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ORIGINAL PAPER

Changes in the groundwater levels and regimes in the taiga zone of Western Siberia as a result of global warming

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Abstract

Groundwater accounts for 30% of the world drinking water resources and is rarely taken into account in climate assessments. Climate change affects groundwater levels and regimes, but there is very little specific research on the future impacts of climate change on groundwater. This study examines data from 15 groundwater wells of various ages for the period from 1965 to 2015. To obtain reliable data, an analysis was made of the groundwater level changes in the upper hydrodynamic zone, which is not disturbed by anthropogenic activity. A statistically significant increase in the average annual groundwater levels in the study area was observed, in agreement with data indicating an increase in groundwater runoff in the winter season for large and medium rivers in the region. To explain the revealed changes in the groundwater levels, an analysis of the characteristic climatic changes (air temperature and amount of precipitation) and the groundwater runoff was performed. In winter, the unfrozen moisture content in the soil has increased; accordingly, groundwater recharge and groundwater levels have increased. Meanwhile, in summer, an increase in evaporation from the drainage basin has occurred as a result of the increasing air temperature. To some extent, this compensates for the changes in the annual runoff and groundwater levels that are hydraulically connected to the rivers.

1 Introduction

Climate change includes both the global warming driven by emissions of greenhouse gases and the resulting large-scale shifts in weather patterns. According to (IPCC 2014), the largest driver has been the emission of greenhouse gases, of which more than 90% are carbon dioxide (CO_2) and methane. Recently, an international research (Sherwood et. al., 2020) has demonstrated how much our climate will change as greenhouse gas emissions increase. The researchers found that climate sensitivity is not so low that it should be ignored, but it is also not so high that there is no hope for the planet's recovery. Climate change has a definite regional pattern with some regions already suffering from enhanced climate extremes and others being impacted little. Each of the last 4 decades has been successively warmer than any decade that preceded it since 1850. According to IPCC's Sixth Assessment Report (AR6) on the physical science basis of climate change, global surface temperature in the first 2 decades of the twenty-first century (2001–2020) was 0.99 °C higher than 1850–1900 (IPCC 2021). Between 1901 and 2018, global mean sea level increased by 0.20 m, where the mean sea level rise rate was 1.3 mm/year between 1901 and 1971, rising to 1.9 mm/year from 1971 to 2006 and further increasing to 3.7 mm/year from 2006 to 2018 (IPCC 2021).

The impact of climate change on natural ecosystems, on biological diversity, on human health and water resources, and on the frequency of floods and droughts is already being observed, and this impact will increase. From this point of view, increasing confidence in regional climate change scenarios is becoming a critical step forward towards the implementation of adaptation and mitigation options (Arneth et al., 2019).

The taiga zone of Western Siberia is characterised by very high and progressive bogging, reaching 40–60% or more in some locations (Eckstein et al. 2015; Neyshtadt 1972). According to Pologova and Lapshina (2002), the peat deposit grows at an average rate of 0.9 mm/year in river

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basins. For example, in the Tomsk region, located primarily in the southern and middle subzones of the taiga, the wetland area is 316,000 km^2, but its volume increases at a rate of approximately 16,000 m3/year (Savichev 2010). It has been reported (Urban et al. 2019) that bogs play significant role in the emission greenhouse gases. Moreover, Western Siberia is a key oil-producing region in Eurasia.

The purpose of this article is to identify the impact of climate changes on the groundwater levels and regimes using a long series of observations in the taiga zone of Western Siberia. It has been previously shown (Savichev 2010; Savichev et al. 2011; Savichev and Makushin 2004; Shiklomanov et al. 2013) that the average increase in the groundwater levels of Quaternary and Palaeogene aquifers in the Tomsk region without evident anthropogenic influences is 0.21 m from the mid-1960s to 2005. In this study, longer series of groundwater level observations (until 2015) are added in order to assess the current hydrogeodynamic regime and to identify the causes of the observed changes.

2 Materials and methods

2.1 Study area

The majority of the Tomsk region is located within the West Siberian Plate, and only its southern and south-eastern parts are located in the area of the Kolyvan-Tomsk folded junction and the northern spurs of the Kuznetsk Alatau. The study area is located within the West Siberian Artesian Basin and corresponds to the middle stream of the Ob River (Fig. 1).

According to geological structure of the West Siberian Artesian Basin, a folded foundation composed of pre-Jurassic rocks and a cover formed by a platform/plateau of flat-lying terrigenous Mesozoic and Cenozoic formations are distinctly distinguished (Fig. 2). The Mesozoic–Cenozoic aquifers are distinguished with sharply different conditions for the formation of groundwater. These aquifers are separated by a thick regional water column of the Upper Cretaceous–Paleogene up to 400–600 m. Regional aquifuge outcrop and the deposits of the cover are a single aquifer at the boundaries eastern and southeastern parts of the basin. The upper aquifers are multilayered facies consisting of more than 30 layers with Palaeogene, Neogene, and Quaternary ages. The aquifers are composed of sand, clay, aleurite, and sand–gravel–pebble sediments. The groundwater is hydraulically connected within the layers. The aquifers are characterised by generally active water exchange, the intensity of which decreases with depth, with the water exchange becoming difficult in the lower part of the floor. The waters of the upper floor are mostly fresh but sometimes slightly saline. Groundwater recharge is primarily from the infiltration of precipitation at elevated regions of the interfluvial sections and the valley side. The groundwater discharge includes riverbeds, the flood plain bench, and the low terrace above the flood plain (Lgotin 2006). The Triassic and the Upper Cretaceous aquifers are composed of sand and clay, have considerably thick and a high head of groundwater with low water exchange conditions. In the marginal part of the artesian basin adjoining the Palaeozoic section, clay rocks are usually absent or lie in the form of separate lenses. Therefore, the deposits in the upper and lower hydrogeological formations represent a single aquifer. Groundwater recharge occurs at the edge of the basin. Groundwater flow (excepting the water in the Upper Cretaceous deposits) is carried out to the centre of the West Siberian Artesian Basin (Lgotin 2006).

