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The response of the water fluxes of the boreal forest region at the Volga's source area to climatic and land-use changes

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Abstract

The project "Volgaforest" was focused on a study of the water budget of the forested Upper Volga catchment in Russia in order to describe:

- the terrestrial water balance of the Upper Volga catchment as a function of external factors, such as climate and land-use, and
- the response of forest ecosystems to these external factors.

Future changes of water budget of the Upper Volga catchment area were estimated from: past and present dynamics of the atmospheric, water and forest conditions, different climatic scenarios and SVAT (Soil–Vegetation–Atmosphere Transfer) and hydrological models.

Analysis of past climatological and hydrological data showed a large atmospheric and hydrological variability of the Upper Volga catchment. During the last 50–60 years the mean annual air temperature increased by 1.2 °C, and annual precipitation increased by 140 mm. However, no significant trend of annual runoff during the last 20 years could be found. Air temperature and precipitation changes were significant during winter and spring but very small in summer. Coniferous and mixed coniferous-broadleaf forests cover at present about 72% of the catchment area. During the last 30 years the area of natural coniferous forests (spruce, pine) decreased from 8.4% to 7% and the area of mixed forests increased from 52% to 59% of the total land area.

Results of field measurements at a forest site showed a large variability of energy and water fluxes during the entire year. Transpiration of the boreal forest ecosystem measured using a sap flow method during the dry summer 1999 was limited by very dry soil water conditions, especially for spruce trees, and during the rainy summer 2000 probably by lack of oxygen in the rooting zone. Transpiration was about 10–20% larger for broadleaf trees (birch, aspen) than for spruce trees.

Model estimations of possible changes in the hydrological regime of the Upper Volga catchment area for climatic scenarios suggest changes of evapotranspiration, surface runoff and soil moisture storage. Reduced snow accumulation, earlier melting, increased runoff reaction on precipitation in autumn and winter and drier soils in summer are the principal impacts on water resources of predicted future climatic changes. Surface runoff during the spring will be higher but summer and autumn runoff can be slightly suppressed by higher transpiration of deciduous tree species. Decreased summer precipitation and increased transpiration will result in decreasing ground water discharge, and lowering water levels of Volga river and of the Upper Volga lakes.

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1. Introduction

Within the framework of the global problem of climate-vegetation interactions the scientific field of "forest and water" is a key area of forest meteorology, hydrology and ecology. During the last 50 years many theoretical and experimental investigations were dedicated to this paramount problem (e.g. Anderson et al., 1976; Bonell, 1998; Brooks et al., 1991; Budyko, 1974; Calder, 1999; Colman, 1953; Fedorov, 1977; Hoover, 1962; Ibrom et al., 1996; Kutchment et al., 1987; Martin, 1996; Miller and Russell, 1992; Moore et al., 2000; Nilsson et al., 1992; Shugart, 1984; Slatyer, 1967). On the one hand, this interest can be explained by the direct influence of the water regime on the functioning of forest ecosystems and on the forest structure (e.g. Budyko, 1974), and, on the other hand, by the water-regulating and water-protecting effects of forests. At present, the different aspects of forest–atmosphere interaction in different spatial and temporal scales are key topics of several large international programs (e.g. International Geosphere-Biosphere Programme (IGBP), International Hydrological Programme (IHP)) and projects (e.g. Global Change and Terrestrial Ecosystems (GCTE), Biospherical Aspects of Hydrological Cycle (BAHC), Global Energy and Water Cycle Experiment (GEWEX), Boreal Ecosystems Atmosphere Study (BOREAS), the Baltic Sea Experiment (BALTEX)). Unfortunately, up to now, many important processes, in particular the processes that control the water exchange between different forest ecosystems, rivers and the atmosphere, and feedback effects of changes of moisture conditions on forest functioning are still very poorly understood and described. It is still not clear, how deforestation, reforestation, forest succession and environmental changes influence the hydrological regime of different geographical regions. Particularly important is the question how the ongoing global warming can be taken into account in planning a rational forest management on regional levels.

Global warming is expected to be particularly large at higher latitudes and, therefore, will affect boreal forests probably more strongly than forests in other latitudinal zones (e.g. IPCC, 1996). Expected additional decreasing precipitation can result in increasing fire frequencies and pest outbreaks. It is, therefore, likely that the average forest age and the carbon storage in the biosphere will decrease. The largest climatic impact may occur at the southern boundary of the boreal forest zone, where the boreal coniferous forest is likely to give way to temperate zone pioneer species or grasslands (Shugart, 1984).

The south-western boundary of the boreal forest community in Russia crosses the area of the Valday Hills. This unique region is, on the one hand, a large area of natural forest resources in Eastern Europe, and on the other hand, a source area of many large East-European rivers which serve as transport arteries and as sources for drinking water and food. In this area several biosphere reserves are situated, where flora and fauna are kept in nearly virgin conditions. The existence of this boreal forest community and the preservation of their hydrological regime mainly depend on two factors: stability of forest ecosystems with respect to changing environmental conditions, and anthropogenic activity. Since, at present, anthropogenic activity at the Valday Hills area is relatively low the main factors that may result in possible changes of structure and functioning of forest ecosystems are environmental changes. The remoteness from large industrial centres and cities results in a relatively low level of direct environmental pollution. This allows to neglect the effect of anthropogenic pollution and to study forest dynamics only with respect to climatic changes.

A very high sensitivity of spruce to droughts may result in successional changes and it could determine the future changes of forests under the influence of global warming (e.g. IPCC, 1996; Vygodskaya et al., 1995). Expected increase of winter temperatures and the frequency of thaws can result in reduction of snow-accumulation during the winter and in soil water deficiency for tree growth in spring and in summer. On the other hand, the gradual increase of the winter precipitation observed during the last 50 years in north-western part of Russia can lead to an increase of snow accumulation, despite of increasing air temperature and frequency of thaws. Frost weather conditions in winter, in this case, could result in a decrease of snow height and an increase of snow density without any significant effect on water capacity and surface runoff (Kutchment et al., 1987). Thus the hydro-meteorological regime and the stability of the boreal forest community of the Valday Hills can be influenced by different environmental factors and processes.

The main attention in this study was focused on the long-term—i.e. past, present and future—hydrological regime of forest ecosystems at the Upper Volga area and on estimation of the impact of expected climatic changes on the boreal forest ecosystems. Volga is the longest river (about 3500 km) of Europe and the principal waterway of Russia, being navigable (with locks bypassing the dams) almost throughout its entire course. Its basin forms about one third of European Russia. It carries one half of the total river freight of

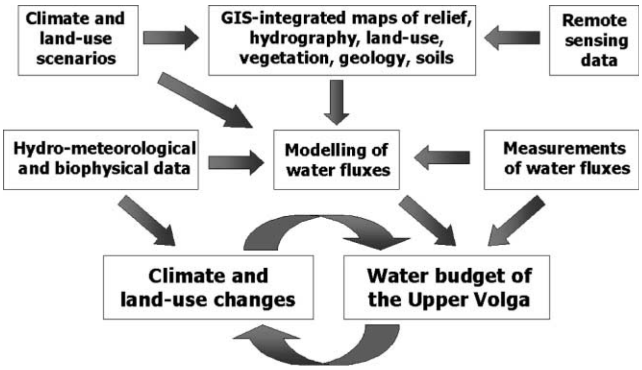

Fig. 1. A diagram of interrelation between different research activities to evaluate the response of the water budget of the boreal forest region at the Upper Volga area to climatic and land-use changes.

Russia and irrigates the vast steppes of the lower Volga region.

Past hydro-meteorological conditions of the Upper Volga area in this study are described using available data from hydro-meteorological network stations and land-use data. Present conditions are quantified using field measurements of vertical energy and water fluxes between forests and the atmosphere at a selected experimental site using different experimental approaches, validated SVAT and hydrological models. Present spatial distributions of the different vegetation and land-use types are derived using remote sensing data from the satellite "Resource-01". Time-series analysis, climatic and land-use scenarios and SVAT and hydrological models compatible with general circulation and regional atmospheric models are used to describe future hydro-meteorological conditions and the water budget of the Upper Volga area under assumed climatic and land-use changes (Fig. 1).

2. Materials and methods

2.1. Site description

The selected catchment area, about 3412 km^2 between 56°20′–57°20′ N and 32°00′–33°20′ E, of Upper Volga which flows into the Caspian Sea, is situated in the southern part of the Valday Hills in Russia at a very sensitive southern boundary of a boreal forest community close to sources of other large European rivers: Dnepr (flows into the Black Sea) and Daugava (Zapadnaya Dvina) (flows into the Baltic Sea) (Fig. 2).

