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Article

Estimation of water storage changes in small endorheic lakes in Northern Kazakhstan; the effect of climate change and anthropogenic influences

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Abstract: Both climate change and anthropogenic activities contribute to the deterioration of terrestrial water resources and ecosystems worldwide. Central Asian endorheic basins are among the most affected regions through both climate and human impacts. Here, we used a digital elevation model, digitized bathymetry maps and Landsat images to estimate the areal water cover extent and volumetric storage changes in small terminal lakes in Burabay National Nature Park (BNNP), located in Northern Central Asia (CA), for the period of 1986 to 2016. Based on the analysis of long-term climatic data from meteorological stations, short-term hydrometeorological network observations, gridded climate datasets (CRU) and global atmospheric reanalysis (ERA Interim), we have evaluated the impacts of historical climatic conditions on the water balance of BNNP lake catchments. We also discuss the future based on regional climate model projections. We attribute the overall decline of BNNP lakes to long-term deficit of water balance with lake evaporation loss exceeding precipitation inputs. Direct anthropogenic water abstraction has a minor importance in water balance. However, the changes in watersheds caused by the expansion of human settlements and roads disrupting water drainage may play a more significant role in lake water storage decline. More precise water resources assessment at the local scale will be facilitated by further development of freely available higher spatial resolution remote sensing products. In addition, the results of this work can be used for the development of lake/reservoir evaporation models driven by remote sensing and atmospheric reanalysis data without the direct use of ground observations.

Keywords: endorheic; lake; Central Asia; evaporation; semi-arid; Kazakhstan; climate change; Landsat; regional climate model; Burabay.

1. Introduction

Water-limited steppe regions of Central Asia are among the ecosystems found to exhibit pronounced responses to climate variability, as observed in recent decades [1]. Pekel et al.[2] using Landsat imagery, documented changes in the global surface water extent over the past thirty years and identified a net increase in continental permanent water cover. However, the largest share (over 70%) of worldwide net loss of permanent water extent is geographically concentrated in the Central Asia and Middle East regions; this can be attributed to both climate change and anthropogenic impacts [2]. Central Asia's territory, where surface water bodies are the main source of fresh water for human needs, consists mostly of endorheic drainage basins including various large terminal lakes such as the Aral Sea, Caspian Sea, lake Balkhash, and Issyk-Kul lake [3–6]. Mason et al.[7] proposed the monitoring of the closed lakes' water volumes and extents as proxy indicators for climate change. Klein et al. [3] using medium-resolution remote sensing data, estimated the seasonal changes in water bodies, such as large lake systems and water reservoirs in Central Asia over the past 27 years (1986-2012). They reported a decrease of surface water area of the Tengiz-Korgaldzhyn lake system in northern Kazakhstan from 1990 to 2012, and stability of water cover extent for Alakol-Sasykol lakes in eastern Kazakhstan for the whole period of the study.

While most of the published research on Central Asia is focused on large lakes such as the Aral Sea, Lake Balkhash, and Issyk-Kul lake [3–5,8], there are a large number of smaller terminal (endorheic) lakes, which are important too for local water resources and in the context of protecting rare ecosystems and biodiversity. For this paper, we investigated the long-term (30 years) changes in areal extent and volume (based on Landsat images, bathymetry maps and DEM data) of several small terminal lakes located in Burabay National Nature Park (BNNP), situated on the southern edge of Northern Eurasia where Siberian land surfaces (characterized by energy-limited evapotranspiration) transcend into water-limited steppes. The (changing) climatic conditions for this distinct region, together with its terrestrial water- and energy balance flux partitioning characteristics, will affect lake evaporation in a unique fashion, in particular of endorheic lakes, where evaporation is an important term of the water balance.

The water balance equation of an endorheic lake can be expressed as:

$$\Delta S = P - E - \Delta G - AWA \quad (1)$$

where ΔS is change in lake water storage, P – precipitation, E – evaporation, ΔG –storage change due to groundwater flow (predominantly feeding the lakes, as derived from isotope analyses; data not shown), and AWA – anthropogenic water abstraction. Eq. 1 assumes that streamflow input/outputs are negligible. ΔG will be a significant term in the water balance of BNNP lakes during years of considerable snowmelt [9]. Although we have some snow survey data available, these are not comprehensive enough and therefore ΔG has not been considered explicitly in this work.

We use Budyko's framework [9] to assess actual evapotranspiration (AET) in the catchments. Lake evaporation as the largest loss term in BNNP lakes water budget is calculated from meteorological equations and its temporal changes are considered in detail. Finally, we also evaluate AWA based on data (available from 2000 to 2013) collected by a local water accounting authority and a hydrometeorological monitoring agency.

Based on the analysis of long-term climatic data from meteorological stations, short-term hydrometeorological network observations as well as regional climate model projections we evaluate the impacts of historic, current and future climatic conditions on the water balance of BNNP lake catchments.

2. Data and Methods

2.1. Study area

BNNP (centered on 53°N, 70°E) is located in the Akmola Province in northern Kazakhstan, in Northern Central Asia (Figures 1 and 2). The climate in BNNP is continental, resulting in cold and semi-arid conditions [10]. The following BNNP lakes were considered (11 in total): Ulken and Kishi Shabakty, Shortandy, Burabay, Akkol, Zhaynak, Maybalyk, Tekekol, Gornoe, Karasie, and Svetloe (Figure 2). For most of this paper we focus on three main lakes for which long-term hydrometeorological observations are available: Ulken Shabakty, Shortandy, and Burabay (Figures 1 and 2).

BNNP watersheds, which control these lakes, are part of the Esil-Tobyl river basin that belongs to the vast Ob river basin draining into the Arctic Ocean. These catchments became endorheic about

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100 years ago when water levels of Shortandy Lake fell below a discharge threshold to the single remaining outlet, Kylshakty River (Figure 2) [10]. A recent review by Yapiyev et al. [10] provides a comprehensive background on the climate, geology, soils, vegetation, landcover, lakes and hydrological processes in BNNP.

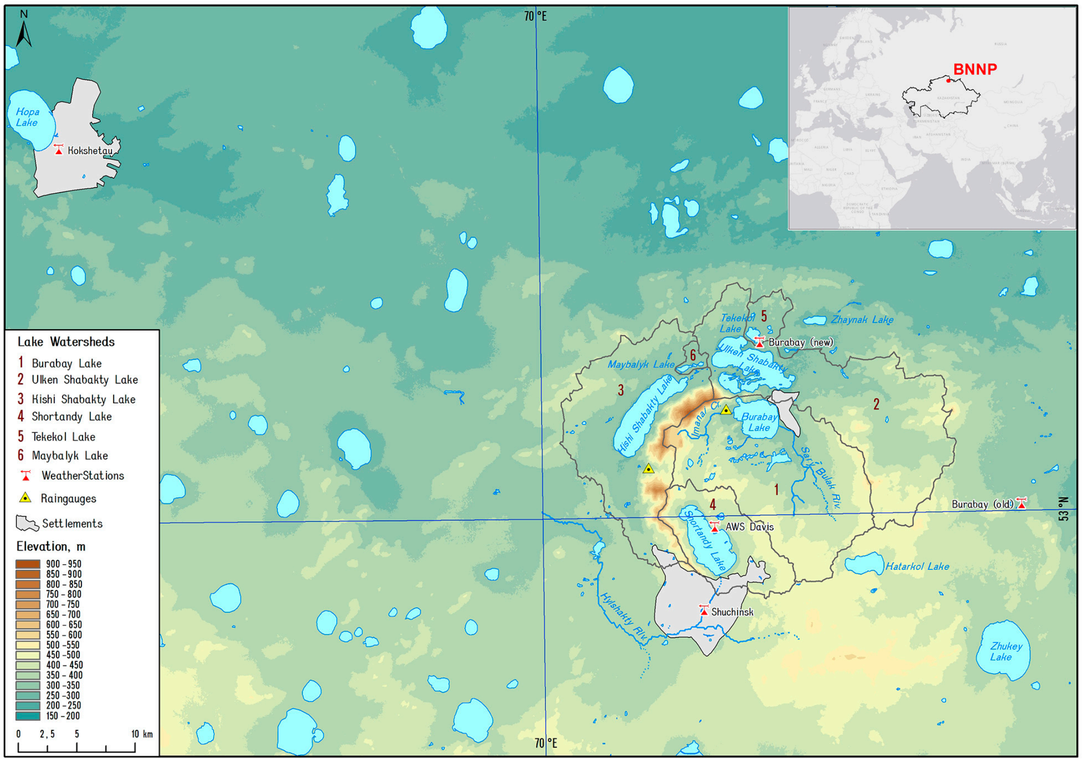

Figure 1. The regional map of BNNP with watershed delineation for 6 key lakes indicated by numbers 1-6. It also provides details on elevation, and the location of weather stations, raingauges, and human settlements locations (see legend).