The study focuses on mostly Quaternary, Palaeogene aquifers penetrated by follow wells 123, 124, 156, 157, 167, 169, 284, 94, 80, 113, 114, 118, and 92 and Upper Cretaceous aquifers penetrated by 79 and 115 (Fig. 1a). The choice of observation points was made based on the absence of a clearly anthropogenic impact on the groundwater and the duration of the groundwater level data series. Typically terrace regime and the recharge of study shallow groundwater originate as the snowmelt and rainwater infiltration during spring–autumn period. Groundwater, penetrated by well 92, are characterised by interfluvial regime. Other wells penetrate the confined water of the spring–autumn recharge. A brief description of the observation points is given in Table 1, and their locations are shown in Fig. 1.

2.2 Methods

Groundwater level data collected during the period from 1965 to 2015 by the Tomsk Exploration Company and from 1996 to 2015 by specialists of Tomskgeomonitoring JSC (the main part of the staff from the Tomsk Exploration Company) as part of a project monitoring of the geological environment of the Tomsk region were used to analyse the groundwater regime (Lgotin 2006, 2015, 2016; Lgotin et al. 2010; Savichev 2010; Savichev et al. 2011; Shiklomanov et al. 2013).

Studies of long-term changes in the groundwater levels include calculations of the average annual (mean) values and errors in the determination, visual and statistical analyses of the average annual groundwater level series, and further comparisons of these results with data concerning the river water regime and exchange related to the studied groundwater, precipitation, and air temperature data. Changes in the climatic characteristics were analysed using the air temperature data and the amount of precipitation recorded at eight meteorological stations in the Tomsk region during the period from 1965 to 2015.

A statistical analysis of the long-term changes in the groundwater levels and climatic parameters was performed. The statistical analysis consisted of verifying the following

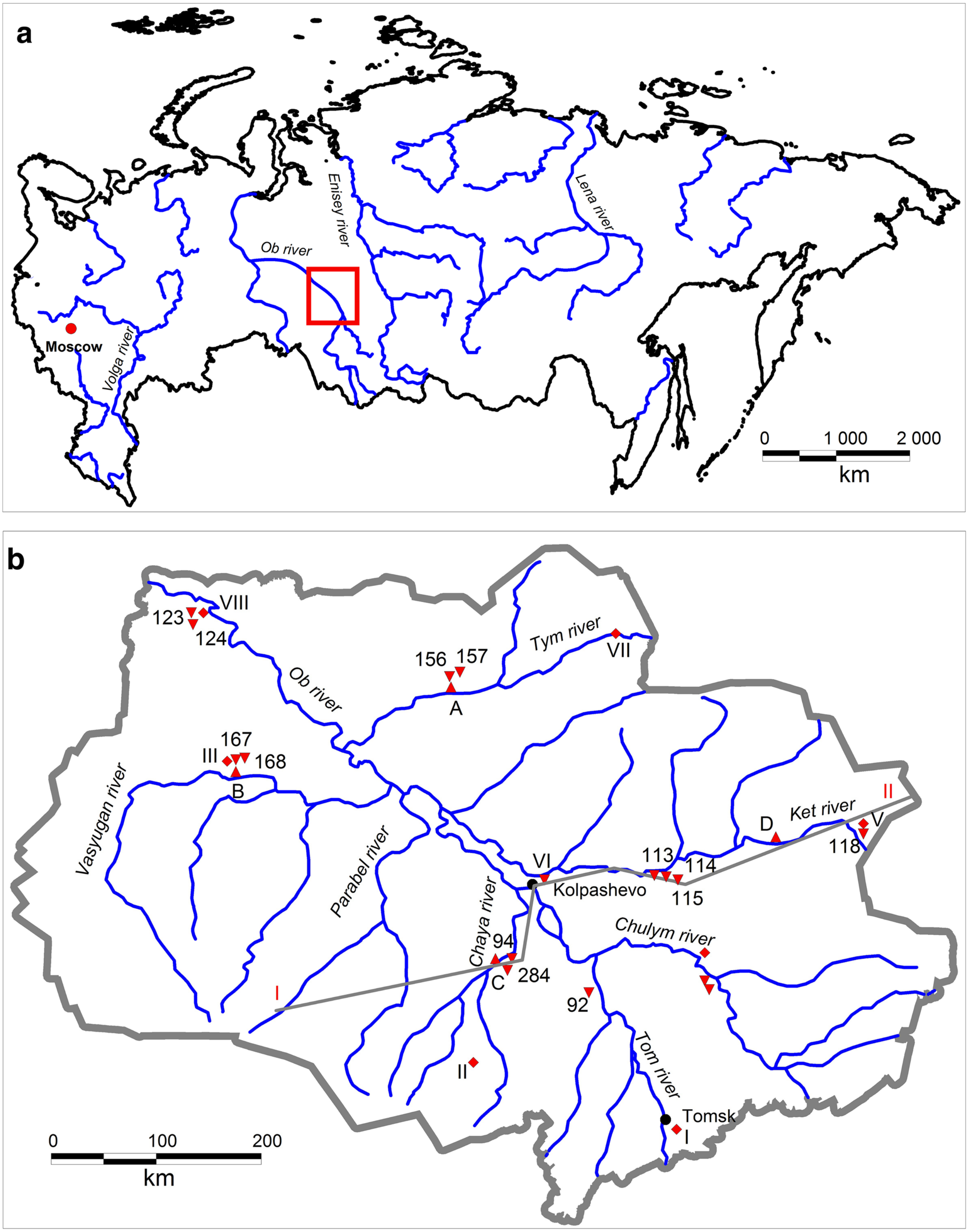

Figure. 1 **a** Location of the study area on a map of the Russian Federation and **b** locations of the sample points. The numbers 92–169 indicate wells, I–VIII indicate meteorological stations of the Federal Service for Hydrometeorology and Environmental Monitoring, A–D indicate hydrological posts, and I-II indicates the hydrogeological profile shown in Fig. 2