The landscape of the Upper Volga area is relatively flat with many small rivers, streams, lakes and bogs. The source of Volga is located at the Razvenizkaya Hill, 323 m above sea level, in the north-western part of the selected Upper Volga catchment. The length of Volga course between its source and Selishy dam is about 102 km and is represented by a continuous chain of lakes: Sterg (18 km^2), Vselug (30 km^2), Peno (17 km^2), Upper Volgo and Lower Volgo (61 km^2). The total area of these lakes is about 126 km^2. The Selishy dam is the outlet of the Upper Volga catchment (Fig. 3).

The vegetation cover is predominantly a mixed forest of spruce, birch, aspen and pine with less than a quarter of the area covered by meadows and agricultural crops. Since the Holocene Norway spruce (*Picea abies* (L.) Karst) is the dominant forest species in the Volga's source area (Vygodskaya et al., 1995). The soils are mostly brown soils with gley and podsol and some peats. The altitude of the catchment varies from 200 to 300 m above sea level (Fig. 3).

2.2. Time series analysis of hydro-meteorological parameters

To analyse long-term climatological data at the Volga source area during the last century the daily meteorological data about precipitation and air temperature from meteorological stations located at and around the Valday Hills were used. Meteorological network at this part of Russia is rather rare. In the time series analysis, therefore, all meteorological data from the stations located up to 200 km around the Upper Volga area were involved. Meteorological station Velikie Luki has the longest continuous records of meteorological parameters in this area (since 1881) and it is located not very far from the Upper Volga area. Meteorological records in local stations in Ostashkov, Zapovednik, Valday, Toropez do not unfortunately exceed a period of 50 years. Long-term meteorological data from the more remote stations Bologoe, V. Volochek, Novgorod, Totma, Smolensk were also used to verify long-term trends.

In time series analysis of the long-term air temperature and precipitation records most attention was paid to:

- monthly and daily mean, maximal and minimal air temperatures,
- maximal amplitude of the mean daily air temperatures,
- monthly averaged daily maximal and minimal air temperatures,
- monthly averaged daily amplitude of the air temperature,
- monthly precipitation amounts,
- number and frequency of days per month without precipitation and with precipitation of different rates (2 mm per day and more, 5 mm per day and more, 10 mm per day and more).

Fig. 2. Geographical location of the selected Upper Volga catchment area (marked by black square).

2.3. Field measurements of energy and water fluxes

An experimental forest site (56°58′ N, 32°52′ E) for measurements of the vertical energy, water and carbon fluxes was selected and established near the small town Peno, about 2 km north–west from the Volga's lake shore (Fig. 3). The forest stand at the site is mixed, composed mostly (according to fraction of basal stem area) of aspen (*Populus tremula* L.) and Norway spruce (*P. abies* (L.) Karst), creating the upper canopy with admixture of birch (*Betula verrucosa* L.), mostly young specimen of mountain ash (*Sorbus aucuparia* L.), alder (*Alnus incana* L.) and rare old pine (*Pinus sylvestris* L.) trees. Ground vegetation cover is very rich in herbaceous species. Forest soil is brown sandy-loam (about 60 cm deep) at drier parts of the site (where underground water is at the depth of about 1.0–1.5 m) and dark-brown clayish-loam about 40 cm deep at wetter parts (where water is at the depth of about 0.0–0.5 m). A clay layer in the sub-soil is typical for soils in this area.

Field measurements at selected experimental site included:

- Meteorological measurements of air and soil temperatures, air humidity, wind speed and wind direction, net radiation, incoming and reflected solar radiation, precipitation amount (since December 1999);
- Forest transpiration measurements using a sap-flow technique (since June 1999);
- Forest inventory (since May 1999).

Sap flow rates were continuously measured in 20 sample trees of the main overstorey tree species as well as understorey woody species during the growing seasons of 1999–2000. Representative size of sample trees was calculated using basal area according to quantiles of total (Cermak and Kucera, 1990). Sap flow was measured at breast height (1.3 m above ground) by the tree trunk section heat balance (THB) method (Cermak et al., 1973, 1982; Cermak and Kucera, 1981; Kucera et al., 1977) in some trees and in parallel by the heat field deformation (HFD) method (Nadezhdina et al., 1998) on all sample trees. Two sensors installed in opposite sides of stems were used on each sample tree. Radial pattern of sap flow was measured with the special HFD sensors before installing the standard sensors for long-term measurements and checked for possible changes at the end of the growing seasons, so that sap flow pattern was characterised by 24 points in each sample tree. Measurements started from early summer (during late phase of leaf flushing in broadleaf species) to October (around leaf fall) in 1999 and from May until the end of September 2000. Data were downloaded every one or two weeks when the measuring devices were checked.

Forest inventory parameters (e.g. number of trees, diameter of basal area) of all trees estimated at the experimental plot were used for up-scaling transpiration data from sample trees to the entire forest stand. Total daily transpiration of individual trees were related to their main stem parameters (diameter or basal area) for

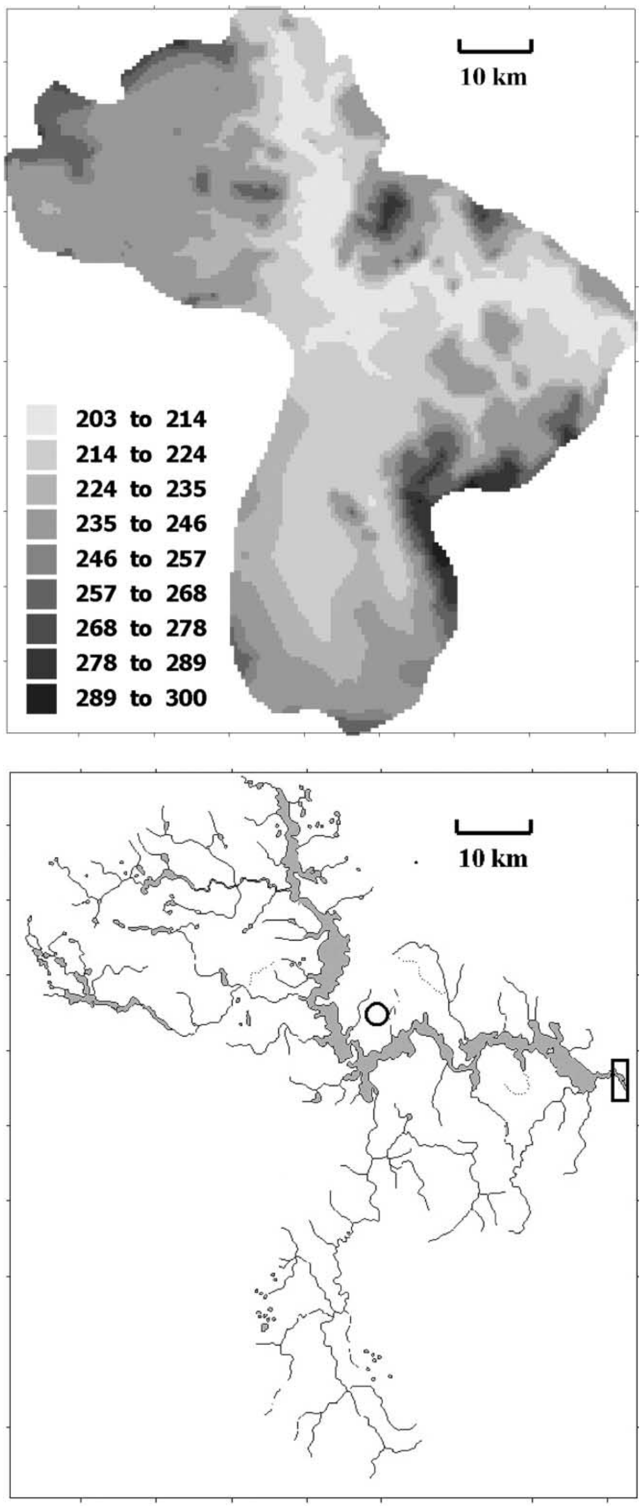

Fig. 3. Digital maps of relief and hydrography of the Upper Volga catchment area. Different altitudes of catchment are shown in relief map by different grey scale in meters. Black rectangle shows the location of Selishy's dam. Black circle shows the location of the experimental forest site near Peno.

each particular day of the study. Transpiration for all tree diameter classes was calculated and these values were multiplied by numbers of trees in classes and summarised for the entire stand area unit. Additional biometric studies were performed on tree root systems in order to characterise differences in their architecture between species and absorbing capabilities at the site. Root systems of the trees were investigated by excavating methods. Diameter of rooted volume in different depths and rooting pattern were estimated as well.

2.4. Model simulations of regional water fluxes

Land surface–atmosphere interaction was described using several modelling approaches of different complexity. The spatial and temporal variability of energy and water fluxes was described using SVAT-Regio model. The hydrological model PREVAH (Precipitation Runoff-EVApotranspiration Hydrological response units, Gurtz et al. (1999)) was used to predict and quantify possible changes of the water regime on regional and local scales under land-use and climatic changes.