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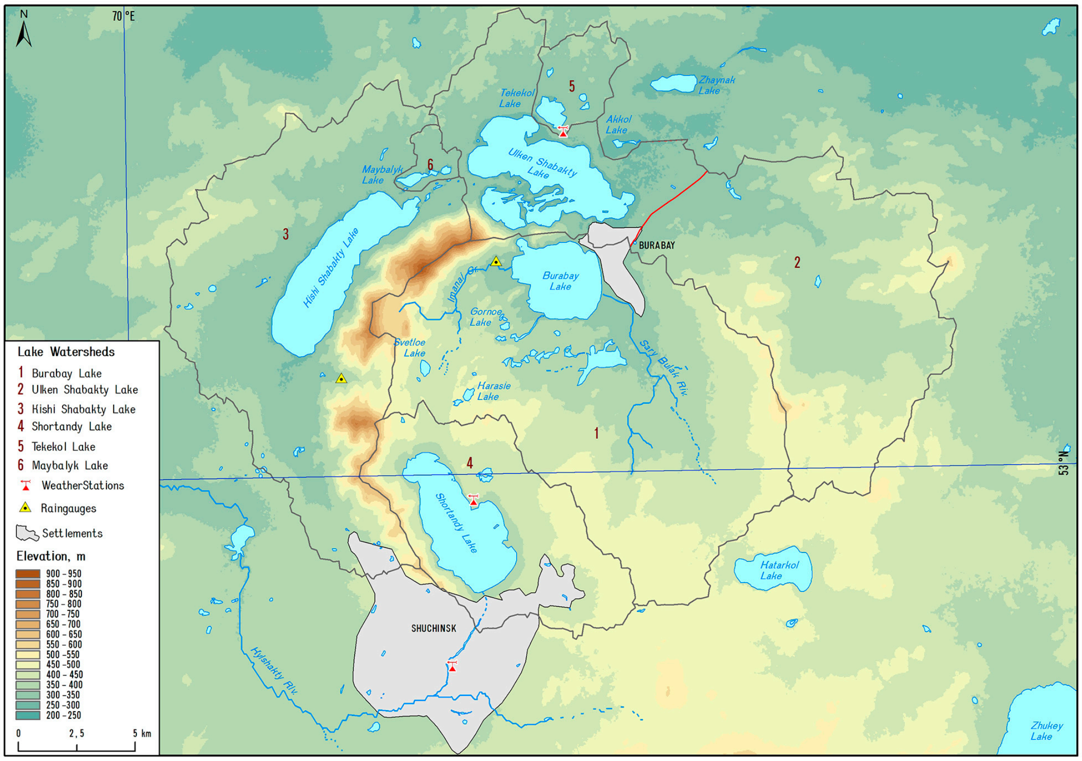

Figure 2. The local map of BNNP and its lakes (and related catchments). The red line dividing Ulken Shabakty watershed represents an asphalt road associated with human settlement expansion around Burabay town.

2.2. Digital Elevation Model, Bathymetry, Landsat, and KazEoSat-2 data

In order to estimate the long-term area and volume changes of the lakes, we used a digital Elevation Model (DEM) of the watersheds - combined with information on the physiography of the lakes' floor based on digitized bathymetry maps (Figure 3) and Landsat imagery to derive lake contours (Figure 4).

2.2.1 Digital Elevation and Bathymetry Models

We used Shuttle Radar Topography Mission (SRTM) DEM with 30 m pixel resolution [11]. Shortandy and Ulken Shabakty lakes have relatively deep basins (maximum depths of 24 and 30 m, respectively) and surface area extent data alone are not sufficient to estimate changes in water storage. Hence, we used recent bathymetry maps to infer the physiography of the lake floor. The bathymetry maps were obtained from Kazakh State Hydrometeorological Agency (Kazhydromet) in the form of high quality scanned images together with coordinate system (WGS-84) and grid. The maps were based on bathymetrical surveys of the lakes conducted in 2012-2013 by Kazhydromet, by means of an echo sounder (EA400 SP; Kongsberg Maritime AS), combined with concurrent GPS measurements (Seapath 20 NAV, Kongsberg Maritime AS) mounted on a boat. The distance between traverses was 100 m (Burabay Lake) and 150-200 meters (Shortandy and Ulken Shabakty lakes), respectively. The survey data were processed in QUINSy (Quality Integrated Navigation System) hydrographic data acquisition, navigation and processing software package (QPS B. V.).

Firstly, georeferencing of the bathymetry maps was conducted by using the *Georeferencer* tool of QGIS (Quantum GIS Desktop, version 2.16), for the preparation of the digital bathymetry models of the physiography of the lake floor for lakes Burabay, Ulken Shabakty and Shortandy. Secondly, the depth of the lakes was digitized and preliminary georeferenced bathymetric map point geographic

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data layers with Z values (shapefiles) were created. Data were projected in the WGS-84/UTM-42N coordinate reference system.

For the determination of the water volume, and delineation of watersheds, an interpolated surface was created. SRTM DEM and bathymetric data on the BNNP lakes were then converted to a triangulated irregular network (TIN) surface using ArcGIS (ArGIS Desktop, version 10.3.1) to render a 3D model of the BNNP basins (Figure 3).

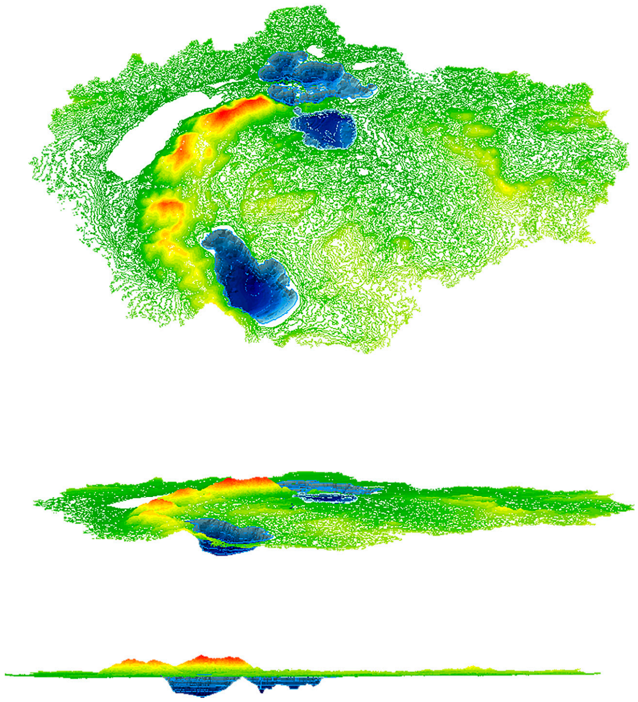

Figure 3. Digital 3D model of Burabay lake basins derived from combining DEM and bathymetry information

2.2.2. Landsat and KazEOSat-2 multispectral data and remote sensing accuracy estimation

The Landsat program provides a long-term global record of high-resolution (pixels size 15-60 m) satellite imagery of the Earth since the early 1970s [12]. We downloaded once-yearly cloud-free Landsat images from 1986 to 2016 (Supplementary materials, Table 1) for the ice-free period (May-October); an example is given Figure 4. Good quality multispectral data were not available for 1997 and 1998 (Supplementary materials, Figure 1). The lakes in the study area are relatively small in size; therefore, to verify the accuracy of lake surface area extent estimations derived from Landsat data, we compared these data with estimates obtained from higher resolution satellite images. For this verification we used data from the KazEOSat-2 satellite that is equipped with an imager of 6.5 m resolution launched on 06.19.2014 as it was designed primarily to provide multispectral data for the Kazakhstani territory [13]. For the intercomparison we used a recent Landsat-8 image (with spatial resolution of 15 m) dated 03.05.2016 and a KazEOSat-2 image dated 05.09.2016, and applied the methodology of water surface area estimation described in Section 2.3.

