or 23.5% of the total Estonian soil cover (Kõlli *et al.*, 2009) and it is also a very common soil in Kalli subbasin. Draining exposes the upper peat layer to oxygen, leading to elevated decomposition rates and net soil carbon losses (Carlson *et al.*, 2015). Several studies indicate positive relationships between the long-term water table depth and soil carbon loss rate in peatlands (Jauhiainen *et al.*, 2008; Couwenberg *et al.*, 2010; Hirano *et al.*, 2009; Jauhiainen *et al.*, 2012; Verwer *et al.*, 2008). On the other hand, the non-closure might be explained because not enough hydrological processes are taken into consideration, for example the intercatchment flow. Another explanation would be the uncertainty of the different data sets and measurement techniques. River flow is generally calculated with rating curves, a relation between stage (river level) and streamflow (discharge), which has high uncertainty (Domeneghetti *et al.*, 2012; Sikorska *et al.*, 2013; Steinbakk *et al.*, 2016), and precipitation has spatial variability, which is not captured by rain gauge point measurements. Today there are several databases that can be used for comparison, such as a high-resolution gauge-adjusted radar precipitation dataset (Overeem *et al.*, 2022).

In this work we have analyzed the changes in the delta storage of the basins, however it is possible to estimate the total storage. Dias & Kan (1999) and Hoeltgebaum (2021) have presented a method for estimating the total storage based on the idea that storage in the watershed is a linear reservoir, i.e. $S = \tau Q$, and τ is a constant. This method can be compared with the Water Equivalent Thickness (WET) from the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) missions from NASA and the German Aerospace Center (German:

Deutsches Zentrum für Luft- und Raumfahrt, DLR). The WET satellite product is monthly data, $1^{o} \times 1^{o}$ grid spatial resolution, however the area covered by GRACE-FO mission data is more than 10 times greater than the area of Reola watershed, i.e. the satellite data shows the influence of other basins nearby. Water in the thin soil layer may also be uncoupled from deep aquifers. In addition, interbasin flow in small watersheds may have some importance. Although there are alternatives to downscaling the GRACE total water storage change (Vishwakarma *et al.*, 2021), there are few alternatives to validate data with high accuracy at smaller spatial scales.

Figures 8a and 8b represent an overview of the large-scale fluxes for Reola and Kalli watersheds. They also confirm the hydrological similarity of the basins with higher precipitation between June and August, the highest streamflow after snowmelt and the highest evapotranspiration in June and July. The storage is decreasing when there is more evapotranspiration and increasing between August and February. Figures 9a and 9b show the yearly sum time series of the hydrological data for Reola and Kalli subbasins, respectively. The linear regressions show that between 2011–2015 there was a trend of increase in the delta storage while between 2016–2020 there was a trend of decrease in the delta storage.

Figure 10 reveals seasonal similarity between changes in the water storage and carbon fluxes. The balances indicate that in recent years the ecosystem at Kalli watershed is slightly becoming a source of carbon and less water is available at the catchment reservoir. NEE has increased from -1.23 μmol m^{-2} s^{-1} in 2015 to -0.62 μmol m^{-2} s^{-1} in 2021, while the water storage change decreased from 0.24 mm in 2015 to -0.05 mm in 2022. The result obtained here is opposite to that obtained by Kont *et al.* (2002). Kont *et al.* (2002) have made simulations based on the Intergovernmental Panel on Climate Change (IPCC) scenarios and they have predicted that in the future groundwater table would rise in Estonia. The forest ecosystems in Estonia have a historical relation with man intervention, the constructed ditch system is one example of how we can interfere in the water and carbon cycle. A question from a practical and regulatory point of view can be raised: how should ditches be managed in the coming years? This will definitely influence the carbon balance in forests.

Conclusions

In this research an integrative methodology was used to evaluate the carbon and water fluxes and their inter-relations in a hemi-boreal forest. Two systems were considered in the analysis: the watershed, or hydrological system, and the SMEAR Estonia 70 m tower footprint area. The representative area of the carbon balance is elastic, that is, it varies every year due to the influence of the wind coming from different directions, however, there is a constant intersection of the two systems and the carbon footprint represents approximately 1/4 of the hydrographic basin. Due to this overlapping of domains it is possible to estimate connections between the carbon cycle and the water cycle. Several hydrological and micrometeorological data at different scales were combined to assess flows at the Järvselja Forest. Hydrological modelling and regionalization were used to obtain flow in unmonitored basins. The balances indicate that in recent years the ecosystem at Kalli watershed is slightly becoming a source of carbon and the delta storage is decreasing at a rate of 0.0042 mm/year, i.e. probably less water will be available at the catchment reservoir. This behavior, which is associated with climate change, may increase peat soil drying and oxidation, and the soil probably will release more carbon in the future.