PREVAH combines spatially distributed raster elements into "Hydrological Response Units (HRU)". It consists of several sub-models such as snow accumulation, interception, soil water storage, runoff generation, discharge concentration and flood routing (Fig. 4).

The snow sub-model describes accumulation and melting of a snow cover. It relies on the combination of temperature index and energy balance approach with a distinction between radiation caused melt in periods without precipitation and advectively induced ablation. The calculation of actual evapotranspiration is based on the Penman–Monteith equation (Monteith, 1965) using temporal changing the maximal stomatal conductance for various classes of vegetation types. Description of

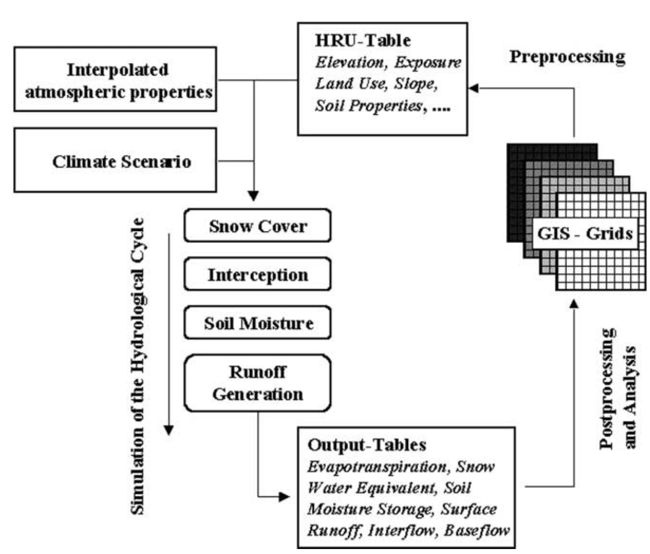

Fig. 4. Scheme of the hydrological catchment model PREVAH (Gurtz et al., 1999).

the run-off formation in the model includes three main runoff components: quick surface runoff, interflow (delayed) and ground water flow as baseflow. Each runoff component is transformed by its specific storage coefficient valid for the whole catchment. The percolation into ground water storage is calculated from data on soil conductivity and moisture content of the upper storage. The calculation of flood routing is based on a combination of linear storage and translation components (Gurtz et al., 1999).

As input information PREVAH requires high-resolution digitised maps of the land surface (e.g. elevation, land use, vegetation, soils) and sub-surface characteristics prepared in a GIS (Geographical Information System) compatible form. An interface to a regional "Climate High-Resolution Model (CHRM)" (Vidale et al., 1999) and to a general circulation model (GCM) allows to dynamically couple regional and local hydrological processes with actual and predicted regional and global atmospheric conditions.

For hydrological modelling of the Upper Volga catchment all necessary digitised maps were prepared with 500 m × 500 m grid resolution. The 13650 grid elements were integrated into 640 hydrological response units with a mean surface of about 23 km^2. The smallest unit has an area of about 0.25 km^2 (1 grid cell) and the largest unit—an area of about 89.5 km^2 (358 grid cells). PREVAH was calibrated and validated for 18 years record of runoff measured at two small catchments (Usadievsky (0.36 km^2) and Tayezhniy (0.45 km^2)) of the Valday Branch of State Hydrological Institute (VBSHI) in Valday (e.g. Schlosser et al., 2000). The Usadievsky (covered mainly by grass) and Tayezhniy (covered mainly by forests) catchments have the longest records of runoff within the Valday Hills area. They are located at about 50 km from the northern border of the Upper Volga catchment. To validate the PREVAH model most attention was paid to data from Usadievsky catchment.

In order to describe the possible response of a water budget of the Upper Volga catchment area to climatic changes different monthly averaged climatic scenarios provided by the GCM ECHAM4 (developed at Max-Planck Institute for Meteorology, Hamburg, Germany) have been used (Roeckner et al., 1996). Most attention was focused on the scenario assuming a twofold increase of CO_2 in the atmosphere. Annual cycles of air temperature and precipitation produced by the ECHAM4 for the Upper Volga area for period from 1990 to 2000 were compared with related annual cycles at local meteorological stations (e.g. Ostashkov, Zapopvednit, Toropez) of the Russian Weather Service. Physiological adaptation of different vegetation types to the new environmental conditions was not considered. However, structural changes of the forest canopy were taken into account in two model scenarios.

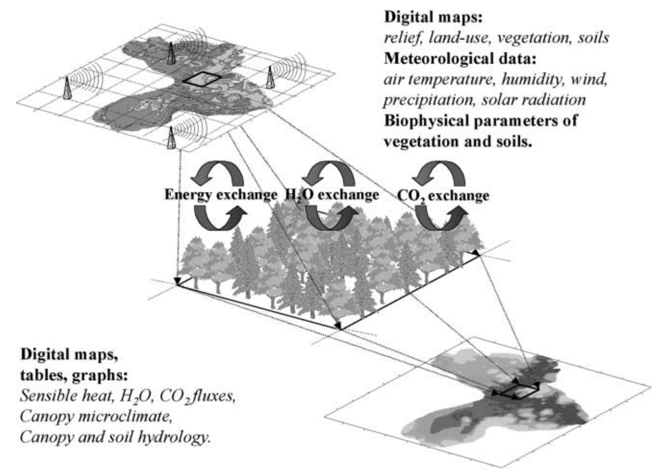

Fig. 5. Modelling the energy, water and carbon budgets of the catchment using SVAT-Regio model.

To describe internal canopy microclimate, dynamics of tree water uptake and partitioning of the energy and water fluxes within the forest canopy complex models of land surface–atmosphere interaction with vertically structured descriptions of the vegetation canopy are required. For such purposes a vertically structured multi-layer SVAT-Regio (Soil–Vegetation–Atmosphere Transfer in Regional scale) model was developed and applied to the Upper Volga catchment area (Fig. 5). Representation of canopy microclimates in SVAT-Regio model allows both vertical and horizontal (between neighbouring grid cells) energy and mass exchange. As input parameters in this model the mean daily meteorological data measured at meteorological stations located within and around the Upper Volga area were used. Moreover, SVAT-Regio used digitised maps of relief, land-use, vegetation and soil in raster format. The modelling procedure consisted of three steps. In the first step, data from different meteorological stations are interpolated to individual grid cells (assumed to be uniform) into which the entire study area is divided. Dimensions of each grid cell can vary from 100 m × 100 m to 10 km × 10 km. In the second step, for each grid cell the different hydro-meteorological parameters and fluxes (energy, H_2O and CO_2 fluxes, canopy microclimate, canopy and soil hydrology, etc.) are simulated with a temporal resolution of 1 h. It is assumed that relief, soil and vegetation cover within each grid cell are spatially uniform. However, vegetation within grid cell can be represented by different plant species. In the last step, modelled parameters and fluxes are scaled up to the entire area.

To describe and quantify the forest-atmosphere interaction on a local scale the one-dimensional multi-layer SVAT model (SLODSVAT) (Oltchev et al., 1996, 1997) was applied. It allows to model canopy microclimate, vertical radiation, sensible heat, H_2O and CO_2

transfer within and above the forest canopy composed of one or various tree species with temporal resolution from 5 min to 1 h. As meteorological input parameters (air temperature, water vapour pressure, wind speed, precipitation rate, solar radiation) for this model the measured meteorological data from both the meteorological tower and the nearest meteorological stations were used. All necessary biophysical canopy and soil parameters used in SLODSVAT model were determined under field conditions in 1999 and 2000.

3. Results and discussion

3.1. Long-term dynamics of hydro-meteorological parameters and land-use pattern

The climate of the Upper Volga area is temperate continental with cold winters (daily temperatures ranging from −10 °C to −20 °C) and mild summers (daily temperatures ranging from 15 °C to 25 °C). The mean annual temperature is about 5.8 °C. The mean annual precipitation amount is about 620 mm. Snowfalls occur from October to March. Winter rainfall varies from 10 to 50 mm per month while summer rainfall varies from 50 mm to 200 mm per month. Peak rainfall occurs more often in the months of June/July.

Analysis of past (since 1881) meteorological data from meteorological station in Velikie Luki, 30 year records of the air temperature and precipitation from surrounding meteorological stations (Ostashkov, Toropez, Zapovednik) and 20 years runoff record from Selishy's dam show a large variability of atmospheric conditions and water regime of the Upper Volga area (Figs. 6 and 7). During the last 50–60 years the mean annual temperature increased by 1.2 °C, and annual precipitation increased by 140 mm (Table 1). At the same time, no significant trend of annual runoff during the last 20 years could be found (Fig. 7). Changes of the air temperature and precipitation were more significant during winter and spring and were very small in summer and in autumn. Spatial distributions of the temperature and precipitation fields are nearly uniform. The trend of frequencies of the days with shower precipitation (days with precipitation more than 5 mm and more than 10 mm) shows a similar shape as the trend of total precipitation. At the same time, any appreciable changes of frequencies of days with/without precipitation during the reported period could not been found.