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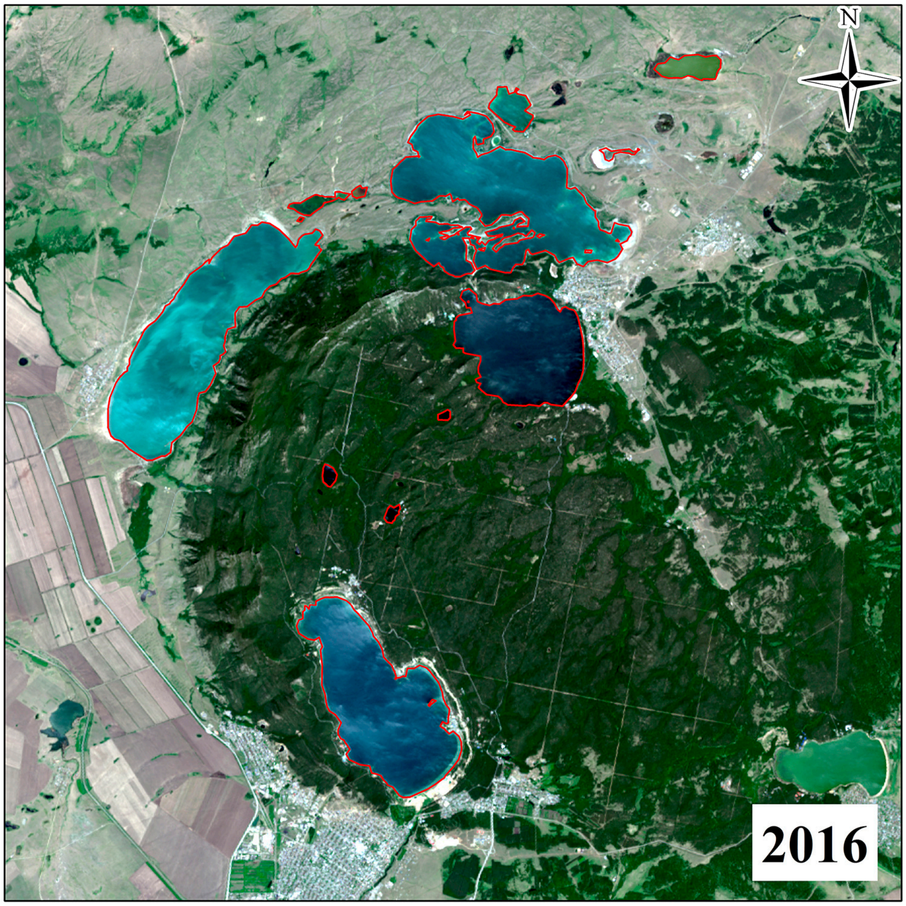

Figure 4. A Landsat image of BNNP with lakes' contours (indicating the extent of surface water) shown in red (image collected on 03.05.2016).

2.3. Lake surface water area and storage calculations

ENVI application (Exelis Visual Information Solutions Inc., version 5.3) was used to perform a supervised classification and to extract water contours as polygon vector objects. A "water" class was created to allow extraction of pixels corresponding to water objects. These data were exported to shapefile format and the areas of the 11 lakes – Ulken and Kishi Shabakty, Shortandy, Burabay, Akkol, Zhaynak, Maybalyk, Tekekol, Gornoe, Karasie, Svetloe were calculated in ArcGIS for each year.

Next, these vector polygons were used for estimating the lakes' volume (water storage). We used ArcGIS's *Polygon Volume* tool to estimate water volumes for each year for Shortandy, Ulken Shabakty, and Burabay lakes.

2.4. Hydrometeorological and Climate data

Historical hydrometeorological observations were obtained from the National Hydrometeorological service of Kazakhstan (Kazhydromet) [14]. Kazhydromet has three hydrometeorological stations in BNNP with different monitoring programmes (see Figures 1 and 2). In addition to BNNP Kazhydromet weather station data for validation (with regards to air temperature and precipitation) of regional climate model output data (see Section 2.5), we used daily air temperature and precipitation data from a regional weather station at Kokshetau located approximately 60 km to the north-west (53°17'1.49"N, 69°23'3.03"E), see Figure 1. We also obtained daily and monthly values for the mean wind speed (10 m) from Kazhydromet weather station located on the northern shore of Ulken Shabakty Lake (53° 7'46.60"N, 70°16'47.52"E; Figure 2) from 2013 to

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2016. Apart from standard hydrometeorological observations, Kazhydromet monitors lake water levels (daily) and lake surface water temperature (measurements are taken twice daily (8:00 and 20:00) during the ice-free period, (1 m from the shore edge at a depth of 5 cm) of lakes Burabay, Shortandy and Ulken Shabakty. Monthly lake surface water temperature data were available for the following time periods: Shortandy from 1980 to 2019 (gaps: 1998-2003); Burabay from 1980-2016 (gaps: 1998-1999); Ulken Shabakty from 1985 to 2016 (gaps: 1994-2006).

We also used rainfall data from a wireless automatic weather station (AWS; Vantage Pro2 Plus model 6163, Davis Instruments, Inc.) with integrated sensor suite (operational from 11.2013 to 10.2016) on the shore of Shortandy Lake (52°59'19.87"N, 70°13'6.48"E), (Figure 2). The AWS was equipped with a tipping bucket rain gauge with 0.2 mm accuracy (Davis Instruments, Inc.). In addition, in 2015 we installed two auto-logging tipping bucket raingauges (Davis Instruments, Inc.) to help to estimate spatial distribution of rainfall in BNNP: one in Kishi Shabakty Lake watershed (53° 2'18.07"N, 70° 8'8.47"E) at 1.5 m height above the ground, the other one in Burabay Lake watershed (53° 4'56.37"N, 70°14'8.90"E) mounted 5 m above the ground (Figure 2). The gauges had 0.2 mm accuracy and were set to log on hourly intervals. The raingauges operated during the rainfall season (April-September) in 2015 and 2016. The precipitation for this period constitutes around 70 % of the total long-term annual amount [10]. The rainfall data from a third Kazhydromet weather station (53° 0'8.00"N, 70°36'38.00"E) located in the eastern part of BNNP was used for the spatial interpolation of rainfall during 2015. Kazhydromet uses Tretyakov raingauges with a windshield to monitor precipitation; therefore, to compensate for wind wind-induced undercatch, we introduced a 4% correction for the tipping-bucket raingauge data [15].

The BNNP area has a complex topography and uneven relief. Spatial interpolation of rainfall data was used to estimate spatial variability of rainfall within the study catchments. For the two years of 2015 and 2016, Inverse Distance Weighed (IDW) interpolation [16] was applied on discreet rainfall data (see Section 2.4) to estimate the spatial distribution of rainfall for the warm season (April-September) in BNNP. The interpolation was performed in ArcGIS (ArGIS Desktop, version 10.3.1) utilizing *Interpolation-IDW* from *Geostatistical Analyst Tools* (ArcToolbox). We used the summed precipitation data (from April to September) from three Kazhydromet weather stations plus three of our own tipping-bucket type raingauges (see Section 2.4 and Figure 2).

Historical data were required to assess the long-term climate and water balance in BNNP (see Section 2.7). The Climate Research Unit (CRU) high-resolution monthly dataset (CRU TS v. 3.24.01 released 01.26.2017 covers 1901-2015 at 0.5° resolution of grid-boxes) available at https://crudata.uea.ac.uk was used [17]. Google Earth Pro graphical Interface was used to download monthly temperature and precipitation data. For evaporation assessment (see Section 2.7.2 and 2.7.3), we required monthly potential evapotranspiration (*PET*); wind speed at 10 m (U_{10}), and dew point temperature (T_d) to calculate actual vapor pressure. We used monthly PET from CRU ~~(~~from 1986 to 2015~~)~~; monthly U_{10} and T_d from a global atmospheric reanalysis ERA-Interim (0.75° resolution of grid-boxes)~~, (~~from 1986 to 2016~~)~~ [18]. Monthly data for each variable were downloaded as NetCDF files, then point data for BNNP (coordinates: 52.75° N, 70.25° E), extracted in R (Rstudio, Inc, software version 1.0) using *rgdal*, *raster*, *ncdf4* packages. CRU's PET data is daily for a given month, so the daily value was multiplied by the number of days in the month and summed as annual totals in Microsoft Excel (Microsoft Corporation, software version 14).

For our lake evaporation estimation validation, we used pan evaporation measurements from Kazhydromet obtained at three stations that were closest to BNNP. These pans are USSR GGI-3000 type: a cylindrical tank with a diameter of 0.618 m and a depth of 0.6 m, buried into the ground with walls protruding 75 mm above the land surface [19] (p.6). The average distance of the pans to BNNP was about 400 km: 1) Kushmurum evaporation pan, located to the west of BNNP (52°27'16.00"N, 64°35'35.00"E, 109 msl); 2) Ertis evaporation pan, located to the east of BNNP (53°12'9.32"N, 75°16'38.03"E, 93 msl); and 3) Bayanaul evaporation pan, located to the south-east of BNNP (50°28'11.78"N, 75°25'3.83"E, 465 msl). All evaporation pans are located in rural areas with steppe landscape.