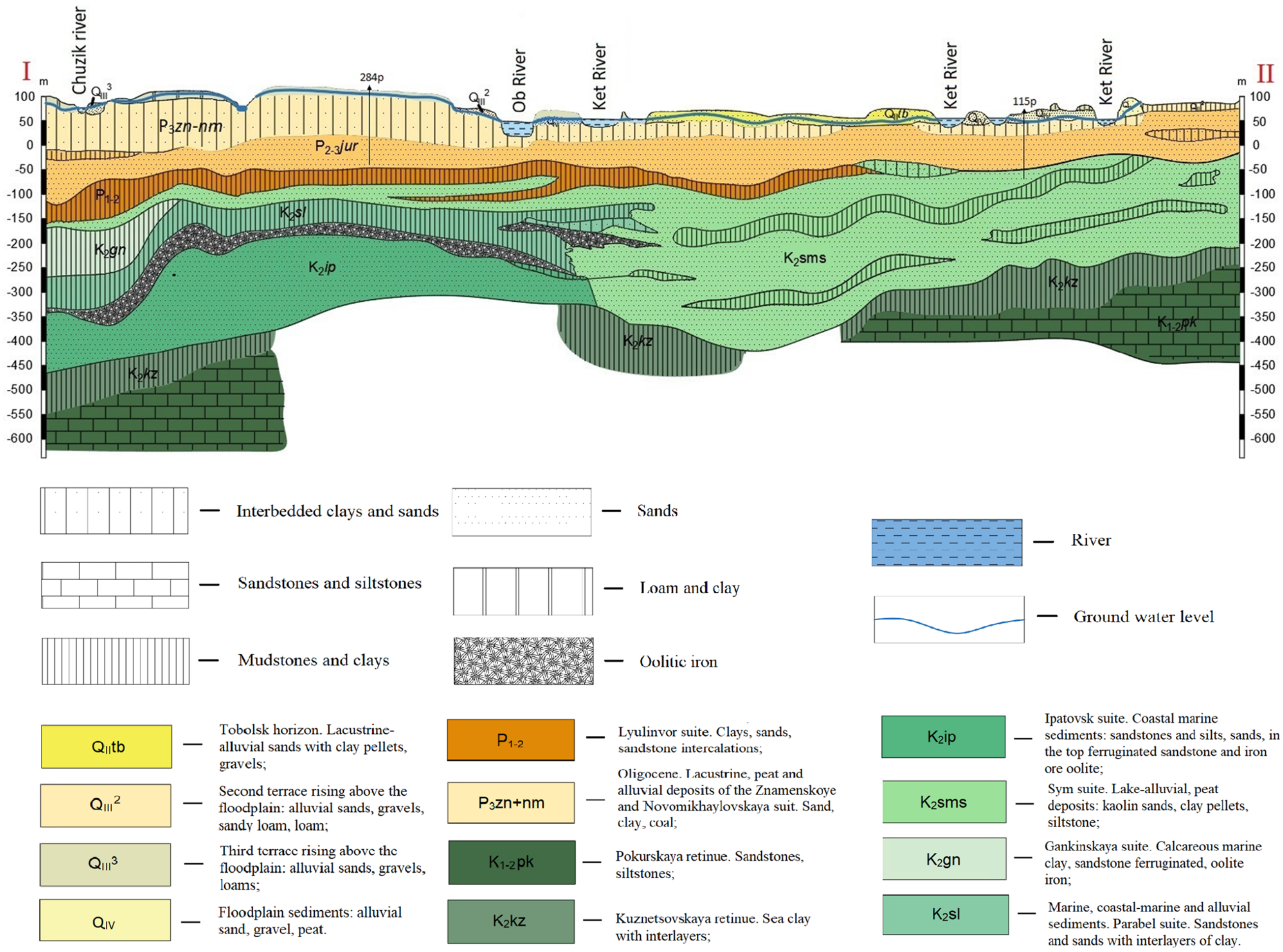

Fig. 2 Hydrogeological profile I-II of the study area. Its location is shown in Fig. 1b