Similar results for long-term variability of hydrometeorological conditions were found also and for other meteorological stations located around the Valday Hills area (Bologoe, Novgorod, V. Volochek, Valday). The revealed long-term trends of the mean air temperature and precipitation for selected meteorological stations were well corresponded to the trends presented in Atlas of the Climate Trend of Europe (Schönwiese and Rapp, 1997) and in the Climate Change review (IPCC, 1996).

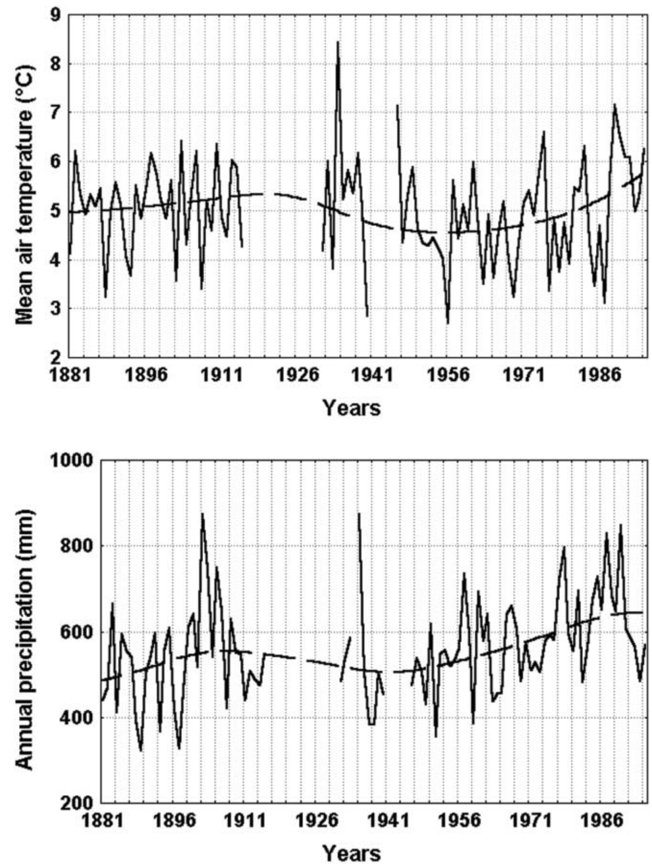

Fig. 6. Trends of the annual air temperature (2 m above ground) and precipitation amount at the meteorological station Velikie Luky (located close to western boundary of the Upper Volga catchment area) from 1881 to 1995.

During the last 50 years the gradual increase of the mean air temperatures was accompanied by decreasing mean daily amplitudes. Such effects were clearly manifested especially in winter months, and were basically combined with a stronger increase of the minimal daily air temperatures. Changes of the maximal daily air temperatures were at the same time relatively small.

Increasing air temperature reflects world-wide warming processes accompanied by intensification of circulation activities in Eastern Europe in winter and in spring due to both the long-term global climate oscillations and anthropogenic factors.

The winter increase of the air temperatures is caused basically by intensification of cyclone activity in the Northern Hemisphere. Frequent cyclones from the west and south-west bring wet and warm maritime air masses from the North Atlantic and Mediterranean, and warm air masses from the Middle East that result in frequent intensive snowfall and snow-thawing in winter. Although increased precipitation, frequent thaws in January–February can result in reducing the snow water

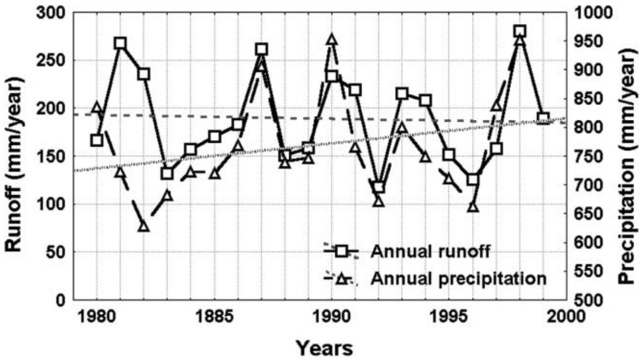

Fig. 7. Trends of the measured annual runoff at Selishy's dam and annual precipitation amount at the nearest meteorological station in Ostshkov for the period from 1980 to 1999.

Table 1
Recent changes of the mean annual and seasonal air temperature, precipitation and runoff at the Upper Volga catchment area

Parameters	Period	Year	Winter	Summer
Air temperature (°C)	Last 50 years	+1.2	+2.9	±0.0
Precipitation (mm/period)	Last 50 years	+140.0	+92.0	−18.0
Runoff (mm/period)	Last 20 years	±0.0	+10.0	−5.0

capacities and soil water storage in spring. Decreased soil moisture and weak precipitation in April–May may further lead to a lack of accessible soil water for tree growth in the beginning of summer.

Changes of land-use pattern and forest cover during the last century were mainly influenced by human factors. 100 years ago Volga's source area was relatively densely populated with very intensive agriculture. Wood was largely used for heating and house-building. Forests covered about 50–55% of Volga's source area in 1850. Gradual migration of rural inhabitants to urban regions in the middle of the last century resulted in slow reforestation. Forest taxation data show that in 1970 forests covered about 71% of the area. These new-forested areas were mainly represented by mixed deciduous and coniferous tree species. Further recurrent cutting of trees with high-quality wood (mainly spruce) lead to a gradual substitution of coniferous forests by low-quality deciduous and mixed forests.

Changes of land-use and forest composition during the last 20–30 years are mainly caused by climatic factors. Despite several recent summer droughts, local forest fires and windthrows, total area covered by forests derived using recent remote sensing data was not significantly changed. Coniferous and mixed coniferous-broadleaf forests cover at present about 72% of the catchment area. Since 1970 areas of natural coniferous forests (spruce, pine) decreased from 8.4% to 7% and areas of mixed forests increased from 52% to 59% of the total land area. At present natural mono-specific coniferous forests can be found only in protected area of the Central Forest Biosphere Reserve (spruce forests) and in areas near the Upper Volga lakes (pine and spruce forests).

Root systems of the tree species growing at the Upper Volga area are naturally adapted to surplus soil moisture conditions and to a high ground water level. During the field campaigns it was observed that broadleaf species have usually deep root systems, while root systems of spruce were typically more shallow. This indicates that deciduous trees are better adapted to low aeration of soil than spruce trees and can, therefore, more easily avoid drought by absorbing water from deeper soil layers (Korotaev, 1987). Moreover, shallow root structure of spruce results in decreasing anchoring ability of root systems and, thus, lowering mechanical stability of forests especially under soil droughts. Broadleaf trees, therefore, could be mechanically more stable and acclimatised to expected warmer and drier weather conditions in summer. Pine trees have a relatively deep rooting system and should be usually not exposed to drought stress.

At the same time, pioneer deciduous species are short-life species, occurring as one of the first successional species at open, well-illuminated places. It cannot sustain over the rotation period of the whole mixed forest and can be replaced by long-life species what can grow even in shaded places (e.g. spruce).

3.2. Field measurements of water fluxes

Fig. 8 gives examples of the diurnal variability among different tree species and between individual trees of the same species during the wet and dry periods of 1999. Diurnal patterns of water uptake and transpiration correspond to long duration of summer days at the experimental site situated in the transition between temperate and boreal latitudes. Water uptake pattern of individual sample trees reflected different shading of crowns of sample trees by their neighbours and also different pattern of root distribution. Highest daily amplitudes of water uptake were reached under non-limiting soil moisture conditions, while low amplitudes were typical for drought conditions. Total daily transpiration of individual trees was clearly related to their size as represented by diameter at breast height. This was true for both, coniferous and broadleaf species. However, transpiration of broadleaf species was somewhat higher over the summer months. No significant differences were found between aspen and other deciduous species in this respect, although the small number of sample trees of less abundant species does not allow a strong statement. However, more pronounced differences occurred in trees with different crown sizes and those growing in different social positions. Particularly,