Forcing or not the closure of the water balance did not influence the conclusions regarding carbon fluxes and trends in the

delta storage. Our analysis was based on the inclination of the delta storage linear regression, so it was not affected. However, a better understanding of the relationship between the total volume of storage and future ecosystem demands for water is needed. As next steps the authors plan to install a hydrometric station to measure river flow and sensors for measuring the water table level and soil moisture at Kalli watershed. This work is of particular importance for societies in ways of helping to predict climate change and water availability in hemi-boreal forests, as the methodology can be applied to different watersheds.

Acknowledgements. This study was partially financed by the Estonian Research Council (grant PRG 1674), and the European Union's Horizon 492 2020 Research and Innovation Programme (grant agreement no. 871115) ACTRIS IMP. The authors are grateful to Erasmus+ Eesti Maaülikool (EMÜ) (Estonian University of Life Sciences) staff mobility programme and to the Network on Environmental Monitoring and Modeling (RESMA) project from the Federal University of Parana (UFPR) – Coordination for the Improvement of Higher Education Personnel (CAPES) – Institutional Internationalization Program (PRINT) for facilitating the exchange of researchers between Brazil and Estonia.

References

Andréassian, V., Mander, Ü., Pae, T. 2016. The Budyko hypothesis before Budyko: the hydrological legacy of Evald Oldekop. – Journal of Hydrology, 535, 386–391. https://doi.org/10.1016/j.jhydrol.2016.02.002.

Are, M., Kauer, K., Kaart, T., Selge, A., Astover, A., Reintam, E. 2020. Water stability of soil aggregates in a 50-year-old soil formation experiment on calcareous glacial till. – Eurasian Soil Science, 53, 619–631. http://doi.org/10.1134/S1064229320050026.

Arold, I. 2005. Estonian Landscapes. (Eesti Maastikud). Tartu, Tartu Ülikooli Kirjastus. 453 pp. (In Estonian).

Brutsaert, W. 2005. Hydrology: An Introduction. Cambridge, Cambridge University Press. 618 pp.

Carlson, K.M., Goodman, L.K., May-Tobin, C.C. 2015. Modeling relationships between water table depth and peat soil carbon loss in Southeast Asian plantations. – Environmental Research Letters, 10(7), 074006.

Carneiro, L., Ostroski, A., Mercuri, E.G.F. 2020. Trophic state index for heavily impacted watersheds: modeling the influence of diffuse pollution in water bodies. – Hydrological Sciences Journal, 65(15), 2548–2560. https://doi.org/10.1080/02626667.2020.1828588.

Chow, V.T., Maidment, D.R., Mays, L.W. 1988. Applied Hydrology. New York, McGraw-Hill. 572 pp.

Couwenberg, J., Dommain, R., Joosten, H. 2010. Greenhouse gas fluxes from tropical peatlands in south–east Asia. – Global Change Biology, 16(6), 1715–1732. https://doi.org/10.1111/j.1365-2486.2009.02016.x.

Di Buò, B., D'Ignazio, M., Selänpää, J., Haikola, M., Länsivaara, T., Di Sante, M. 2019. Investigation and geotechnical characterization of Perniö clay, Finland. – AIMS Geosciences, 5(3), 591–616.

Dias, N.L., Kan, A. 1999. A hydrometeorological model for basin□wide seasonal evapotranspiration. – Water Resources Research, 35(11), 3409–3418.

Domeneghetti, A., Castellarin, A., Brath, A. 2012. Assessing rating-curve uncertainty and its effects on hydraulic model calibration. – Hydrology and Earth System Sciences, 16(4), 1191–1202.

Duchon, C.E., Essenberg, G.R. 2001. Comparative rainfall observations from pit and aboveground rain gauges with and without wind shields. – Water Resources Research, 37(12), 3253–3263.

Flerchinger, G.N., Cooley, K.R. 2000. A ten-year water balance of a mountainous semi-arid watershed. – Journal of Hydrology, 237(1–2), 86–99.

Georgievsky, M.V., Mamaeva, M.A. 2020. Water resources of the Russian part of the Baltic Sea basin and their possible changes under global warming. – Negm, A.M., Zelenakova, M., Kubiak-Wójcicka, K. (eds.). Water Resources Quality and Management in Baltic Sea Countries. Cham, Switzerland, Springer, 159–208.