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2.5. Regional Climate Model

2.5.1. Model description

PRECIS (*Providing REgional Climates for Impact Studies*) is a regional climate model, developed by the Met Office Hadley Centre [20]. The regional climate model in PRECIS (HadRM3P) is based on the atmospheric component of the Met Office HadCM3 (Hadley Centre Coupled Model version 3) model. PRECIS has a horizontal resolution of 25 km and outputs more than 130 meteorological variables at sub-daily, daily, monthly and annual temporal frequencies.

In this paper PRECIS RCM is driven by HadGem ES2 Global climate model (GCM) boundary conditions. Future projections (from 2007 to 2050) of HadGem ES2 model include two greenhouse gas concentration scenarios also known as Representative Concentration Pathways (RCP), namely RCP 2.6 (lowest greenhouse gas concentration levels) and RCP 8.5 (highest greenhouse gas concentration levels).

2.5.1. PRECIS Model validation measures

PRECIS's performance in reproducing the current climate was investigated using various statistical measures. The modelled temperature and precipitation data were compared with observed station data (1986-2004) on a daily basis. Model bias and root mean square error (RMSE) were calculated for the climatological seasons, which are SON (September, October, November - autumn), DJF (December, January, February - winter), MAM (March, April, May - spring), and JJA (June, July, August - summer). Daily values for each station were compared with the daily value for the model's grid box in which the station was located. For each station, bias (BIAS) and Root Mean Square Error (RMSE) for temperature and precipitation were calculated according to the following equations:

$$\mathrm{BIAS}=\overline{\mathrm{M}}-\overline{\mathrm{O}} \tag{2}$$

$$\mathrm{RMSE}=\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}\sqrt{(\mathrm{O_i}-\mathrm{M_i})^2} \tag{3}$$

Here, M-modelled data; O-observed station data; N-number of points; overbars symbolize mean values.

2.6. Evaporation

2.6.1. Budyko curve and actual evapotranspiration for BNNP area

Our research concerns a local-scale impact study. For assessment of climate controls in the BNNP catchments we used the Budyko curve in terms of P-E. The well-established Budyko framework is widely used in catchment hydrology to assess the long-term annual water balance [21–23]. We applied Budyko's curve, using a standard formulation for the aridity index as proposed by Budyko [9,22], to infer annual actual catchment evapotranspiration:

$$\overline{AET} = P \times F(\varphi), \tag{4}$$

where $\overline{AET}$ is mean annual actual evapotranspiration for the catchment (mm/year), P is annual catchment precipitation for a given year (mm/year), φ is the aridity index defined as the ratio PET/P, and $F(\varphi)$ is the Budyko function:

$$F(\varphi) = \{\varphi\,[1-\exp(-\varphi)]\tan(\varphi^{-1})\,\}^{1/2} \tag{5}$$

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PET and *P* data from CRU (see Section 2.4, from 1986-2015) were used to calculate the aridity index. CRU's PET is based on the Penman-Monteith grass reference evapotranspiration equation (FAO 56) [17].

2.6.2. Lake evaporation models

Lake evaporation is the single largest loss term in the water budget of endorheic lakes (see Eq. 1), including those in BNNP [10]. To calculate lake evaporation, we used the widely used mass transfer or aerodynamic method, based on Dalton-type equations. We tested the mass transfer method which employs a wind and lake area functions proposed by Harbeck in 1962 [24,25] and found a good agreement with the evaporation measured by Eddy Covariance Method during September-and October 2016 on Shortandy lake (unpublished results) as well as with lake evaporation estimates based on measurements of long-term pan evaporation (see Section 2.4):

$$E_L = (2.909 \times U_2) \times A^{-0.05} \times (e_w - e_a) \qquad (6)$$

Here E_L is the open water (lake) evaporation (mm/day), U_2 is the wind speed at 2 m (m/s), A is lake surface area (m²), e_w is the saturation vapor pressure (kPa) at water surface temperature, and e_a is the vapor pressure (kPa) at air temperature. The saturation vapor pressure (e_w) and the vapor pressure (e_a) are estimated from monthly lake surface water temperature (T_w) and monthly dew point temperature (T_d), respectively, using the following formulations:

$$e_w = 0.6108 \times exp\left[\frac{17.27 \times T_w}{T_w + 237.3}\right] \qquad (7)$$

$$e_a = 0.611 \times 10^{\left[\frac{7.5 \times T_d}{T_d + 237.3}\right]} \qquad (8)$$

A simple and widely applied scaling law was used to convert U_{10} to U_2 [26]:

$$U_2 = 0.75 \times U_{10} \qquad (9)$$

We used a common pan-to-lake evaporation coefficient 0.7 [18; p.6)] to convert the annual pan evaporation total to the annual lake evaporation sums.

2.7. Water abstraction

Finally, for a detailed analysis of the impact of human water consumption on the lakes' water balance in BNNP we estimated anthropogenic water abstraction (AWA) in the watersheds of Burabay, Shortandy and Ulken Shabakty lakes. The water abstraction data were taken from Kazhydromet's latest report on the water balance in BNNP [27], and from the Esil Basin Inspection body for regulation of use and protection of water resources, which is responsible for water accounting in BNNP. The water abstraction data were available from 2000 to 2013. The water use data for Ulken Shabakty were combined with those for the smaller adjacent watershed of Tekekol Lake (Figure 2). Sewer water from these three watersheds is discharged outside of these catchments in the north-east near Zhaynak Lake [10]. To estimate the proportion of water abstraction with regards to its effect on the water balance of these lakes, we calculated the following abstraction components: 1) percent abstracted water in watershed of the lake relative to lake volume for each year 2) in mm/year for watershed area; and 3) in mm/year to the lake surface area for that year.

$$\text{Change in water storage} = \frac{\text{Water abstraction}}{\text{Area}} \qquad (11)$$

$$\text{Percent of lake volume change per year} = \frac{\text{Water abstraction}}{\text{Lake volume for the year}} * 100\ \% \qquad (12)$$

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An example calculation for Burabay Lake for the year 2000 is given in Appendix A.1. The absolute values of water abstraction are reported in thousands m^3/year (see Figure 8a).

3. Results

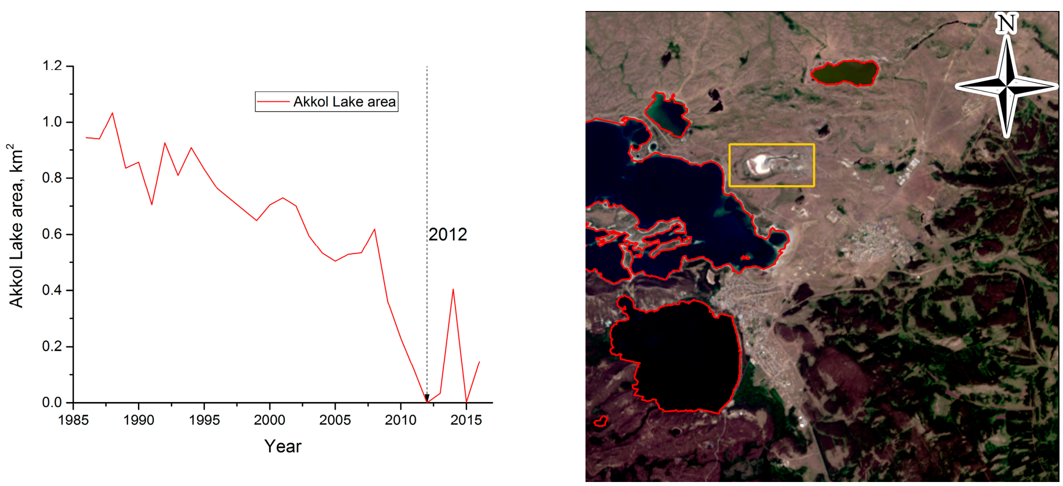
3.1. Accuracy of lake area estimations by remote sensing

The comparison of Landsat surface area estimates (30 m resolution) with those obtained with a higher resolution image (KazEOSat-2) is presented in Table 1. The percentage difference between the two estimates is very small (< 1.4 % of lake area), in particular for lake Burabay, the smallest of the three lakes.

Table 1. Accuracy of lake area measurements based on Landsat-8 and KazEOSat-2 images, 2016

Lake	Lake surface area, km^2 (KazEOSat-2)	Lake surface area, km^2 (Landsat-8)	Difference %
Shortandy	14.554	14.75	1.35
Ulken Shabakty	17.819	18.03	1.18
Burabay	9.985	9.96	-0.25

In addition to the verification of our lake area estimates from Landsat by the higher resolution KazEOSat-2image, the accuracy is also corroborated by the fact that with our method we registered the disappearance of Akkol Lake in 2012 (Figure 5ab), verified by ground observations (see also Table 2 in Supplementary Materials).