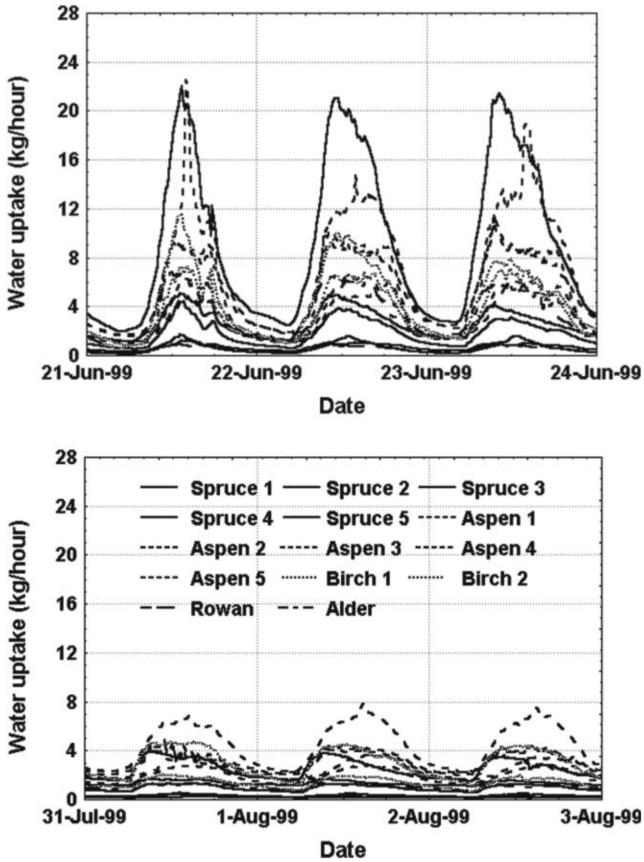

Fig. 8. Diurnal variability of water uptake for different tree species under different soil moisture conditions (wet (June 1999) and dry (July–August 1999)) at the experimental site near Peno.

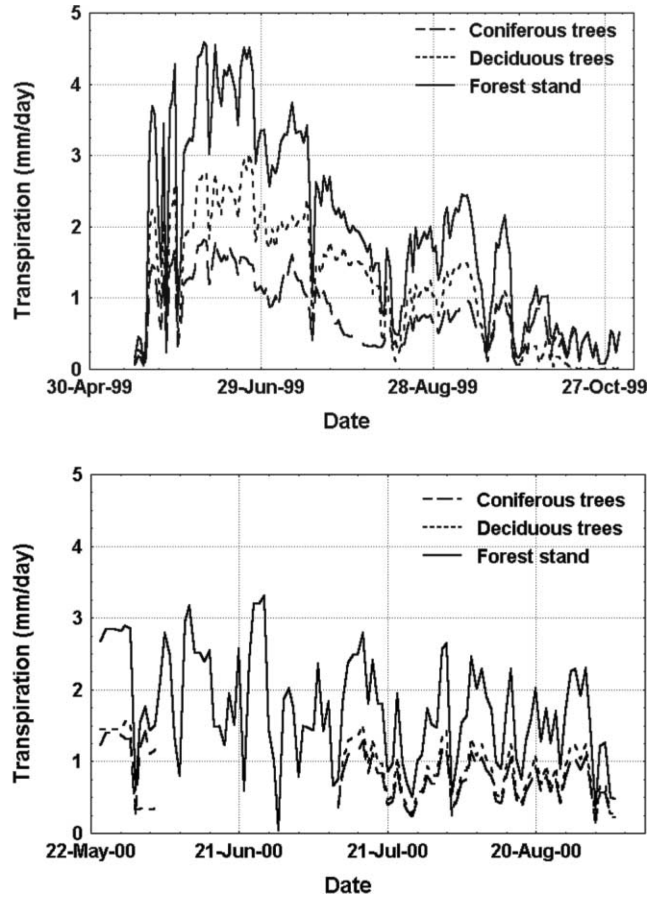

Fig. 9. Seasonal variability of daily transpiration of coniferous and deciduous trees during the measuring periods in 1999 and 2000 at the forest experimental site near Peno.

trees which occurred in places where the canopy was opened by accidental windfall transpired significantly more than trees of the same size growing in places, where they were more shaded by neighbouring trees. Transpiration was lower in trees with partially damaged crowns.

Total forest transpiration rates that were calculated from the sap flow measurements at tree scale revealed significant differences between the years 1999 and 2000 (Fig. 9). Weather conditions in June–July were evidently much drier during 1999 (total June–July precipitation amount was about 47.0 mm) than in 2000 (about 97.8 mm). Maximal transpiration rates were observed in May–June 1999 that were associated with development of new foliage in broadleaf trees. Low precipitation and dry soil conditions resulted in a gradual decrease of transpiration (especially for spruce trees). Soil drying in July and in the beginning of August 1999 was accompanied by a strong decrease of the ground water level (up to 100 cm). At the beginning of August the moisture content of the upper 20 cm soil layer ranged between 28% and 35% of full field capacity. Decreasing water discharge, stream flows and water levels in small lakes were observed as well. Transpiration pattern changed significantly after strong rains in August 1999. Despite of the high soil water content, transpiration rates were significantly smaller during late summer and autumn than the spring values. Early summer transpiration rates of the wet year 2000 did not reach the high spring values of 1999. During the rest of the vegetation period 2000 transpiration rates were maintained at this relatively low level. These results indicated both, limited soil water supply during drought 1999 and limited root water uptake even under excess of water. The latter can be interpreted as a lack of soil aeration due to surplus water content that in turn limits root respiration and subsequently metabolism in 2000.

3.3. Modelling the regional water fluxes

3.3.1. Model validations and calibrations

Calibration and validation of applied SVAT-Regio and PREVAH models were performed using results of the field measurements of transpiration and evapotranspiration at the forest experimental site near Peno (period from 1999 to 2000) and long-term run-off records at Usadievsky catchment of the VBSHI in Valday (period from 1966 to 1974 was used for validation and period from 1966 to 1967 for calibration of PREVAH). All necessary biophysical parameters were estimated during the field campaigns in 1999–2000.

Comparisons of daily and hourly transpiration rates modelled and measured using the sap flow technique at the forest experimental site for dry 1999 and wet 2000 showed a satisfactory correlation of modelled and measured fluxes. Maximal differences were observed in spring, during leaf flush of deciduous trees and in autumn in the period of leaf fall. The selected experimental site in overstorey is represented by different tree species (about six different types) of different ages and structures that makes it very difficult to scale-up from individual trees characterised by significant biophysical diversity (Fig. 8) to the entire forest canopy. Thus, obtained correlation between modelled and measured fluxes can be characterised as very good for such complex forest community (Fig. 10).

In July–August 1999 summer drought had a different impact on water regime of different tree species (Figs. 8 and 9). A parameterisation of such variability and complexity requires usually a detailed description of biophysical properties of different tree species within a forest community that is very complicated and usually not acceptable for application in regional SVAT models. Applied model parameterisations (PREVAH, SVAT-Regio) to describe evapotranspiration and transpiration rates in forest communities were based on averaged effective characteristics of the forest structure and physiology of the different tree species. Despite of such approximations modelling results showed that applied models adequately described a decrease of overstorey and understorey water fluxes during the period of limiting soil water conditions in summer 1999 (Fig. 10).

Comparisons of the runoff rates modelled (PREVAH) and measured at a small catchments Usadievsky for period from 1966 to 1974 showed that PREVAH allows to adequately describe annual and seasonal variability of hydrological regime for a small catchment area. Nash and Sutcliffe's coefficient (R^2) (Nash and Sutcliffe, 1970) estimated using daily data sets was 0.72. PREVAH very well reproduces the beginning and the duration of the main melt season. However, the prediction of runoff rates in late summer and autumn is less precise (Fig. 11).

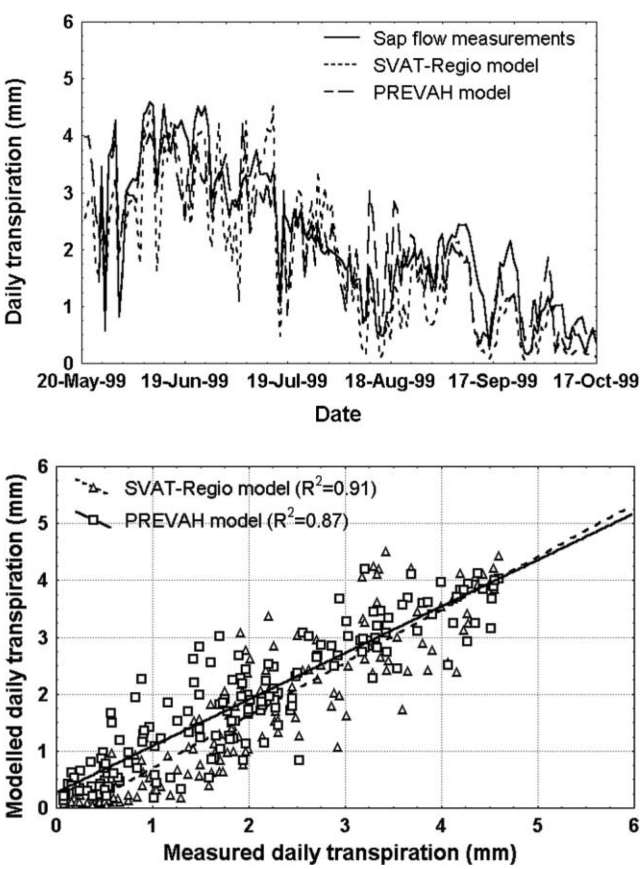

Fig. 10. Comparisons of modelled (SVAT-Regio and PREVAH models) and measured (sap flow method) overstorey transpiration of the mixed forest ecosystem at experimental site near Peno during the vegetation period of 1999.