Table 1 Points of groundwater observations

Well number	Aquifer age	Type of groundwater recharge and regime	Observation period
156	P_3lg	Confined aquifer, spring–autumn recharge	1971–2010
157	P_1pr	Confined aquifer, spring–autumn recharge	1970–2010
167	$P_{2\text{-}3}tv$	Confined aquifer, spring–autumn recharge	1972–2015
169	$Q_{II}tb+2Q_{III}tb$	Shallow aquifer, spring–autumn recharge, terrace regime	1972–2010
284	P_2jr+P_3nm	Confined aquifer, spring–autumn recharge	1975–2010
94	$1Q_{III}$	Shallow aquifer, spring–autumn recharge, terrace regime	1965–2015
79	K_{2sms}	Confined aquifer, spring–autumn recharge	1965–2015
80	P_3lg	Shallow aquifer, spring–autumn recharge, terrace regime	1965–2010
113	$2aQ_{III}+Q_{II\ tb}+N_1$	Confined aquifer, spring–autumn recharge	1968–2012
114	P_3lg	Confined aquifer, spring–autumn recharge	1968–2012
115	K_{2sms}	Confined aquifer, spring–autumn recharge	1968–2010
118	$Q_{II}tb$	Shallow aquifer, spring–autumn recharge, terrace regime	1968–2010
92	aQ_{2tb}	Shallow aquifer, interfluvial regime	1965–2015
123	$1Q_{III}$	Shallow aquifer, spring–autumn recharge, terrace regime	1968–2015
124	$1Q_{III}$	Shallow aquifer, spring–autumn recharge, terrace regime	1968–2010

null hypotheses: (1) randomness, with the help of the Pitmen criterion π, Eqs. (1)–(3), and (2) the homogeneity of the series, by means of Student's test S, Eq. (4), and the Fisher criterion F, Eq. (5). The conclusions concerning the fluctuation of the series or the nonrandom changes were made with a significance level of α = 5% in the case where the calculated statistics (S, F and π) exceeded the corresponding critical value.

$$\pi = r_* \cdot \sqrt{\frac{N-2}{1-r_*}} \tag{1}$$

$$r_* = k_1 \cdot \sqrt{\frac{D_1}{D_x}} \tag{2}$$

$$X = k_1 \cdot t + k_2 \tag{3}$$

where X is the value of the study indicator, t indicates the calendar year, k_1 and k_2 are empirical constants, N is the sample number, and D_1 and D_X are the dispersion values of t and X, respectively.

$$S = \frac{|A_1 - A_2|}{\sqrt{N_1 \cdot D_1 + N_2 \cdot D_2}} \cdot \sqrt{\frac{N_1 \cdot N_2 \cdot (N_1 + N_2 - 2)}{N_1 + N_2}} \tag{4}$$

$$F = \frac{\max(D_1;D_2)}{\min(D_1;D_2)} \tag{5}$$

where A_1 and A_2 indicate the sample means, D_1 and D_2 indicate the sample variances, and N_1 and N_2 indicate the numbers of the compared samples (Khristoforov 1993; Lloyd 1984). Conclusions concerning the fluctuation of the series or the nonrandom changes were made with a significance level of α = 5% in the case where the calculated statistics (S, F, and π) exceeded the corresponding critical value.

To study the statistical relationships of the groundwater levels, the correlation coefficients r and the errors δr = (1 − r2)·(N − 1) − 0.5 were calculated. Correlation coefficients were accepted as statistically significant (with a significance level of 5%), if they satisfied the condition |r|≥ 2·δr.

To explain the results, the annual and monthly water balances of the rivers were calculated. This method is generally appropriate for rivers in the West Siberian Plain corresponding the category of rivers with catchment areas from 2000 to 50,000 km^2 (Hydrology of land 1988). The calculation of the water balance was performed for a homogeneous period, where:

$$Y_a \approx P_a - E_a \tag{6}$$

where Y_a, P_a, and E_a are the average annual values of the river runoff (for a long-term, homogeneous period), precipitation, and evaporation, respectively. The monthly liquid precipitation values P(Ta ≥ 0) were taken as the monthly sum of the atmospheric precipitation at an air temperature Ta higher than or equal to 0 °C. Accordingly, the frozen precipitation P(Ta < 0) was determined from the monthly rainfall at an air temperature of less than 0 °C.

Evaporation from the catchment surface E_i in the i-th month is calculated using the Hargrave equation, Eq. (7), incorporating the recommendations of Allen (1998):

$$E_i = k_{E,1} \cdot M_i \cdot R_0 \cdot (T_{a,i} + k_{E,2}) \cdot \sqrt{T_{a,\max,i} - T_{a,\min,i}} \tag{7}$$

where R_0 indicates the extraterrestrial radiation in kJ/(cm2·month), $T_{a,max,i}$ and $T_{a,min,i}$ indicate the maximum and minimum monthly mean air temperature values in °C, respectively, and k_E and k_T are empirical coefficients calculated using the Nash–Sutcliffe criterion (Mei and Anagnostou 2015) with the maximum approximation to the values of the long-time average annual monthly evaporation calculated according to the Penman–Tortweit method (Allen et al. 1998; Hendriks 2010) from measurements of the energy budget method elements at meteorological stations in Western Siberia.

The volumetric water and ice contents of the soil were calculated. Following Befani and Kalinin (1983) and Dyukarev (1991), the calculation of the soil moisture was performed using Eqs. (8)–(10):

$$w_i \approx \frac{w_{1,i,b} + w_{1,i,b}}{2000} \tag{8}$$

$$w_{1,i,e} = (w_{1,i,b} + P_i(T_a \ge 0) + h_{sm,i}) \cdot \exp(-0.007 \cdot E_0) \tag{9}$$

$$E_{0,i} = 0.18 \cdot \left(T_{a,i} + 25\right)^2 \cdot \left(1 - f_{a,i}\right) \tag{10}$$

where w_i is the monthly average soil moisture in m3 water/m3 soil, $w_{1,i,b}$ and $w_{1,i,e}$ are the moisture content in the top 1 m of soil at the beginning and end of the i-th month in mm, respectively, $E_{0,i}$ is the evapotranspiration in mm/month, and $f_{a,i}$ is the average monthly relative atmospheric air humidity in fractions of a unit. The calculation starts at the end of March. The original/initial moisture content in the meter-deep layer (at the end of March) is selected based on the minimum of the sum of the absolute deviation of the calculated and measured values. The water yield from snow $h_{sm,i}$ beginning in the i-th month is determined by the difference in the moisture content for months i and i − 1:

$$h_{sm,i} = \delta_{WS}\left(WS_i - WS_{i-1}\right) \tag{11}$$

where WS_i is the liquid–water content in the snow cover in the i-th month.