(a) (b)

Figure 5. The shrinking of Akkol Lake demonstrated by Landsat imagery analysis supported by ground observations. **(a)** The change in surface water area of Akkol Lake, determined from Landsat imagery, from 1986 to 2016 with a dotted vertical line showing the temporary disappearance of surface water in 2012; see also Table 2 in the supplement. **(b)** The Landsat image snapshot of BNNP for 2012 with the dry lake floor of Akkol Lake clearly visible (the yellow rectangle).

3.2. Changes in surface area and water storage of BNNP lakes

The changes in total BNNP lake surface area (11 lakes; as shown in Figure 1) is presented in Figure 6a. The overall surface area of BNNP lakes has been steadily decreasing since 1987 (R^2 = 0.55).

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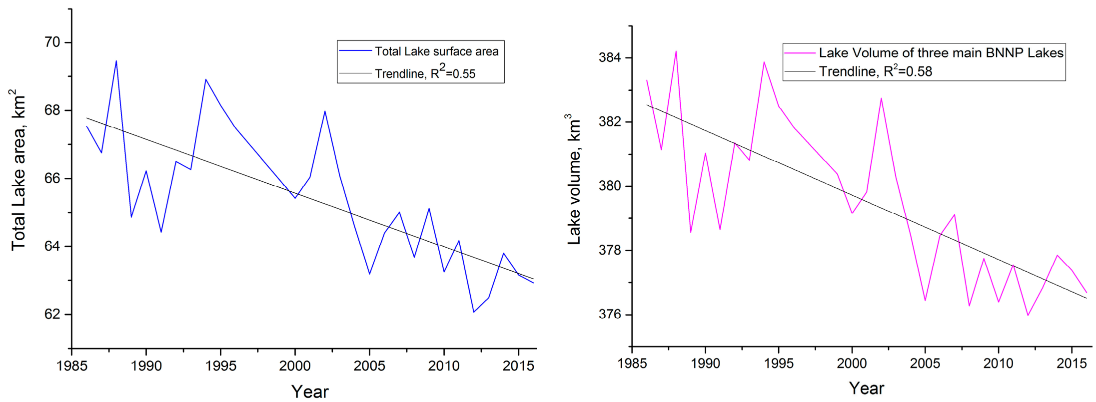
As the main lakes are of tectonic origin and have deep basins, we also show the water volume changes for the three main lakes combined (see Fig. 6b) which displays a similar downward trend (R^2=0.58).



(**a**) (**b**)

Figure 6. The change in surface water area and volume of BNNP lakes between 1986-2016 **(a)** The change of total surface area of 11 BNNP lakes: Ulken & Kishi Shabakty, Shortandy, Burabay, Akkol, Zhaynak, Maybalyk, Tekekol, Gornoe, Karasie, Svetloe), see Figure 2 for location of the lakes; **(b)** The change in total volume of three main BNNP lakes (Ulken Shabakty, Shortandy & Burabay), see Figure 3 (3D model of BNNP basins) and related text for the methodology used.

The total lake surface water area of eleven BNNP lakes decreased from 67.5 km² in 1986 to 62.9 km² in 2016 (a reduction of 4.6 km² or ~7% of the average total area). This surface water area change is predominantly due to the decrease in areal extent of three lakes: Ulken and Kishi Shabakty, Shortandy (a reduction of 4.8 km²). This was partially compensated for by the increase of surface area of other smaller lakes. The surface water area of some small lakes (with area of 1 km² or less) in BNNP has in fact increased since 1986. This increase is evident for steppe lakes (Zhainak, Tekekol, Maybalyk) as well as forest lakes (Gornoe, Karasie, Svetloe). The areal surface water extent of Burabay Lake had also slightly increased from 9.64 km² to 10.00 km (see Supplementary Materials, Table 2).

The total water volume of the three main lakes (Ulken Shabakty, Shortandy & Burabay) changed from 383.3 km³ in 1986 to 376.7 km³ in 2016 (a reduction of 6.6 km² or 1.7%). This water volume change is due to the reduction of Ulken Shabakty Lake by ~3.8 km³ (2.3% decrease), and Shortandy Lake by ~3.4 km³ (1.9% decrease), a reduction of 7.2 km³ in total, while Burabay Lake's volume increased by 0.6 km³ (+2%). The drops in surface lake extent and water volume occurred in the following years: 1989, 1991, 1999-2000, 2004-2005, 2008, 2010 and 2012. During the last ten years (2006-2016) both lake area and volume stabilized, approximately fluctuating around an average value: 63.6 km² in terms of area and 377.3 km³ in terms of water volume (See Figure 6a and 6b). These results are in agreement with data on BNNP lake levels during the past 100 years [10].

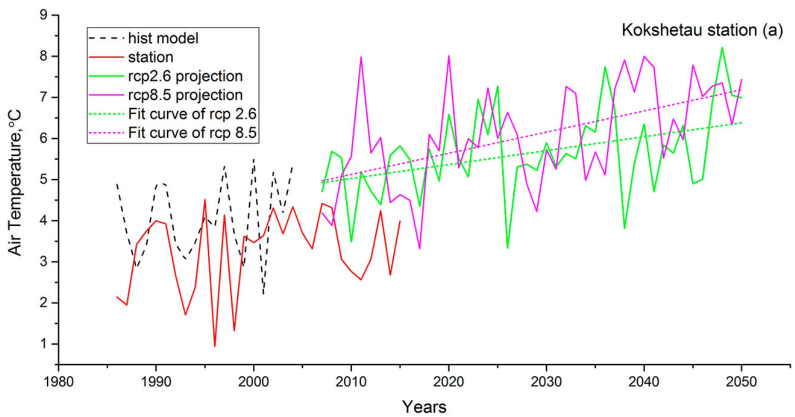
3.3. Regional Climate Model predictions and performance

The historical model estimates and station observations for air temperature and precipitation are presented in Figure 7. The RCM performance against daily ground observations (see Section 2.5) is summarized in Table 2. The comparison shows a reasonably small BIAS but high RMSE. Although PRECIS overestimates the precipitation compared to station data, it performs best for Kokshetau which is more representative of Northern Central Asian climate.

Table 2. Seasonal model performance testing for daily historical model outputs versus daily station data (1986-2004), for Kokshetau and Shuchinsk (see also Fig. 1 and Fig.7).

BIAS	Shuchinsk Precipitation, mm	Shuchinsk Temperature, °C	Kokshetau Precipitation, mm	Kokshetau Temperature, °C
Winter	0.80	1.94	0.19	0.57
Spring	0.86	2.07	0.54	1.70
Summer	0.35	1.57	0.05	1.04
Autumn	0.59	1.08	0.19	0.16
RMSE				
Winter	2.28	9.78	1.82	9.55
Spring	3.83	12.72	3.27	12.51
Summer	5.89	6.41	6.12	6.31
Autumn	3.19	11.10	2.87	11.14

The projections show a slight decrease in precipitation (Figure 7c and 7d) for both scenarios (RCP 2.6 and 8.5), especially with increased greenhouse gases concentrations. However, the projected changes in precipitation are quite small. The air temperature is predicted to increase by 1.9°C (RCP 2.6) and 2.5° C (RCP 8.5), between 2007 and 2050 for both locations. Both stations have the same historical and projected air temperature due to the relatively coarse spatial resolution of the model output. Seasonally, when compared with station data, the model shows better results for precipitation in autumn and summer (Kokshetau and Shuchinsk) and for air temperature in autumn (both Kokshetau and Shuchinsk), see Table 2.