3.3.2. *Modelling regional evapotranspiration, transpiration and canopy microclimate*

Results of various modelling experiments using the regional SVAT-Regio model for different periods from 1990 to 2000 show a significant spatial and temporal variability of energy and water fluxes. This spatial variability was mainly influenced by local weather conditions (e.g. air temperature, solar radiation, precipitation) and did also depend on relief, land surface and vegetation properties. Minimal modelled differences between daily evapotranspiration and transpiration of similar forest ecosystems were observed during rainy days (up to 5–10%). Maximal differences were found in sunny days under dry conditions (up to 20–30%). Relief, land surface and vegetation cover also influence energy and water fluxes mainly due to the enormous natural variability of optical and physiological vegetation properties. Contribution of understorey vegetation and soil surface to total forest evapotranspiration did generally not exceed 10–15% of total forest evapotranspiration (Fig. 12). It was generally dependent on leaf area index (LAI), tree density and species composition and soil moisture conditions. A maximum of about 30–50% was calculated for sparse mixed and deciduous forest stands and for windthrow areas.

In order to quantify effects of sub-grid relief and land-use heterogeneity to regional water fluxes several modelling experiments using SVAT-Regio model for contrasting summer periods of 1994, 1996 and 1999 were provided. For model experiments relief, land-use, vegetation and soil data with spatial resolution from 500 m × 500 m to 10 km × 10 km were used. For each

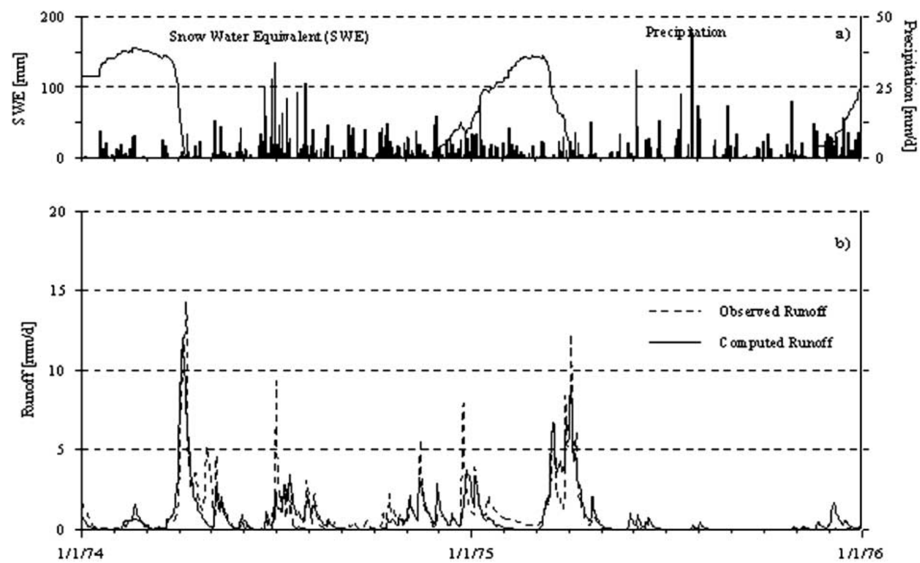

Fig. 11. Comparison of modelled (PREVAH) and measured (Usadievsky catchment) total runoff for period from 1974 to 1976.

grid cell the hourly, daily and monthly overstorey and understorey transpiration and evapotranspiration were estimated.

Modelling results showed that decreasing the spatial grid resolution of the model from 500 m × 500 m to −10 km × 10 km can result in significant differences of daily and hourly regional evapotranspiration rate (up to 24%) and in small differences (up to 5%) of the monthly and seasonal evapotranspiration rates. The sign of such changes does mainly depend on atmospheric and soil conditions and on heterogeneity of relief and vegetation properties in the considered area. More significant differences were detected for the changes of local evapotranspiration and transpiration due to averaging simplifications of sub-grid relief and vegetation properties (up to 30% for daily evapotranspiration). Sensitivity of regional evapotranspiration to grid cell resolution was gradually decreased with increasing the area of the considered catchment (sub-catchment) and depended on relief (slope, exposure), land-use and vegetation properties. Impacts of horizontal fluxes between neighbouring grid cells on local vertical atmospheric fluxes were generally depended on local land surface and weather conditions. A maximal modelled impact of horizontal fluxes on vertical hourly sensible and latent heat fluxes was observed under contrasting weather conditions in 1999 and was not exceed 20% (used grid resolution in model was 500 m × 500 m).

3.3.3. Modelling the hydrological regime under present and future climatic and land-use conditions

Hydrological PREVAH model was used for simulation of hydrological regime of the Upper Volga catchment under present and future climatic conditions. For modelling of the present annual and seasonal variability of principal water budget components three meteorological data sets (produced by the GCM ECHAM4 and by the regional CHRM models, and measured at three surrounding meteorological stations (Ostashkov, Toropez, Zapovednik)) for period from 1990 to 2000 were used.

A comparison of seasonal cycles of air temperature, precipitation and global radiation produced by ECHAM4 and CHRM models with data measured at meteorological stations showed that the performance of the air temperature estimations was satisfied for both applied models. Modelled precipitation was overestimated between January and April and their maximal values were shifted from July to June. A reason for these differences is connected both with different initial meteorological information (e.g. GCM ECHAM4 uses data from meteorological stations included in global international network, only) and, with scales of averaging for applied models resulting in a smooth of local heterogeneity of land surface (e.g. grid resolution of the GCM ECHAM4 is 2.5° × 2.5°, roughly 20 time larger than the entire Upper Volga catchment).

Results of modelling estimations show that seasonal cycle of total runoff differs significantly depending on selected input data (Fig. 13). A very high winter precipitation simulated by GCM in 1990–2000 resulted in a large snow accumulation and higher snow melt rate in comparing with the other data sets. Duration of the melting period was roughly equal for all applied data. It was usually continued from the second part of March to the middle of May. Runoff dynamics during the summer mainly depends on precipitation amount and duration of periods with rainy and dry weather. Short-term and heavy showers resulting in a strong increase of local surface runoff not always lead to any significant splashes

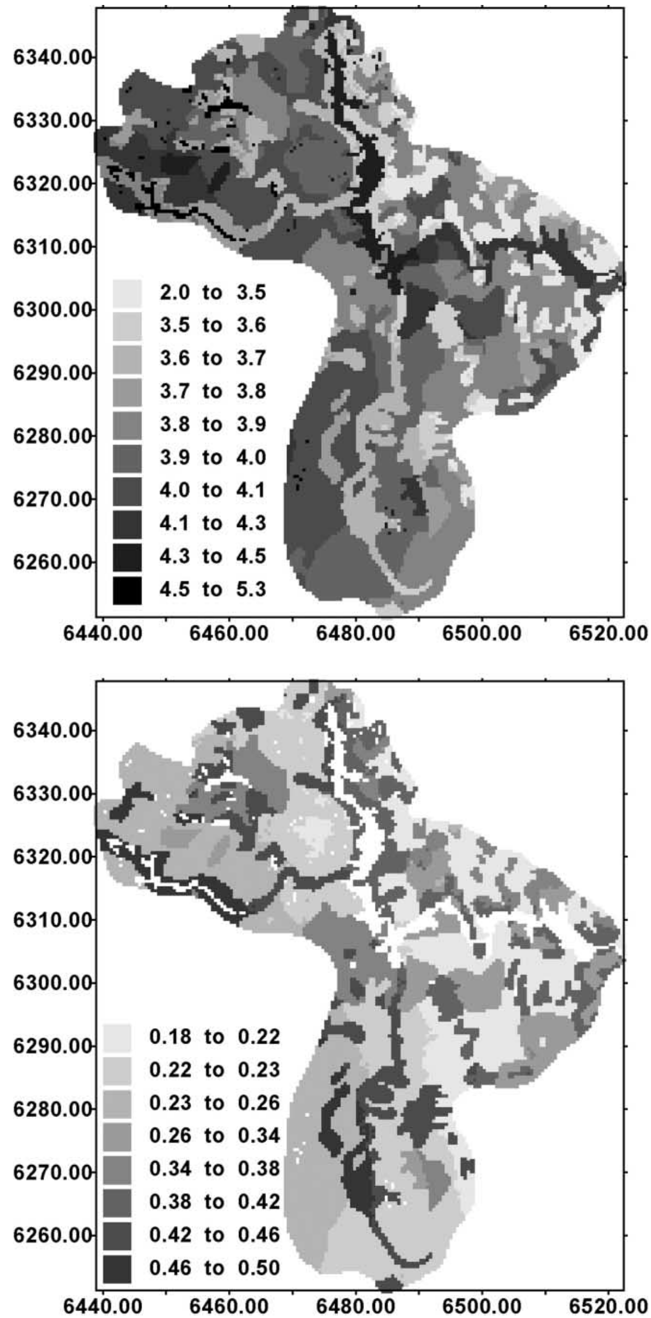

Fig. 12. Examples of modelled daily total and understorey evapotranspiration (mm) for sunny day of 15 June 1999. Contribution of understorey and soil to total evapotranspiration for meadows and sparse forest stands ranged between 5% and 30%.

of runoff on a regional scale. Such dependencies were very well represented within all modelling experiments.