Groisman, P.Y., Legates, D.R. 1994. The accuracy of United States precipitation data. – Bulletin of the American Meteorological Society, 75(2), 215–228.

Hirano, T., Jauhiainen, J., Inoue, T., Takahashi, H. 2009. Controls on the carbon balance of tropical peatlands. – Ecosystems, 12, 873–887. https://doi.org/10.1007/s10021-008-9209-1.

Hoeltgebaum, L.E.B. 2021. Quantifying mass and energy balance terms at the watershed scale: a case study at Wahoo Creek. (Quantificação dos termos dos balanços de massa e energia na escala da bacia hidrográfica: estudo de caso em Wahoo Creek). – Doctoral Dissertation. Curitiba, Brazil, Federal University of Paraná. 140 pp. (In Portuguese).

Istanbulluoglu, E., Wang, T., Wright, O.M., Lenters, J.D. 2012. Interpretation of hydrologic trends from a water balance perspective: The role of groundwater storage in the Budyko hypothesis. – Water Resources Research, 48(3), W00H16.

Jauhiainen, J., Hooijer, A., Page, S.E. 2012. Carbon dioxide emissions from an *Acacia* plantation on peatland in Sumatra, Indonesia. – Biogeosciences, 9(2), 617–630.

Jauhiainen, J., Limin, S., Silvennoinen, H., Vasander, H. 2008. Carbon dioxide and methane fluxes in drained tropical peat before and after hydrological restoration. – Ecology, 89(12), 3503–3514. https://doi.org/10.1890/07-2038.1.

Kalvīte, Z., Lībiete, Z., Kļaviņš, I., Bārdule, A., Bičkovskis, K. 2021. The impact of beaver dam removal on the chemical properties of water in drainage ditches in peatland forests. – Scandinavian Journal of Forest Research, 36(1), 1–14.

Kljun, N., Calanca, P., Rotach, M.W., Schmid, H.P. 2015. A simple two-dimensional parameterisation for Flux Footprint Prediction (FFP). – Geoscientific Model Development, 8(11), 3695–3713. https://doi.org/10.5194/gmd-8-3695-2015.

Kõlli, R., Astover, A., Noormets, M., Tõnutare, T., Szajdak, L. 2009. Histosol as an ecologically active constituent of peatland: a case study from Estonia. – Plant and Soil, 315, 3–17. https://doi.org/10.1007/s11104-008-9792-0.

Kont, A., Jaagus, J., Oja, T., Järvet, A., Rivis, R. 2002. Biophysical impacts of climate change on some terrestrial ecosystems in Estonia. – GeoJournal, 57, 169–181. https://doi.org/10.1023/B:GEJO.0000003614.07684.60.

Krasnova, A. 2022. Greenhouse gas fluxes in hemiboreal forest ecosystems. – Doctoral Dissertation. Tartu, Estonia, University of Tartu, Institute of Ecology and Earth Sciences, Department of Geography. 185 pp.

Krasnova, A., Soosaar, K., Uri, V., Mander, Ü., Krasnov, D., Noe, S. 2019. Hemiboreal forests under the 2018 Europe heat wave. – Proceedings of the EGU General Assembly, Austria, 7-12 April 2019. Vienna, 21, EGU2019-8604.

Kumpulainen, R.A., Greiling, R.O. 2011. Evidence for late Neoproterozoic glaciation in the central Scandinavian Caledonides. – Arnaud, E., Halverson, G.P., Shields-Zhou, G. (eds.). The Geological Record of Neoproterozoic Glaciations. London, Geological Society of London, Memoir 36, 623–628.

Larson, L.W., Peck, E.L. 1974. Accuracy of precipitation measurements for hydrologic modeling. – Water Resources Research, 10(4), 857–863.

Legates, D.R., DeLiberty, T.L. 1993. Precipitation measurement biases in the United States. – JAWRA Journal of the American Water Resources Association, 29(5), 855–861.

Liivamägi, S., Somelar, P., Mahaney, W.C., Kirs, J., Vircava, I., Kirsimäe, K. 2014. Late Neoproterozoic Baltic paleosol: Intense weathering at high latitude? – Geology, 42(4), 323–326.

Mazur, K., Schoenheinz, D., Biemelt, D., Schaaf, W., Grünewald, U. 2011. Observation of hydrological processes and structures in the artificial Chicken Creek catchment. – Physics and Chemistry of the Earth, Parts A/B/C, 36(1–4), 74–86. https://doi.org/10.1016/j.pce.2010.10.001.

