Assessment of the effect of climate change on water balance of West Siberian Plain based on the Mezentsev model

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Abstract. Estimation of the effect of climate change on the water balance and water regime in West Siberian Plain taking into account the feedbacks generated by the change in the landscape characteristics due to changing climate is given. The methodological approach is based on the application of the model of interrelationship between energy and water balance of land surface for determination of the balance characteristics in dependence on the on-site climatic data at the present time and on the predicted near-surface air temperature and atmospheric precipitation over the period 2021–2030. It is shown that the projected increase in temperature and evapotranspiration would not lead to the expected decrease in flow depth even in the southern dry regions. At the same time, soil moisture in summer would decrease everywhere. All these cause transformation of the catchment landscape conditions which in turn influences the water storage and water availability at local, catchment-size and regional scales.

1. Introduction

West Siberian Plain is one of the largest alluvial lowland plains on the Earth. It covers an area of 2.5 million km² from the north to the south, from the coast of the Kara Sea to steppes of Kazakhstan, from the Urals in the west to the Yenisei River in the east. The plain has a trapezoid shape: the distance from the south to the north reaches nearly 2,400 km, and the width in the south and north – from 1,900 to 800 km, respectively. The size of the plain and the flatness of its relief produce distinct zonality of climate and landscapes in West Siberia: a wide range of landscape zones is present here, from tundra and forest tundra in the north through taiga occupying a central part of the area to forest steppe and steppe in the south. Almost the whole area of plain is drained by the Ob River and its tributaries bringing about of 400 km³ of fresh water to the Arctic Ocean. A considerable part of the study area is occupied by swamps of different type and permafrost. Climate warming is very noticeable in West Siberia, particularly in the Arctic coastal areas.

The relevance of a study of induced by climate change dynamics in the characteristics of water balance and water regime of the West Siberian Plain, constituting significant part of the Ob River watershed and of the whole Arctic basin, is determined by the fact that significant alterations of climate and landscapes are observed in this area and formation of the fresh water inflow to the Arctic ocean occurs. Transformation of the hydrological cycle, water balance, river runoff in turn affects climate processes. These interrelations are not purely understood by now. Study of freshwater
balance and water regime transformations in West Siberia, the permafrost degradation are important from the point of view of increasing hydrological risks [1] in a process of economic development.

2. Methods of research and initial data

Methodological approach is based on the method of hydro-climatic calculations (the HCC method) developed by V S Mezentsev [2]. The method, in general referred to the Budyko curve [3, 4], provides solution of the equations depicting interrelationship between energy and water balance of the active layer of land surface site for obtaining a set of energy and water balance parameters in West Siberian Plain and other areas at the present time and under future projections of climate change.

The HCC method is a mathematical model for transformation of atmospheric precipitation into soil water, runoff and evapotranspiration from the surface of catchment area. Evapotranspiration $Z$ is determined by the water equivalent of climate energy resources $Z_M$, the total water availability on the land surface $H$ representing the sum of corrected atmospheric precipitation $X$ and changes in soil water content $(W_1 - W_2)$ within the active layer during the computation interval (all the listed variables are expressed in mm of water depth over a unit area) as well as dimensionless parameters $n$ and $r$. Parameter $n$ shows the influence of landscape conditions on runoff formation and parameter $r$ characterises the soil ability to bring water to the evaporating surface and spend it on evaporation, depending on the granulometric composition of soil [2]. According to the HCC method the formula for the runoff $Y$ depth prediction is as follows [2]:

$$Y = H - Z = (X + W_1 - W_2) - Z_M \left[ 1 + \left( \frac{X + W_1 - W_2}{Z_M} \right)^{-rn} \right]^{\frac{1}{n}}$$

As a result of the HCC method application the fields of characteristics such as: the energy resources of climate, the energy resources of evaporation (or the maximum potential evaporation), the loss a proportion of energy resources of climate for snow and ice melting (including thawing the active layer of permafrost), the total soil moisture, the total water availability and its values for the certain time intervals (decade, month, year), the water content in the active layer of soil at the beginning and the end of the calculation time interval, the evaporation depth, runoff depth, the coefficients of water availability, evaporation, runoff are obtained. Some of these variables are controlled by means of direct measurements at selected for project implementation key sites and small catchments.

The feedbacks are realised along the following chain: 1) change in climatic characteristics and degree of water availability for the land surface site; 2) change in landscape characteristics – respectively, the parameters $n$, $r$ and the active layer thickness, especially in areas covered with permafrost, peatlands etc.; 3) further change in the degree of water availability, and the cycle closes. In these conditions, it is particularly important to estimate the model parameters, taking into account the change in their values over time.