(**a**)

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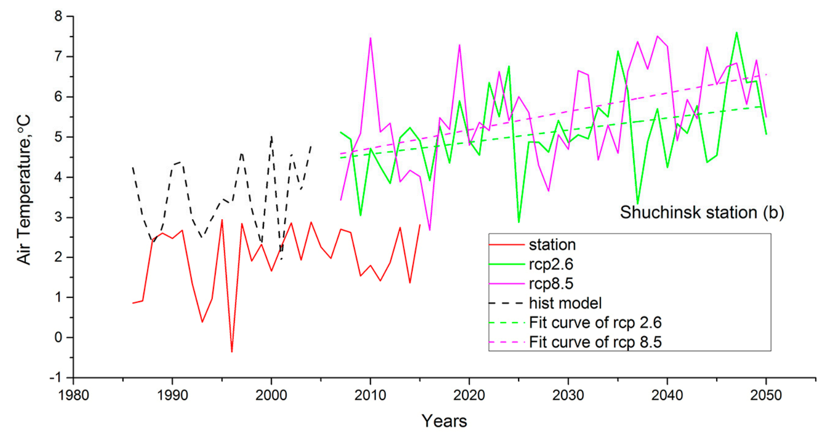

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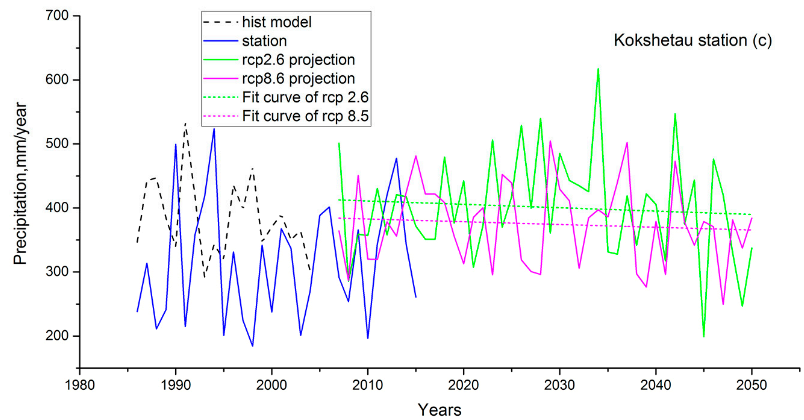
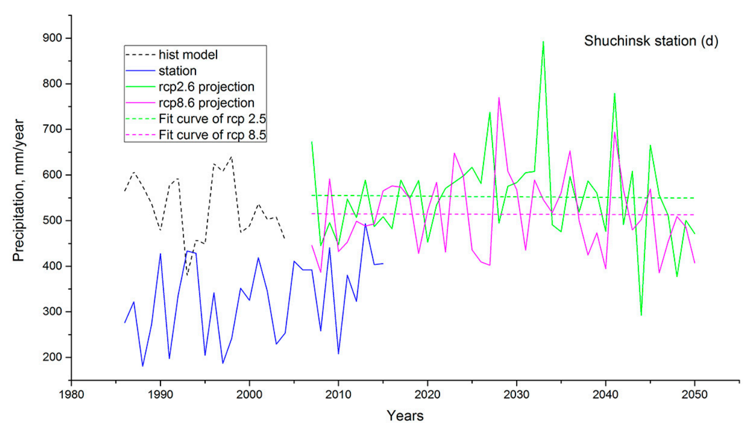


(**c**)



(**d**)

Figure 7. Time-series of mean annual air temperature (a & b) and total annual precipitation (c & d) for Kokshetau and Shuchinsk weather station locations, respectively: historical model outputs (1986-

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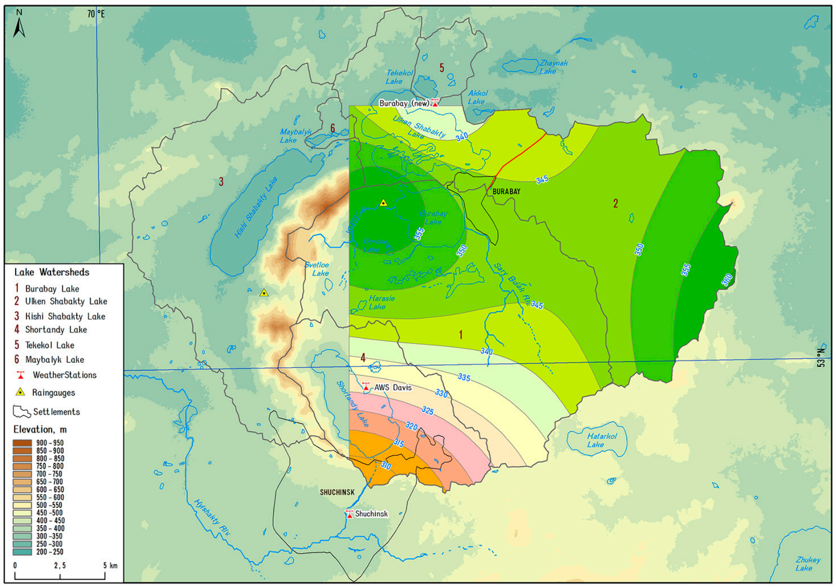
2004), station data (1986-2004) and model projections (2007-2050). Historical observation values are derived from daily data.

3.4. Precipitation and Evaporation

3.4.1. Spatial rainfall distribution

Figure 8 shows that higher rainfall is observed in the north-western part of BNNP, in Lake Burabay watershed, and in the eastern part of BNNP, in the watershed of Ulken Shabakty Lake, due to orographic effects and prevailing South-West winds. The shrinking lakes, Shortandy and Ulken Shabakty are located in modest "rain shadows", Shortandy lake in particular, while Burabay Lake is in a more favorable position to harvest orographic rainfall.



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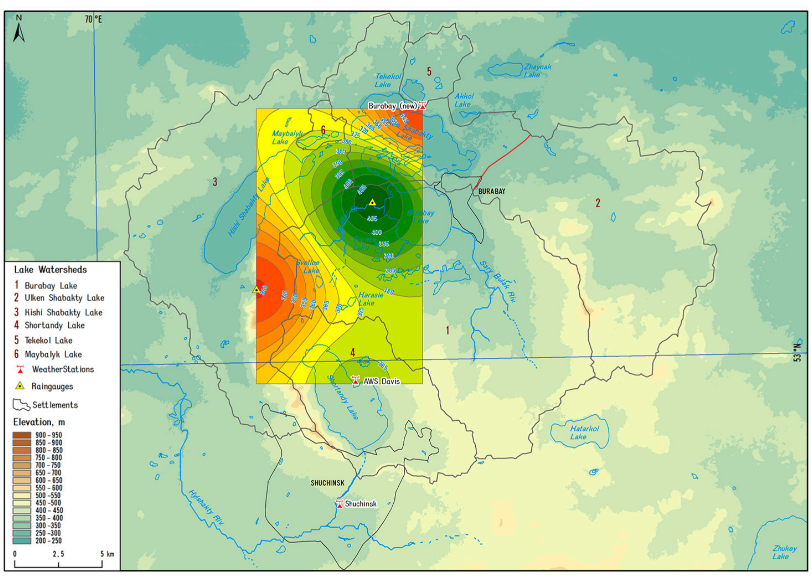
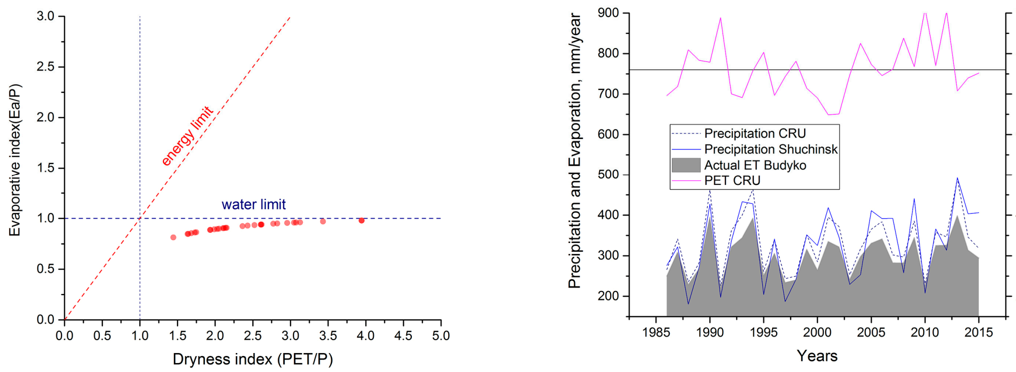


(**b**)

Figure 8. Spatial distribution of rainfall for **(a)** 2015 and **(b)** 2016 obtained by IDW interpolation of rainfall gauge data. The weather stations and the raingauges are indicated on the map.

3.4.2. Precipitation, PET and AET for catchment

The Budyko curve allows inference of the maximum possible long-term $\overline{AET}$ for a catchment taking into account atmospheric demand (PET) and available water (P). The Budyko curve analysis provided a mean thirty year AET value of 300 mm/year for BNNP (see Figure 9b). Calculated AET varies between 221 and 399 mm/year throughout the 30-year period. Mean PET (from CRU) for the same period was 760 mm/year. CRU and Shuchinsk weather station mean precipitation values were 331 and 329 mm/year, respectively, and showed a very good agreement (Figure 9b). The dry years are 1988, 1991, 1995, 2004, 2008, 2010, and 2012; these have the highest PET values: 809, 889, 803, 826, 838, 911, 904 mm/year and mostly low P (Shuchinsk precipitation data): 181, 198, 205, 253, 258, 208 and 314 respectively (Figure 9b). The driest years are 1988, 1991 and 2010 when Budyko dryness index (PET/P) has values of 3.43, 3.94 and 3.95 accordingly; these years also have the highest P-E difference. The long-term evaporation index (AET/P) is 0.92, which means that around 90% of the precipitation in BNNP catchments is lost through evapotranspiration.