The calculation of the ice content of the soil Λ for months with negative soil temperatures (in °C) is performed by the selection specified by Gelfan (2007).

The base flow (groundwater) is determined according to Hendriks (2010), Mei and Anagnostou (2015), and Shiklomanov et al. (2013):

$$Y_{g,i} = \begin{cases} Y_i, \ i = 12, \ 1, \ 2, \ 3 \\ Y_3 + (Y_{12} - Y_3) \cdot \frac{(i-3)}{(12-3)} \end{cases} \tag{12}$$

where Y_{i} and $Y_{\mathrm{g,i}}$ are the streamflow and baseflow, respectively, in the i-th month of the year. The boundaries of the winter period (December and March) are selected according to the regional climatic and hydrological conditions (Methodological recommendations 2004).

3 Results

We previously studied the groundwater levels in the Tomsk region using data from observation wells 157p, 169p, 94p, 81p, 114p, and 63p for the period from the beginning of observation to 2005 (Savichev and Makushin 2004). We observed an average increase in the groundwater levels of 0.21 m from the mid-1980s to 2005 (in comparison with the previous period 1960–1980). The greatest increase occurred in winter (on average 0.23 m), and the lowest increase occurred in the summer–autumn period (on average 0.09 m). In addition, increases in the average annual and average seasonal levels of groundwater in wells 94p, 157p, 81p, and 63p were observed for the entire period (Lgotin et al. 2010; Shiklomanov et al. 2013). According to Savichev and Makushin (20,040), in active water exchange zones without evident anthropogenic influences, the average monthly groundwater levels increased on average from 0.1 to 0.4% in the period from 1980 to 2003 compared to the period from 1960 to 1970. At the same time, stable growth of groundwater levels was typical for the winter season and the beginning of the spring flood (the flood peak occurs in May and June).

An analysis of the observation data for the period from 1965 to 2015 confirmed the above conclusions. We observed a further increase in the groundwater levels, on average 0.34 m, including 0.32 m for the subsurface waters of the Quaternary sediments (seven wells), 0.35 m for the Palaeogene deposits (six wells), and 0.37 m for the Cretaceous sediments (two wells). Violations in the homogeneity of the mean annual value series of the groundwater levels were recorded in 73% of cases (wells 156p, 157p, 167p, 284p, 94p, 79p, 80p, 113p, 114p, 118p, and 92p). Assignable changes in the mean annual groundwater levels over the entire period of observation were observed in 8 out of 15 wells (157p, 167p, 284p, 94p, 79p, 80p, 114p, and 92p). The maximum increase in the groundwater level was observed in Quaternary sediments near the village of Krivosheino on the border of the Ob River valley (well 92p, well depth 24 m) (Fig. 3). A significant increase in groundwater level (0.3–0.9 m/year) was also detected in

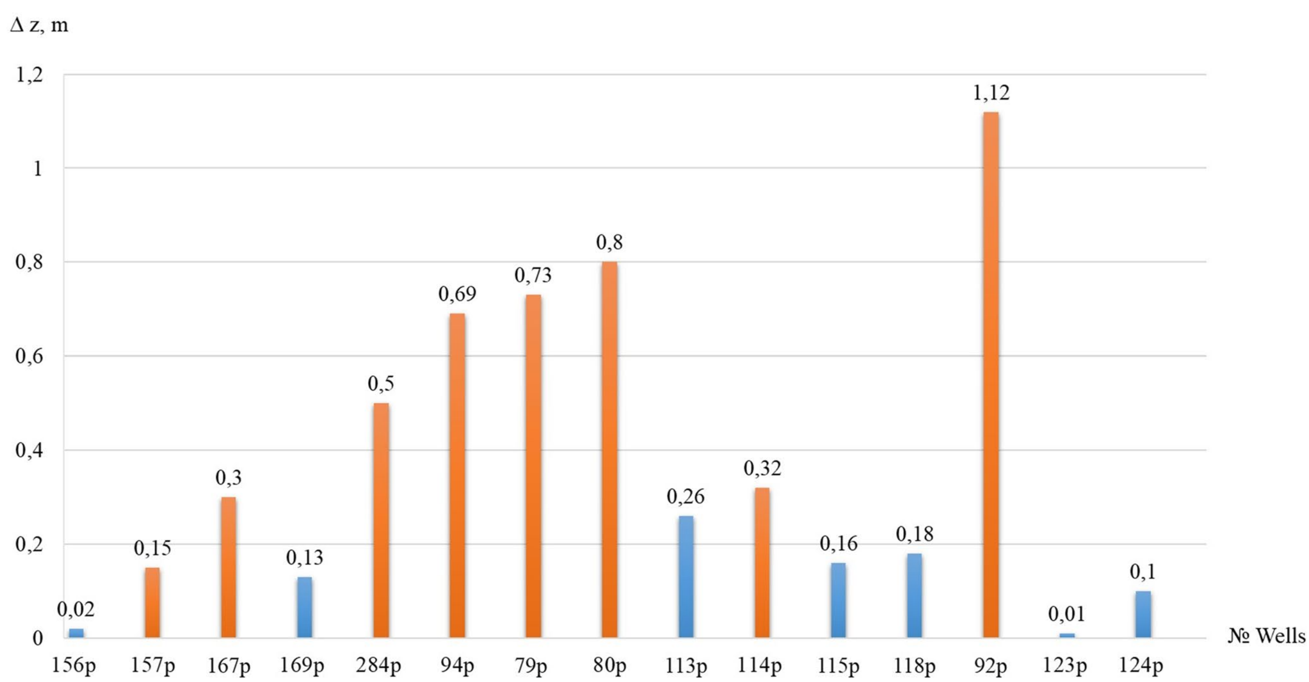

Fig. 3 Change of the mean annual groundwater levels for the period with 1965–1994 and 1995–2015