The dataset (http://meteo.ru/data) of annual and monthly surface air temperature and atmospheric precipitation observed at 31 representative weather stations (WS) of Roshydromet distributed within the continental area of West Siberia in temperate latitudes (excluding stations located closer to the Arctic Ocean coast) over the period 1966–2015 was used for climate change statistical analysis. The observational period was divided into the baseline (1966–1985) and modern (1986–2015) subperiods. The forecast period was set as 2021–2030.

For prediction of the mean annual, seasonal and monthly air temperature and precipitation at each weather station for 2021–2030 we used an adaptive model – the method of exponential smoothing. Such adaptive forecasting models have a self-tuning mechanism that makes possible continuously taking into account changes in the characteristics of the time series [5]. The method allows making short-term forecasts, when the presence of long-term trends remains questionable. Forecasting was carried out in the StatSoft STATISTICA framework [6].
3. Results and discussion

Main results of the study relate to the prediction of changes in air temperature and precipitation, the calibration of the model parameters and the model application for predicting possible changes in the water balance components and landscape transformations in the study area.

3.1. Modern climate change characterisation and short-term prediction

Modern climate change in the study area is manifested: 1) in the rise in surface air temperature, 2) the change in atmospheric precipitation rates and regime and 3) the increase in the frequency of anomalous (often extreme) hydro-meteorological events. The study of the long-term variability of monthly temperatures and the sums of atmospheric precipitation made it possible to assess their changes over the period 1986–2015 compared with the baseline period until 1985 [7].

The 1980s regime shift represented a major change in the Earth’s geophysical and biophysical systems and occurred at slightly different times almost everywhere around the world [8]. This shift corresponds to the mid-1980s change in the time series of climatic and hydrologic parameters also in West Siberia.

Forecast deviations of the mean annual values of air temperature and atmospheric precipitation for 2021–2030 from the 2001–2015 means of observational data are as follows. The rise in the surface air temperatures would be expected in winter (November to March) north from 65°N. Winter would be warmer than at the beginning of the 21st century by 0.7–0.8 °C. On the contrary, south of 65°N would experience a significant decline in the mean winter temperature and virtually return to the 20th century normal [7]. Possible cause of such changes might be the natural climatic variability.

The winter precipitation in the third decade of the 21st century would be less than in the beginning of the century. In general, decrease in winter precipitation might be explained by the increase in the frequency of occurrence of the meridional circulation forms [9], when the anticyclonic pressure fields would be formed over the study area.

Air temperature in summer (June to August) would increase. This will continue the trend of more intensive temperature growth in the area north from 60 °N compared to the south area located in the southern taiga zone: 0.6 and 0.3 °C, respectively. The rates of summer precipitation over West Siberian Plain would fall slightly compared with the beginning of the century, but there would be more precipitation than in the 20th century.

3.2 Estimation of the model parameters n and r

A technique to determine the n parameter value taking account of the intensity of landscapes drainage and runoff formation is presented in [10]. It was also proposed to estimate n using digital elevation models and the Wetness Index [11]. The problem of the influence of natural conditions on water balance is considered in [12] including detailisation of the computational scheme based on the Mezentsev HCC model that allows taking into consideration characteristics of the underlying surface.

In order to highlight the role of climatic conditions in water balance formation the values of parameters $n$, $r$ and the field-capacity moisture content $W_{\text{MIN}}$ were set constant at all weather stations: $n = 3$ (slowly drained area), $r = 2$ (medium loam), and $W_{\text{MIN}} = 300$ mm in the soil active layer of 1 m thick. The field-capacity moisture content $W_{\text{MIN}}$ then was calculated taking into account the dynamics of the active layer thickness over time dependent on the surface air temperature dynamics.

From all water balance elements the most accurately measured is a stream water flow, reflecting current moisture of the active layer in a small catchment. Therefore continuous hydrological monitoring has been organised in three small catchments located in different climatic conditions for the model calibration. Monitoring of stream water level, soil, water and air temperature was conducted using automatic appliances. The instruments were developed and manufactured in the Institute of Monitoring of Climatic and Ecological Systems, Siberian Branch of Russian Academy of Sciences. The catchments to be monitored and modelled were chosen 1) in zone of oligotrophic bogs in southern taiga, 2) foothill area of southern taiga and 3) zone of palska complexes in forest tundra. Some hydraulic techniques were used for stream water discharge computations. The values of $r$ parameter
were obtained using optimisation procedures based on a task to achieve the best match of the model water flow for the study period with the observed one.