Gradual increasing the surface runoff in October–November was mainly caused by increasing precipitation and significantly decreasing evapotranspiration rates. Maximal ground water recharge was occurred during the melting period in spring and during a short time in autumn. Summer ground water recharge was relatively small.

Comparisons of modelled evapotranspiration patterns during period from 1990 to 2000 for all applied meteorological data sets showed a very good agreement. Total annual evapotranspiration was significantly smaller than precipitation amount (up to 50–60% of total precipitation). At the same time predicted summer evapotranspiration exceeded always the observed summer precipitation.

Annual modelled dynamics of soil moisture conditions was mainly influenced by annual variability of precipitation. Maximal soil moisture was observed during melting periods in spring and minimal soil moisture-in the second part of summer (July–August). The low precipitation amount in the period between July and October reduces the soil moisture recharge in autumn and can lead to a lack of the soil water during winter. A soil moisture recharge, which can be possibly observed simultaneously with runoff generation during the thaws in winter, was not taken into account in applied model algorithms.

Expected future climatic changes can have significant impacts on hydro-meteorological conditions of the Upper Volga area. Model estimations of GCM EC-HAM4 according to the "$2 \times CO_2$" scenario result in an increase of the annual air temperature by +3.0 °C and increase of precipitation by about 11% (Fig. 14). Maximal increase of precipitation can be expected in spring (by 45%). In summer model predicts a decrease of precipitation by 14%. Predicted changes of the mean monthly air temperatures are positive and evenly distributed during the year. Predicted changes of global solar radiation are small. In spring they are negative (about 10–20%) and in autumn they are positive (about 4–8%). It should be expected, that due to rather heterogeneity of the Upper Volga area, the spatial distributions of the air temperature and especially global radiation and precipitation amount can be differ from predicted mean values. Such variability was not considered within present study.

Model simulations of the expected future hydrological regime show that climatic changes may produce significant changes of the water budget of the Upper Volga region (Table 2, Figs. 14 and 15). All model estimations show a possible shift of the beginning of the melt season from April to March and its end from May to April. The higher air temperatures result in a decrease of snow cover accumulation in winter and in a reduction of the spring flood power and ground water recharge despite of increasing precipitation (Fig. 15). The contribution of snowmelt to total annual runoff sinks by 30–40%.

Shorter period with snow cover leads to significant changes of radiation and energy balances of the atmosphere–vegetation interface resulting in an increase of the evapotranspiration rate in early spring and in late autumn. Early beginning of the vegetation period results

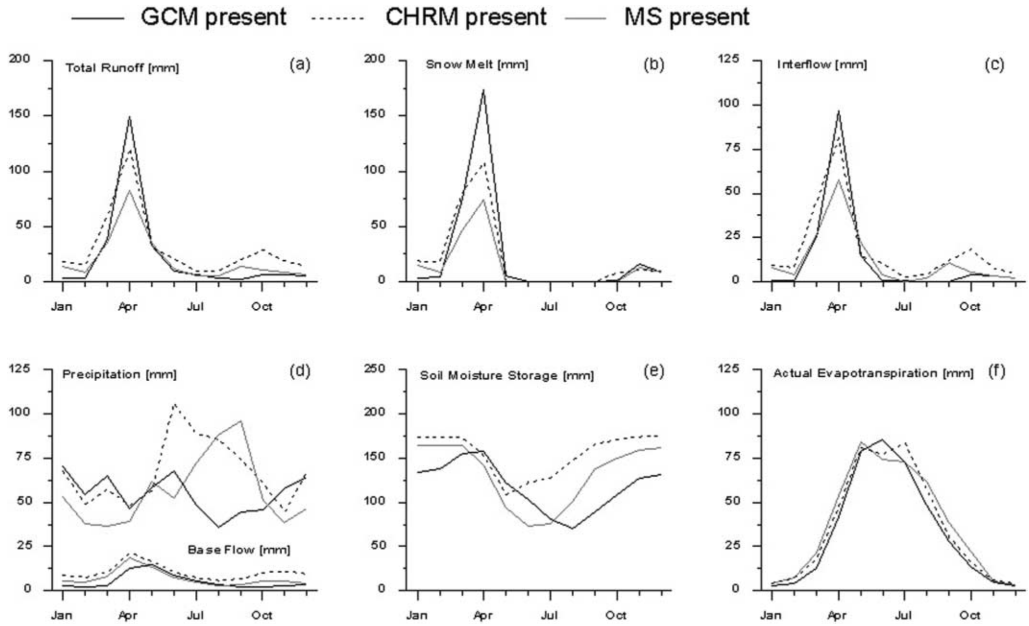

Fig. 13. Averaged seasonal variability of water balance components under present climatic conditions modelled by PREVAH using three different data sets (model estimations by the GCM ECHAM4 (GCM) and by the regional CHRM models, and measurements at surrounding meteorological stations (MS)).

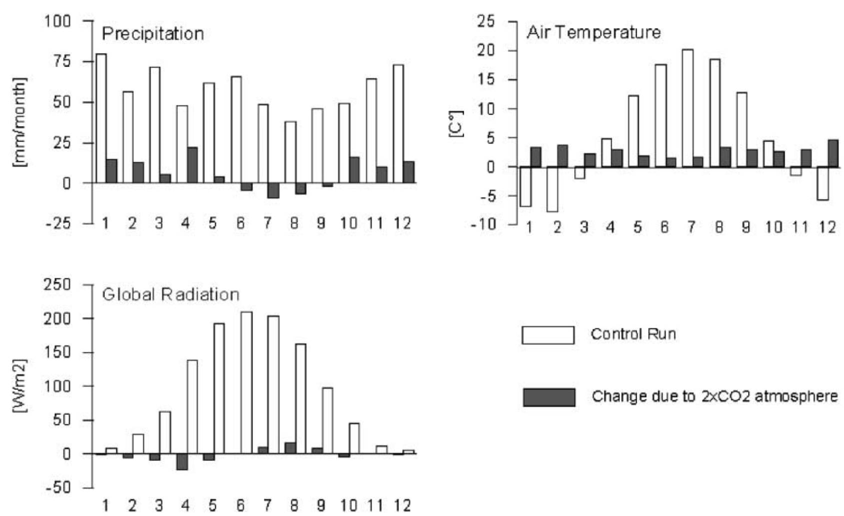

Fig. 14. Mean monthly changes of the air temperature, precipitation and global radiation under GCM $2 \times CO_2$-scenario. "Control Run" represents the present annual variability of the air temperature, precipitation and global radiation which was derived by the GCM ECHAM4 and averaged for period from 1990 to 1999.

Table 2
Annually averaged air temperature (*T*), global radiation (GR), precipitation (*P*), simulated actual evapotranspiration (ET), total runoff (*R*) and contribution of snow melt to total runoff (SR, in percent of the total runoff) for present (CTRL) and modelled future (SCEN) climatic conditions

Catchment	Input data	*T* (°C)	GR (Wm^{-2})	*P* (mm)	ET (mm)	*R* (mm)	SR (%)
Upper Volga	MS-CTRL	4.1	114	717	462	255	74%
Upper Volga	MS-SCEN	7.0	112	763	478	294	52%
Upper Volga	GCM-CTRL	5.6	97	660	397	266	78%
Upper Volga	GCM-SCEN	8.5	95	730	408	327	61%
Upper Volga	CHRM-CTRL	4.2	95	808	431	367	69%
Upper Volga	CHRM-SCEN	7.1	93	861	452	410	33%

Three different data sets were used to assess present and future ET and *R*: model estimations by the GCM ECHAM4 (GCM) and by the regional CHRM models, and measurements at surrounding meteorological stations (MS).