Quaternary, Palaeogene, and Cretaceous sediments in the catchments of the Chaya (Podgornoe, wells 94p and 284p) and Chulym rivers (Zyryanskoe, wells 79p and 80p), with the most significant increase in the groundwater levels occurring after 1995. Figure 3 shows a statistically significant trend, highlighted in orange, that was determined for the period under study, where Δz indicates the change in the groundwater level in metres per year in the wells in the period up to 1994 and in the period from 1995 to the end of the observations.

Note that correlations are observed in a significant part of the study area between the fluctuations in the mean annual values of the groundwater levels in sediments of different ages. The closest correlation is between wells that penetrate Neogene–Quaternary, Palaeogene, and Cretaceous deposits in the Ket-Chulymsky District in the eastern part of the Tomsk region. The correlation is especially high in the middle part of the catchment of the Ket River (wells 113p, 114p, and 115p) and in the Palaeogene and Cretaceous sediments in the middle part of the catchment of the Chulym River (wells 80p and 79p). For the left-bank plain (or flat) part of the Middle Ob Basin (the watersheds of the Vasyugan and Chaya rivers in the western part of the Tomsk region), the correlation between the groundwater levels of the Quaternary and Palaeogene deposits is less pronounced.

The more connected fluctuations of the groundwater levels in the Ket-Chulymsky District can be explained by the better aquifer permeability in this region. The correlation of the catchments of the left tributaries of the Ob River is due to the extensive distribution of argil sand ground, clay and sand with interlayers of clay, which are characterised by very poor filtration properties.

To explain the revealed changes in the groundwater levels, we analysed the homogeneity and randomness of the mean annual air temperature series Ta(a), sums of the positive Σ Ta(≥0) and negative Σ Ta(<0) mean monthly air temperatures, annual precipitation sums P and precipitation for the warm precipitation P(Ta≥0), with an average monthly temperature of greater than or equal to 0 °C and equal, and cold precipitation P(Ta<0) seasons with respect to the data of eight meteorological stations for the same period as the analysis of the groundwater levels. As a first approximation, we can assume that the value of P(Ta<0) corresponds to the total snow fall and that the value of P(Ta≥0) corresponds to rain.

We find that, since the early 1970s, the average annual air temperature Ta(a) and the sum of the positive monthly mean air temperatures Σ Ta(≥0) have increased. Statistically, significant changes in other climatic characteristics were observed in the following cases. (1) An increase in Σ Ta(<0) was observed at the meteorological stations in Kolpashevo (central part of the Tomsk region), Pervomaiskoye (southern part of the Tomsk region), Tomsk (southern part of the Tomsk region), and Aleksandrovskoe (northern part of the Tomsk region). (2) An increase in P was observed at the meteorological stations in Tomsk and Kolpashevo (Fig. 4). (3) An increase was observed in P(Ta<0) at the meteorological stations in Sredniy Vasyugan (northwestern part of the Tomsk region), Tomsk and Kolpashevo. (4) An increase was observed in P(Ta≥0) at the meteorological stations in Kolpashevo and Vanjil-Kynak (northeastern part of the Tomsk region). A decrease in the atmospheric precipitation (P and P(Ta≥0)) was observed only at the Ust-Ozernoye meteorological station in the eastern part of the Tomsk region. To

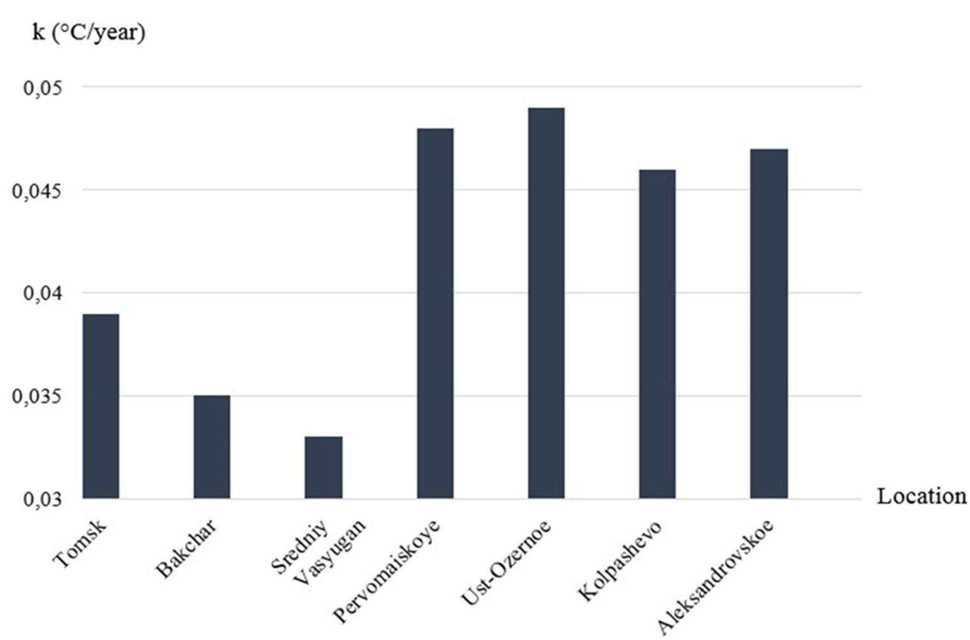

Fig. 4 The results of a statistical analysis of the data mean annual air temperature (k is the value of air temperature increase in °C/year for the study period)

test this hypothesis, first, we calculated the underground component of the river flow using Eq. (2). Second, we verified the average annual river discharges of the Chaya, Vasyugan, Tym, and Ket rivers and their groundwater recharge components with respect to homogeneity and randomness (Fig. 5).