(**a**) (**b**)

Figure 9. Long-term precipitation and evaporation trends in BNNP. (a) Budyko curve, each dot represents Budyko dryness index for 1 year; (b) total annual precipitation from Shuchinsk weather station (see Figure 2) and CRU; potential evaporation (PET) from CRU data (straight line is mean PET, value 760 mm/year) and actual evapotranspiration for catchment derived from Budyko curve based on CRU PET, precipitation for period 1986-2015 (see section 2.4 and 2.7.2)

3.4.3. Lake evaporation

The long-term annual lake evaporation for Burabay, Ulken Shabakty and Shortandy Lakes are shown in Figure 12 (solid lines) together with pan evaporation observations multiplied by the pan-to-lake coefficient (dashed lines). The highest mean open water evaporation is 590 mm/year for Burabay Lake (calculated for 29 years), and 530 and 514 mm/year for Ulken Shabakty and Shortandy Lakes (calculated for 18 and 23 years), respectively. Calculated annual lake evaporation varies between 399 and 736 mm/year throughout the 30-year period. Although there are gaps in lake evaporation due to missing lake surface water temperature data (see Section 2.4) the results show an increase in lake evaporation since 2008.

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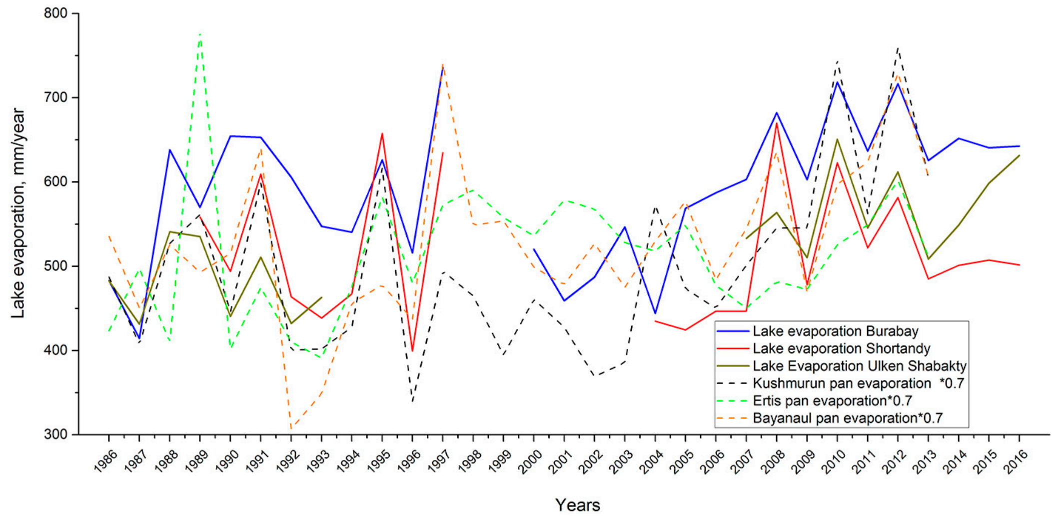


Figure 10. Annual lake evaporation (solid lines) for three BNNP lakes for 1986-2016 with annual pan evaporation data (1986-2013) from three observation sites, located ~ 400 km away (dashed lines; these were the closest pan evaporation data available).

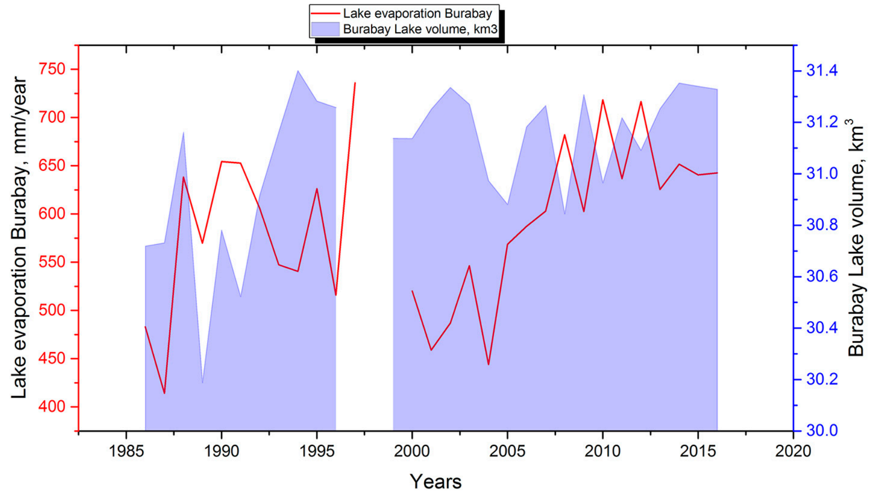
The open water evaporation for Burabay Lake is highest (more than 700 mm/year) in 1995, 2008, 2010, 2012 and 2015 amounting to 736, 709, 765, 821, 704 mm/year respectively (Figure 10). The lake evaporation is highest for Ulken Shabakty Lake in 2010, 2012, 2015 and 2016 totaling to 651, 612, 599 and 631 mm/year accordingly (Figure 11). The largest evaporation totals for Shortandy Lake are found in 1991, 1995, 1997, 2008, 2010 and 2012 reaching 609, 658, 635, 670, 623 and 581 mm/year, respectively. The correlation coefficients between annual lake evaporation and pan evaporation totals are shown in Table 3. Overall, there is a good correspondence between pan and lake evaporation, and the correlation is particularly strong between Ulken Shabakty lake evaporation and Kushmurun pan evaporation (see also Figure 10). We compared monthly wind speed from ERA-Interim with available Kazhydromet data for 2011-2016 and found a good agreement (Pearson correlation coefficient ~ 0.92).

Table 3. Correlation between annual lake evaporation (their direction in relation to BNNP between brackets) and pan evaporation (with the pan-to-lake coefficient applied). For details see Data and Methods: Sections 2.4 and 2.6.2)

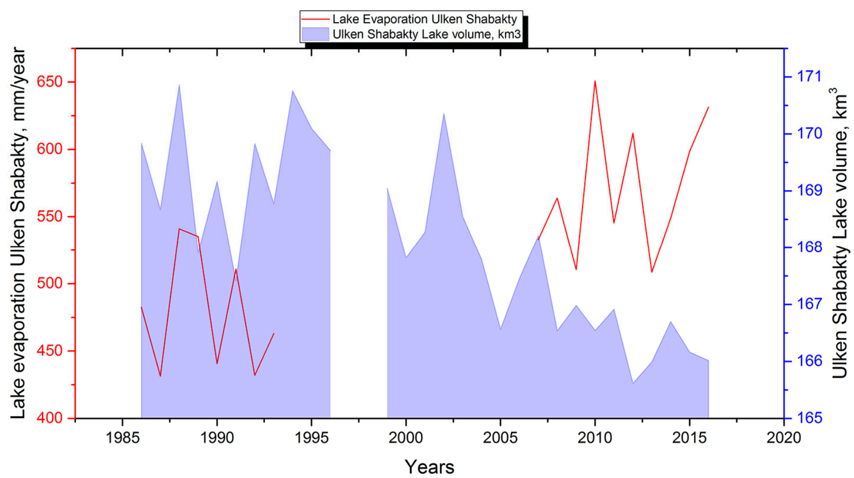
Lake/Pan	Kushmurun (W)	Ertis (E)	Bayanaul (SE)
Burabay	0.61	0.02	0.58
Ulken Shabakty	0.90	0.46	0.71
Shortandy	0.63	0.41	0.56

By considering the estimated mean annual lake evaporation, we can estimate the loss of water through evaporation for 30-year period to constitute 18.8, 6.1 and 4.4 % (0.18 km^3, 0.31 km^3, and 0.25 km^3 in water volume terms) of mean lake volumes for Burabay, Ulken Shabakty and Shortandy lakes accordingly.

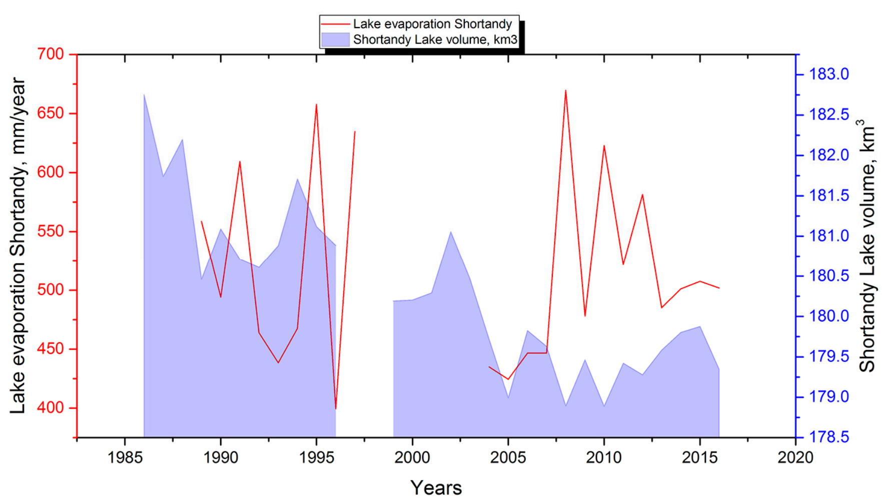
Lake evaporation controls the water budget of the main BNNP lakes. The lake surface areas and volumes experienced decline in dry years or the years following dry years with high catchment PET (see Figure 9b) and lake evaporation: 1989, 1991, 1999-2000, 2004-2005, 2008, 2010 and 2012.