3.3 Water balance change
Some results of modelling water balance components based on the HCC method are presented in Figure. Total volume of the modelled climatic runoff increases despite of evaporation growth. The relative moisture of soil active layer, obtained as the ratio of soil moisture content in active layer to its field-capacity moisture content, markedly increases in spring and decreases in summer. The most visible change is traced between the means of hydro-climatic characteristics for the forecast (2021–2030) and baseline (1966–1985) periods.

**Figure.** Seasonal variations of the modelled evapotranspiration (1), runoff (2) and relative moisture of soil active layer (3) averaged over three zonal subareas and over time – over the baseline, the second half of modern and the forecast periods: a) forest tundra to northern taiga, b) middle to southern taiga and c) southern taiga to forest steppe [7]

3.4 Change in land surface characteristics
To detail the feedbacks depending on the climate dynamics it is necessary to take into consideration, first, the dynamics of active layer thickness. In the HCC method [1], the initial active layer thickness is set equal to 1 m. Such a replacement of the actual thickness of the active layer by the constant works well in the conditions of the forest steppe and southern taiga. As our studies have shown, in these regions the ratio of the sum of negative temperatures to the sum of positive ones is close to one i.e. is equivalent to the layer thickness of 1 m. To the north, this temperature ratio decreases to 0.24 (Tazovskoye WS, 67.5°N 78.7°E), and it increases to 1.44 to the south (Shadrinsk WS, 56.1°N 63.6°E), which corresponds exactly to the expected thickness of the active layer in these areas.

According to our predictions, at the northern stations Tazovskoe, Tarko-Sale (64.9°N 77.8°E) for the period 2021–2030 the most significant increase in the active layer thickness is expected to be 39–45% (10–15 cm) compared to the period 1966–1985. In the central part of the study area a significant increase in the active layer thickness by 10–20% is also expected. At the southern stations of Tara
(56.9°N 74.4°E), Shadrinsk, Barabinsk (55.4°N 78.3°E) an insignificant increase in the active layer thickness by 4–5% (4–7 cm) is estimated.

Second, an expected change in the vegetation cover is estimated from the equation given in [12]. According to our data, in the central and north-western part of West Siberia the largest change in the structure of vegetation is expected in the direction to less hydrophilic species. For example, Nyaksimvol (62.4°N 60.9°E) and Khanty-Mansiysk (61.0°N 69.0°E) WS show the transition from wetter to drier meadows. Less significant changes in the same direction are expected in the remaining areas.

Third, in 2021 – 2030 the expected dynamics of climatic conditions and vegetation cover would contribute to hydromorphic transformation of soils, with the exception of the south-western part of West Siberia (Shadrinsk WS). The most intensive process of hydromorphic transformation would be demonstrated north of 60°N by the gradually increasing values of \( r \) (parameter reflecting water-physical properties of soils). An accurate quantitative assessment of this process is difficult to give, since the mineral soil formation is highly inert. In organogenic soils, especially peat, changing the parameter \( r \) value can occur during only one season. For example, in the Vasyugan mire of more than 50,000 km² in area the drought of 2012 has led (due to the less snowy winter of 2011–2012 and hot dry summer 2012) to drying the active layer of peat soils and reduction in water regulation ability. According to parameter optimisation outcomes for the model catchment, the field-capacity moisture content decreased by 1.5 times, and the parameter \( r \) increased from 1.7 to 2.5. It is obvious that it might provide more favourable conditions for burnout of the upper horizons of peat.

4. Conclusions

Short-term statistical prediction of changes in the average air temperature and atmospheric precipitation for the period 2021–2030 has been made based on the method of exponential smoothing. The HCC method proposed by V S Mezentsev was applied in order to estimate the changes in water balance components in different zones, regions and landscapes of West Siberian Plain. It is shown that the projected increase in air temperature and evapotranspiration in parallel with the atmospheric precipitation growth would not lead to the expected decrease in water flow depth even in the southern dry regions of steppe. At the same time, soil moisture in summer would decrease everywhere.

The projected change in the long-term average annual, seasonal and monthly water balance components estimated on a basis of the Mezentsev model applied for transformation of atmospheric precipitation into soil water, runoff and evapotranspiration from the surface of catchment area would cause change in land surface state and landscape dynamics directed to the drier soil conditions during the warm part of a year. All these cause transformation of the catchment landscape conditions which in turn influences the water storage and water availability characteristics on local, catchment-size and regional scales.

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