4 Discussion

The above findings generally agree with the data collected by other authors (Adamenko et al. 2000; Groisman et al. 2012; Paromov et al. 2017) concerning the apparent climate warming in the taiga zone of Western Siberia since the 1950s, including in March and December. Climate warming can expand the boundaries of the warm period; this is indirectly indicated by data showing an increase in the values of Σ Ta (≥ 0). Therefore, we assume that, in some cases, infiltration increases in the pre-winter period (November–December) and that spring snowmelt begins earlier in the year. Accordingly, the ordinate of the decay curve of the groundwater runoff increases; this decay curve can be considered, to a first approximation, to be equal to the river runoff during winter, the period of river ice cover and seasonal snow cover, that is, icecaps, on the river catchments.

The results for the period of 1995–2015 given in Table 2 indicate a statistically significant (with a significance value of 5%) increase in the groundwater recharge component of the Chaya and Tym rivers (compared to the period from 1965–1972 to 1994). This coincides with the results of an earlier analysis of the groundwater runoff and average winter (December–March) water discharge from the period up to 2005–2007 (Shiklomanov et al., 2013).

In this work, the water balance, moisture, and ice content of the soil were calculated. The results of these calculations are presented in part in Table 2 and allow us to conclude that an increase in the soil moisture occurs throughout the year and that a decrease in the soil ice content occurs in the winter.

This study reveals a statistically significant increase in the mean annual groundwater levels of the Quaternary, Palaeogene, and Cretaceous sediments in the Tomsk region under conditions unchanged by economic activity. Our findings agree with data showing an increase in the winter dry-weather flow for large and medium rivers in the region (Shiklomanov 2013).

In addition, the following facts were noted. (1) During some months, the effective moistening (i.e. moistening and formation of river runoff) of the catchment area has increased. (2) The date of the establishment of snow cover has shifted to later in the year, while the spring melting of the snow now begins earlier. (3) During the winter period, the unfrozen moisture content in the soil has increased. As a result, the groundwater feed and groundwater levels have increased. At the same time, with increasing air temperature in summer, the period of evaporation from the catchment area has increased, which to some extent compensates for changes in the yearly river runoff and groundwater levels that are hydraulically associated with the rivers.

The revealed trends indicate that, with air temperature increasing, there will be a further increase in groundwater levels due to the annual distribution of precipitation. As a result, there will be an accompanying increase in the effective moisture during the winter and spring periods and a decrease during the summer.

However, it is impossible to exclude contributions of regional or more large-scale factors to changes in the water

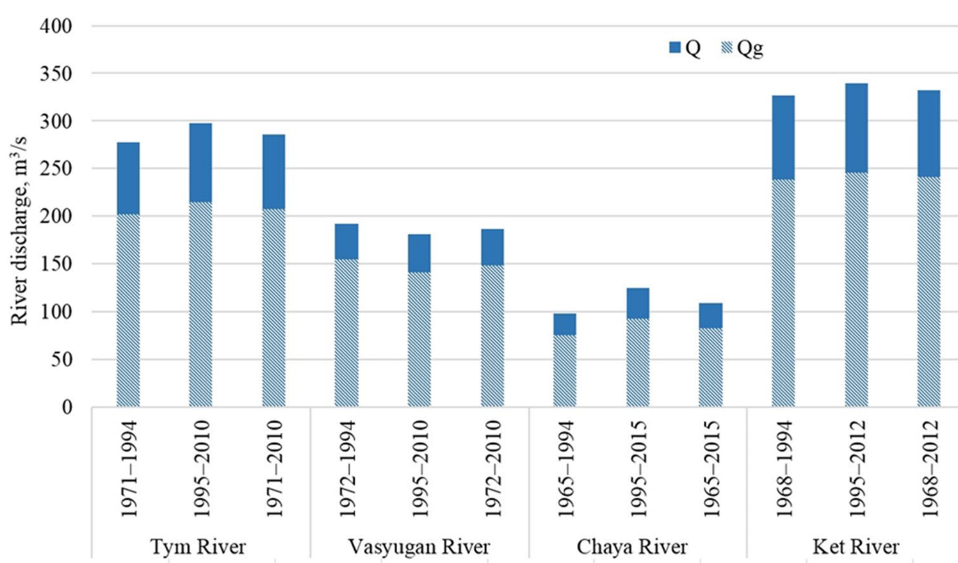

Fig. 5 The results of a statistical analysis of the data average annual river discharge Q Chaya, Vasyugan, Tym, and Ket rivers and their groundwater recharge component Qg (Eq. 12)

Table 2 Changes in the mean values of the amount of the monthly average precipitation (ΔP mm), the amount of precipitation for the warm (ΔP(Ta ≥ 0)) and cold (ΔP(Ta < 0) mm) periods, the water yield from snow cover (Δhsm, mm), evaporation (ΔE mm), surface (ΔY, mm) and groundwater (ΔYg, mm) flow, air temperature (ΔTa, C), soil moisture (Δw, m3/m3) and ice content (ΔΛ, m3/m3), and groundwater level (ΔZ94p, m) of the Chaya River catchment in Podgornoe cross section, from the periods 1965–1994 and 1995–2015