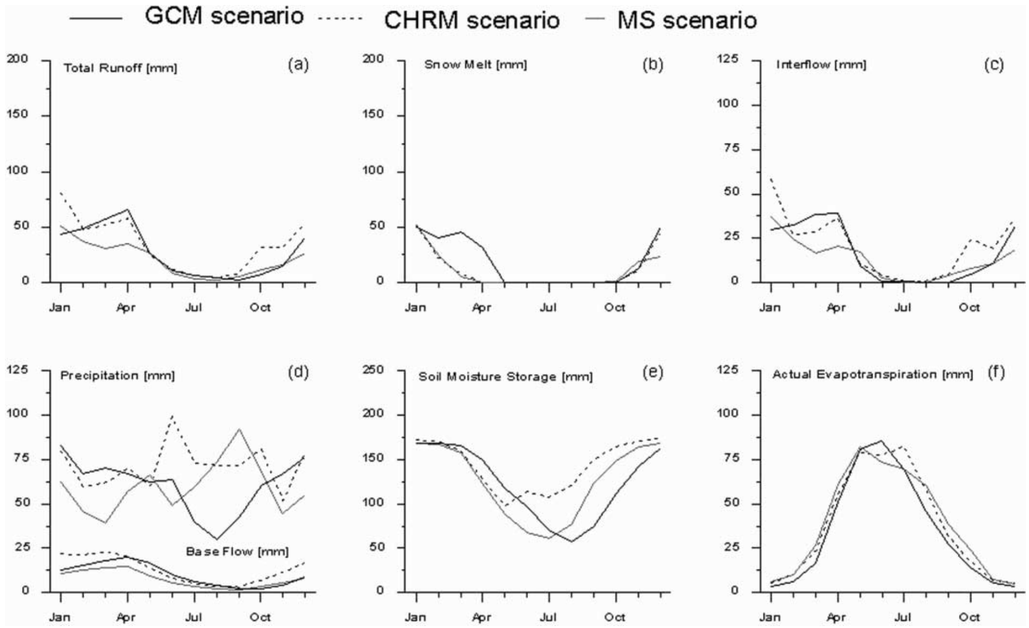

Fig. 15. Expected future seasonal variability of water balance components modelled by PREVAH using three different data sets (model estimations by the GCM ECHAM4 (GCM) and by the regional CHRM models, and measurements at surrounding meteorological stations (MS).

in a more intensive transpiration in spring that together with reduced precipitation and increased global radiation may lead to deficit of available soil water in summer. As was already shown such processes should be very critical for stability of spruce forest community.

Increasing the autumn precipitation after relatively dry summer results in a faster recovery of saturated soil moisture conditions, in increasing the surface runoff, ground water recharge and actual evapotranspiration (mostly due to increase of evaporation of the intercepted rain water).

Described modelling estimations for expected future hydrological regime were carried out for different scenarios of vegetation and land-use changes. Scenario without taking into account the changes of land-use and forest structure was considered as well. It is obvious that present climatic warming will lead to gradual displacement of the coniferous by deciduous species at the Upper Volga catchment and to a shift of the southern boundary of boreal forest community to the north. However, such structural changes have usually a long-term tendency (100 years), while the described climatic scenarios can be expected already in 40–60 years.

Expected future vegetation changes of the Upper Volga area can be mainly connected with impact of both climatic and anthropogenic factors. As it was already mentioned, however, the Upper Volga area is characterised by very low level of anthropogenic pressure and air pollution. Thus, a direct influence of any anthropogenic factors can be ignored. Therefore, main factors that should be considered to describe possible future land-use changes are: natural deforestation, reforestation of old agricultural and urban areas, and change of forest species composition due to climatic changes.

Several methods were applied to describe possible vegetation changes in this area. Present tree growth was described using results of forest inventory. Long-term successions of the different forest types were modelled using the forest dynamics model "TREEDYN3" (Bossel, 1994). These modelling results were further used to derive possible future scenarios for long-term forest changes. To describe future land-use changes in the first assumption, a simple stochastic method was used. It is based on data of the actual and recent spatial distributions of the various land-use types within the Upper Volga catchment. The method consists in a cell by cell analysis of the land-use grid by a filter matrix (e.g. 5×5-grid points) which is shifted gradually through the whole grid domain. The determined absolute frequency of the various land-use types within the matrix generates the scenario for the cell located in the centre of the matrix. Generated reforestation scenario assuming 13% increase of the total forest area predicts a slight increase of the total evapotranspiration (by 3–4%), and a decrease of surface runoff (by 2–3%) and a ground water recharge (by 1–2%). Similar effects can be provided by the changes of forest composition (increasing the part of broadleaf species and decreasing the part of coniferous trees) due to expected global warming. Modelling results showed that higher transpiration ability and stability of broadleaf trees to summer droughts can result in increasing transpiration and evapotranspiration (despite of the reduced summer interception) rates and decreasing ground water recharge. Such effects can be manifested more significantly under dry weather conditions. Deforestation scenario assuming 5% decrease of the total forest area (about 10% decrease of coniferous and about 3% mixed and deciduous forests) predicts a small increase of total surface runoff (1–2%) and decrease of total evapotranspitration (up to 2%). No significant changes of ground water recharge could be found.

4. Conclusion

Possible future changes of water budget of the Upper Volga catchment area were deduced using the analysis of past and present dynamics of the atmospheric, water and forest conditions, different climatic scenarios and developed and validated (via field measurements) SVAT and hydrological models.

Analysis of the past climatic conditions showed that during the last 50–60 years the mean annual temperature increased by 1.2 °C, and annual precipitation increased by 140 mm. Maximal increases of the mean air temperature (about +3.0 °C) and precipitation (about +90 mm) were occurred in winter. At the same time, summer changes of the air temperature and precipitation were very small. Long-term patterns of the annual runoff (recorded at the Selishy dam) and precipitation (from neighbouring meteorological stations) showed similar patterns in their inter-annual variability. However, despite of precipitation increase, no explicit trend of annual runoff during the last 20 years were found. At the same time, the surface runoff in winter during the last 20 years was increased by about 10 mm, and summer runoff was slightly decreased by about 5 mm.

Results of field measurements at selected forest site near Peno showed a very high sensitivity of energy and water fluxes to atmospheric conditions. Transpiration of the forest ecosystem at selected forest experimental site during summer 1999 was limited by the very dry soil water conditions (especially for spruce trees) and during the wet summer 2000 probably by the lack of oxygen in the rooting zone. Transpiration of broadleaf trees was about 10–20% larger than transpiration of spruces. Maximal differences were observed during a period of very dry weather in July–August 1999. Higher sensitivity to the lack of soil water (observed in 1999) for the spruce trees could be well explained by shallow structure of spruce roots compared to root systems of deciduous tree species (e.g. aspen, birch). A deficit of soil water can result not only in lower transpiration and assimilation rates of spruce trees, but also in decrease of their anchor ability. Analysis of recent aircraft images showed an occurrence of very strong windthrows in forest areas recently covered by spruce forests (especially in swampy southern part of the Upper Volga catchment area). Spruce trees at the Upper Volga area, therefore, seem to be less stable and less adapted to soil droughts. All these processes as well as forest fires and pest outbreaks result in a very difficult prediction procedure for possible future changes of vegetation and hydrological regime at this area. According to Holdridge's life zone definition boreal forest zone is confined to isotherms of the mean annual air temperature between 3° and 6° (Holdridge, 1967). Analysis of the present trend of the air temperature shows that the mean annual air temperature, at present, is close to the critical level 6°. Thus, it can be expected, future increase of the air temperature and decrease of summer precipitation can significantly increase degradation risk of coniferous forest communities at the Upper Volga area.

To quantify possible scenarios for changes of the main water fluxes at the Volga source area in the future, the hydrological PREVAH model was applied. The model was calibrated and validated using results of hydro-meteorological measurements at several experimental sites. Different climatic (provided by GCM ECHAM4) and land-use scenarios were used to describe possible future weather and vegetation conditions. It is clear, that such scenarios cannot provide exact predictions of future climatic and vegetation conditions. However, they can describe the main trends of their changes. Such knowledge, therefore, can be very useful for the future planning of water and forest management.

Performed modelling experiments showed that expected climatic changes can significantly influence the water regime of the Upper Volga region. Surface runoff during the spring may be higher than today but summer and early autumn runoff may be slightly reduced due to higher transpiration of deciduous tree species. Decreased summer precipitation can result in a decrease of surface runoff and soil water storage. Therefore, it can be expected, water levels of Volga and of the Upper Volga lakes in summer will probably be lower than today. Significant impacts on the hydrological regime of the Upper Volga catchment area due to land-use changes during the modelling experiments with PREVAH model were not found.

Acknowledgements

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