McIntyre, N., Wheater, H., Lees, M. 2002. Estimation and propagation of parametric uncertainty in environmental models. – Journal of Hydroinformatics, 4(3), 177–198. https://doi.org/10.2166/hydro.2002.0018.

Mohajerani, H., Zema, D.A., Lucas-Borja, M.E., Casper, M. 2021. Understanding the water balance and its estimation methods. – Rodrigo-Comino, J. (ed.). Precipitation. Amsterdam, Oxford, Elsevier, 193–221.

Nash, J.E., Sutcliffe, J.V. 1970. River flow forecasting through conceptual models part I–A discussion of principles. – Journal of Hydrology, 10(3), 282–290.

Nemri, S., Kinnard, C. 2020. Comparing calibration strategies of a conceptual snow hydrology model and their impact on model performance and parameter identifiability. – Journal of Hydrology, 582, 124474. https://doi.org/10.1016/j.jhydrol.2019.124474.

Noe, S.M., Kimmel, V., Hüve, K., Copolovici, L., Portillo-Estrada, M., Püttsepp, Ü., Jõgiste, K., Niinemets, Ü., Hörtnagl, L., Wohlfahrt, G. 2011. Ecosystem-scale biosphere–atmosphere interactions of a hemiboreal mixed forest stand at Järvselja, Estonia. – Forest Ecology and Management, 262(2), 71–81. https://doi.org/10.1016/j.foreco.2010.09.013.

Noe, S.M., Niinemets, Ü., Krasnova, A., Krasnov, D., Motallebi, A., Kängsepp, V., Jõgiste, K., Hõrrak, U., Komsaare, K., Mirme, S., Vana, M., Tammet, H., Bäck, J., Vesala, T., Kulmala, M., Petäjä, T., Kangur, A. 2015. SMEAR Estonia: Perspectives of a large-scale forest ecosystem–atmosphere research infrastructure. – Forestry Studies / Metsanduslikud Uurimused, 63(1), 56–84.

Overeem, A., van den Besselaar, E., van der Schrier, G., Meirink, J.F., van der Plas, E., Leijnse, H. 2022. EURADCLIM: The European climatological high-resolution gauge-adjusted radar precipitation dataset. – Earth System Science Data, Discussions. https://doi.org/10.5194/essd-2022-334. (In review).

Pan, X., Helgason, W., Ireson, A., Wheater, H. 2017. Field-scale water balance closure in seasonally frozen conditions. – Hydrology and Earth System Sciences, 21(11), 5401–5413.

Perrin, C., Michel, C., Andréassian, V. 2003. Improvement of a parsimonious model for streamflow simulation. – Journal of Hydrology, 279(1–4), 275–289. https://doi.org/10.1016/S0022-1694(03)00225-7.

Piotrowski, A.P., Napiorkowski, J.J., Osuch, M. 2019. Relationship between calibration time and final performance of conceptual rainfall-runoff models. – Water Resources Management, 33, 19–37. https://doi.org/10.1007/s11269-018-2085-3.

Reaver, N.G., Kaplan, D.A., Klammler, H., Jawitz, J.W. 2020. Reinterpreting the Budyko framework. – Hydrology and Earth System Sciences, Discussions. https://doi.org/10.5194/hess-2020-584. (In review).

Rice, J.S., Emanuel, R.E. 2019. Ecohydrology of interannual changes in watershed storage. – Water Resources Research, 55(10), 8238–8251.

Richey, A.S., Thomas, B.F., Lo, M.-H., Famiglietti, J.S., Swenson, S., Rodell, M. 2015a. Uncertainty in global groundwater storage estimates in a Total Groundwater Stress framework. – Water Resources Research, 51(7), 5198–5216. https://doi.org/10.1002/2015WR017351.

Richey, A.S., Thomas, B.F., Lo, M.-H., Reager, J.T., Famiglietti, J.S., Voss, K., Swenson, S., Rodell, M. 2015b. Quantifying renewable groundwater stress with GRACE. – Water Resources Research, 51(7), 5217–5238. https://doi.org/10.1002/2015WR017349.

Safeeq, M., Bart, R.R., Pelak, N.F., Singh, C.K., Dralle, D.N., Hartsough, P., Wagenbrenner, J.W. 2021. How realistic are water□balance closure assumptions? A demonstration from the southern sierra critical zone observatory and kings river experimental watersheds. – Hydrological Processes, 35(5), e14199. https://doi.org/10.1002/hyp.14199.

Scott, R.L., Biederman, J.A. 2019. Critical zone water balance over 13 years in a semiarid savanna. – Water Resources Research, 55(1), 574–588. https://doi.org/10.1029/2018WR023477.