Period	ΔP, mm	$\Delta P(T_a \geq 0)$, mm	$\Delta P(T_a < 0)$, mm	Δh_{sm}, mm	ΔE, mm	ΔY, mm	ΔY_g, mm	ΔT_a, C	Δw, m^3/m^3	$\Delta \Lambda$, m^3/m^3	ΔZ_{94p}, m
I	−2.3	0.0	−2.3	0.0	−0.3	0.7	0.7	−1.7	0.000	0.002	0.79
II	0.5	0.0	0.5	0.0	1.1	0.7	0.7	2.2	0.018	−0.015	0.75
III	5.9	0.0	5.9	0.0	2.2	0.7	0.7	1.7	0.024	0.000	0.63
IV	1.9	1.9	0.0	24.9	3.3	1.5	0.8	1.4	0.045	0.000	0.66
V	−3.9	−3.9	0.0	−13.1	5.0	4.4	0.9	1.8	0.021	0.000	0.80
VI	17.7	17.7	0.0	0.0	2.7	−0.2	1.0	0.2	0.004	0.000	0.78
VII	4.9	4.9	0.0	0.0	2.3	1.3	1.1	0.0	0.007	0.000	0.60
VIII	5.8	5.8	0.0	0.0	1.9	1.2	1.1	0.2	0.007	0.000	0.56
IX	−0.5	−0.5	0.0	0.0	1.1	1.8	1.2	0.0	0.006	0.000	0.59
X	0.3	0.3	0.0	0.0	1.1	1.8	1.3	0.9	0.004	0.000	0.66
XI	2.8	0.0	2.8	0.0	0.5	1.9	1.4	0.8	0.002	0.000	0.71
XII	5.0	0.0	5.0	0.0	0.1	1.5	1.5	0.2	0.002	−0.007	0.72
$\sum_{year}$*	38.0	26.1	11.9	11.9	20.8	17.2	12.4	–	–	–	–
$\bar{A}_{year}$**	3.2	2.2	1.0	1.0	1.7	1.4	1.0	0.6	0.012	−0.002	0.69

balance. As a result, for example, there may be an increase in not only the groundwater levels within the West Siberian Plain but also the levels of the Caspian Sea (Bolgov 2007). Indirect proof for this assumption is provided by data showing a simultaneous groundwater level increase in the taiga zone of the Ob River Basin and decrease in the piedmont of the Altai Mountains located at the upper reaches of the Ob River (Savichev et al. 20,110). These trends are not directly related to anthropogenic impacts such as groundwater and hydrocarbon production, the drainage of swamps, forest melioration, or deforestation, and their impact on the groundwater within the Tomsk region at present can be characterised as primarily local.

5 Conclusions

Statistically significant increases in the average annual groundwater levels of the Quaternary, Palaeogene, and Cretaceous sediments in the study area were observed. In 8 of the 15 wells, there were increases in the average annual groundwater levels (approximately 0.34 m). The maximum increase was observed in the case of the Quaternary sediments in a well with an interfluvial groundwater regime. Analyses of the changes in the average monthly and annual air temperature and the amount of precipitation showed that there was a general increase in the average annual and sum of the positive monthly average air temperatures. An increase in the period of the year with positive temperatures was observed, that is, the end of the autumn period shifted to a later date and the beginning of the spring period shifted to an earlier date. At the Kolpashevo and Tomsk meteorological stations, there was an increase in the average annual precipitation during the warm and cold seasons. Extending the boundaries of the warm period in some cases will lead to an increase in infiltration during the pre-winter period and to early snowmelt during the spring.

With respect to the underground component of river runoff in the study area, an increase over the past 20 years was observed for the catchment of the Chaya River while a decrease in the period of 1971–1994 was observed for the Tym River.

The calculations of the water balance, humidity, and ice content of the soil indicated an increase in the unfrozen moisture content in the soil and a decrease in the ice content during the winter period. Increases in the effective moisture content of the catchment area lead to increased river runoff.

These changes in the water balance elements and climatic and hydrophysical characteristics affect the groundwater feed and, as a consequence, increase the groundwater level. However, evaporation from the catchment is also increased by the increasing air temperature in the summer, which can in part compensate for changes in the groundwater runoff.

The findings in the work confirm that global warming affects the entire ecosystem of the Earth. Climate change should be fully integrated into the water management process. Better use and management of water resources today will ease the challenges of tomorrow. It is necessary to improve knowledge of the groundwater reaction on the impact of climate change; to identify indicators of climate change impact on groundwater; and to evaluate the methods and means to develop the necessary measures.

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Author contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Oleg Savichev and Julia Moiseeva. The first draft of the manuscript was written by Oleg Savichev. Julia Moiseeva and Natalia Guseva reviewed and commented on the first draft of the manuscript. Oleg Savichev has supervised the research work. All authors read and approved the final manuscript.

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Data availability We have all the raw, processed data and result products, and if it is required, we can provide the processed data and documents.

Code availability All the calculations and plots have been done using various tools in MS Excel.

Declarations

Ethics approval Not applicable to this manuscript as there was no potential conflict of interest, not involved human/or animals and no other participant that need informed consent.

Consent to participate Not applicable to this manuscript as this study did not involve human participants that need informed consent.

Consent for publication The submission is the independent work of the authors. It has not been submitted and not published or accepted for publication and is not under consideration for publication in another journal or book. The submission has been approved by all relevant authors, and all persons entitled to authorship have been so named. All authors have seen and agreed to the submitted version of the manuscript.

Conflict of interest The authors declare no competing interests.

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