Searcy, J.K., Hardison, C.H. 1960. Double-Mass Curves. Manual of hydrology: Part 1. General Surface Water Techniques, Geological Survey Water-Supply Paper 1541-B. Washington D.C., US Government Printing Office. 66 pp.

Sikorska, A.E., Scheidegger, A., Banasik, K., Rieckermann, J. 2013. Considering rating curve uncertainty in water level predictions. – Hydrology and Earth System Sciences, 17(11), 4415–4427. https://doi.org/10.5194/hess-17-4415-2013.

Steinbakk, G.H., Thorarinsdottir, T.L., Reitan, T., Schlichting, L., Hølleland, S., Engeland, K. 2016. Propagation of rating curve uncertainty in design flood estimation. – Water Resources Research, 52(9), 6897–6915. https://doi.org/10.1002/2015WR018516.

Tamm, O., Maasikamäe, S., Padari, A., Tamm, T. 2018. Modelling the effects of land use and climate change on the water resources in the eastern Baltic Sea region using the SWAT model. – Catena, 167, 78–89. https://doi.org/10.1016/j.catena.2018.04.029.

Vaisala. 2012. User's guide: Vaisala weather transmitter, WXT520. Helsinki, Finland, Vaisala Oyj. 167 pp.

Valéry, A. 2010. Modeling precipitation – flow under snow influence: Elaboration of a snow module and evaluation on 380 catchment areas. (Modélisation precipitations – débit sous influence nivale: Elaboration d'un module neige et évaluation sur 380 bassins versants). – Doctoral thesis. Paris, France, Institut des Sciences et Industries du Vivant et de l'Environnement AgroParisTech. 417 pp. (In French)

Vanags-Duka, M., Bārdule, A., Butlers, A., Upenieks, E.M., Lazdiņš, A., Purviņa, D., Līcīte, I. 2022. GHG emissions from drainage ditches in peat extraction sites and peatland forests in hemiboreal Latvia. – Land, 11(12), 2233. https://doi.org/10.3390/land11122233.

Verwer, C., van der Meer, P., Nabuurs, G.-J. 2008. Review of carbon flux estimates and other greenhouse gas emissions from oil palm cultivation in tropical peatlands – Identifying the gaps in knowledge. Alterra-rapport No. 1731. Wageningen, The Netherlands, Alterra. 44 pp. https://edepot.wur.nl/38226.

Vishwakarma, B.D., Zhang, J., Sneeuw, N. 2021. Downscaling GRACE total water storage change using partial least squares regression. – Scientific Data, 8, 95. https://doi.org/10.1038/s41597-021-00862-6.

Vrugt, J.A., ter Braak, C.J.F., Clark, M.P., Hyman, J.M., Robinson, B.A. 2008. Treatment of input uncertainty in hydrologic modeling: Doing hydrology backward with Markov chain Monte Carlo simulation. – Water Resources Research, 44(12).

Wang, S., Huang, J., Li, J., Rivera, A., McKenney, D.W., Sheffield, J. 2014. Assessment of water budget for sixteen large drainage basins in Canada. – Journal of Hydrology, 512, 1–15. https://doi.org/10.1016/j.jhydrol.2014.02.058.

Wang, S., Pan, M., Mu, Q., Shi, X., Mao, J., Brümmer, C., Jassal, R.S., Krishnan, P., Li, J., Black, T.A. 2015. Comparing evapotranspiration from eddy covariance measurements, water budgets, remote sensing, and land surface models over Canada. – Journal of Hydrometeorology, 16(4), 1540–1560. https://doi.org/10.1175/JHM-D-14-0189.1.

Waring, R.H., Running S.V. 1998. Forest Ecosystems. Analysis at Multiple Scales. San Diego, California, Academic Press. 370 pp.

Wei, X., Huang, S., Huang, Q., Leng, G., Wang, H., He, L., Zhao, J., Liu, D. 2021. Identification of the interactions and feedbacks among watershed water-energy balance dynamics, hydro-meteorological factors, and underlying surface characteristics. – Stochastic Environmental Research and Risk Assessment, 35, 69–81. https://doi.org/10.1007/s00477-020-01896-9.

Woronko, B., Zagórski, Z., Cyglicki, M. 2022. Soil-development differentiation across a glacial–interglacial cycle, Saalian upland, E Poland. – Catena, 211, 105968. https://doi.org/10.1016/j.catena.2021.105968.

Received April 20, 2023, accepted September 14, 2023