Lake evaporation Burabay
Burabay Lake volume, km3
Lake evaporation Burabay, mm/year
Burabay Lake volume, km3
Years

(a)


Lake Evaporation Ulken Shabakty
Ulken Shabakty Lake volume, km3
Lake evaporation Ulken Shabakty, mm/year
Ulken Shabakty Lake volume, km3
Years

(b)


Lake evaporation Shortandy
Shortandy Lake volume, km3
Lake evaporation Shortandy, mm/year
Shortandy Lake volume, km3
Years

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(**c**)

Figure 11. Annual lake evaporation for three BNNP lakes for 1986-2016 with annual lake volume changes: (a) Burabay Lake, (b) Ulken Shabakty Lake (c) Shortandy Lake.

3.5. Anthropogenic water abstraction and related impacts

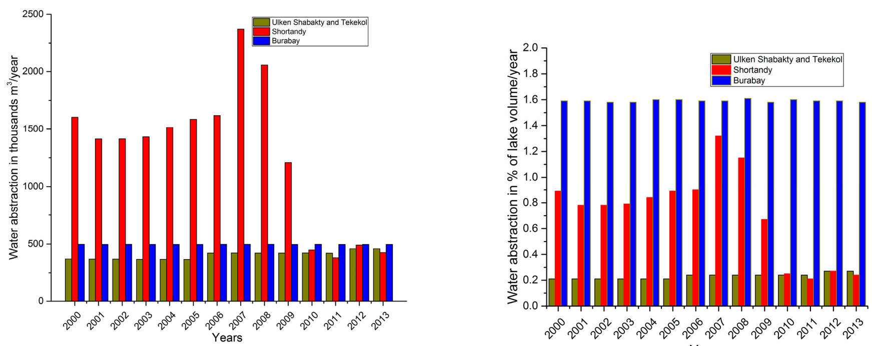
The data in Table 4 shows that the AWA for the three main lake watersheds has been stable over the 14 year time period between 2000-2013.

Table 4. Total anthropogenic water abstraction in the watersheds of three main BNNP lakes (2000-2013). Lakes: (3) Burabay, Ulken Shabakty with Tekekol and Shortandy (see also Fig 12).

Lake	Years	AWA total (in thousand m^3/year)	AWA total (in % of lake volume/year)	AWA total (in mm/year for watershed area)	AWA total (in mm/year for Lake surface area)
Burabay	2000	496	1.59	3	50
	2001	495	1.59	3	49
	2002	496	1.58	3	49
	2003	495	1.58	3	49
	2004	495	1.6	3	50
	2005	495	1.6	3	51
	2006	496	1.59	3	50
	2007	496	1.59	3	50
	2008	496	1.61	3	51
	2009	495	1.58	3	49
	2010	496	1.6	3	51
	2011	495	1.59	3	49
	2012	495	1.59	3	50
	2013	495	1.58	3	50
Ulken Shabakty and Tekekol	2000	370	0.21	2	18
	2001	369	0.21	2	18
	2002	369	0.21	2	17
	2003	367	0.21	2	18
	2004	367	0.21	2	18
	2005	365	0.21	2	19
	2006	421	0.24	3	21
	2007	422	0.24	3	21
	2008	421	0.24	3	21
	2009	421	0.24	3	21
	2010	422	0.24	3	21
	2011	420	0.24	3	21
	2012	458	0.27	3	24
	2013	459	0.27	3	24
Shortandy	2000	1605	0.89	23	107
	2001	1413	0.78	20	93
	2002	1414	0.78	20	92
	2003	1431	0.79	20	94
	2004	1514	0.84	22	101
	2005	1586	0.89	23	108

2006	1619	0.9	23	108
2007	2371	1.32	34	159
2008	2057	1.15	29	140
2009	1208	0.67	17	79
2010	447	0.25	6	31
2011	380	0.21	5	26
2012	490	0.27	7	33
2013	426	0.24	6	29

Table 4 and Figure 12 show that the water abstraction in the watersheds of Burabay, Ulken Shabakty and Tekekol lakes has not significantly changed during the 14 year period from 2000 to 2013. The water consumption in the Shortandy Lake watershed, where the largest settlemen of Shuchinsk town is located, dropped after 2008 (Figure 9). The amount of water used for human consumption at most amounts to 1.6% of the lake volume in Burabay Lake watershed and 1.3% of the lake volume in Shortandy Lake watershed, which has the largest absolute water abstraction volumes (Table 1 and Figure 8). Direct water abstraction from the lakes was prohibited in 2008 by state authorities; however, this did not change the decline of lake levels. Nowadays, potable water supply comes from a source outside of the BNNP [10].



(a) **(b)**

Figure 12. Water abstraction in three main watersheds in BNNP (2000-2013) **(a)** in thousands m^3/year, **(b)** in % of lake volume/year. Lakes: Ulken Shabakty with Tekekol, Shortandy and Burabay.

4. Discussion

Central Asia's endorheic basins and lakes are under intensive pressures from both climate change and anthropogenic activities [6]. Many endorheic lakes have shrunk considerably in both Central Asia and worldwide posing a threat to fragile ecosystems and human populations[6]. BNNP lakes have been experiencing a decline for the past 100 years with the highest water level drops reported for Shortandy (19 m) and Ulken Shabakty (12 m) lakes [10]. We tried to assess the state of these small endorheic lakes subjected to a semi-arid climate over a thirty year period. Our findings show that the water storage decline in BNNP lakes for those thirty years can be seen as a "dramatic" one from "today's" perspective. Shortandy and Ulken Shabakty water volumes have declined during the past three decades, but the volume reduction is only around 2%. The surface area of some smaller lakes even increased.

The endorheic lakes in BNNP are regulated primarily by climate variability. The lake evaporation dominates the water budget of BNNP lakes leading to a steady decline of lake levels, although the more recent increases in P have caused lake levels to stabilize. Our Budyko curve

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analysis shows that BNNP catchments are under water-limited conditions most of the years. The increase in PET in the last decade signals the rising atmospheric demand, and related higher lake evaporation rates.

The higher open water evaporation in Burabay Lake can be explained by higher surface water temperatures as this lake volume is more than five times smaller than Shortandy and Ulken Shabakty Lakes. The long-term stability of Burabay Lake is determined not only by its smaller volume but also by the fact that it has a larger catchment size which increases water harvesting via run-off and sub-surface recharge [10]. After the last drought in 2012, the lake levels have been recovering due to higher than usual precipitation amounts. Overall, lake water storage variations show that BNNP lake volumes have been in balance with current climate conditions during the past decade. The spatial distribution of precipitation in BNNP indicates that declining lakes located in “rain shadows” and smaller lakes with increased surface area both in steppe and forest catchments have better conditions to harvest rainfall, and thereby maintain or increase their current size.

Though under state protection, Burabay catchments are intensively influenced by anthropogenic activities [10]. Though direct human influence, such as water abstraction in the lakes’ watersheds has a moderate or minimal impact, the indirect impacts such as construction of roads or hotels, and expansion of settlements may pose a bigger threat to lake level decline. The expansion of Burabay settlement in the catchment of Ulken Shabakty Lake caused the isolation of a large portion of drainage basin of this lake (Figure 2). As a result the effective watershed now measures 56.8 km^2 (the watershed/lake surface area ratio ≈ 3.15, instead of 8 if one takes the DEM delineated watershed area). The isolated portion of the Ulken Shabakty watershed is forested which means that it can conserve water by holding snowfall during the cold period (that will melt in springtime and add to lake water volume via groundwater inflow of melted snow water that has percolated through the soil profile), and has higher rainfall as demonstrated by our spatial rainfall interpolation. However, exact quantification of such impacts requires further investigation through detailed hydrological modelling, with the use of higher resolution remote sensing data.

The reduction of anthropogenic water abstraction in BNNP watersheds may be of minor significance for the lakes’ water balance, but it could be beneficial for local populations as the lake waters have very high fluoride content that has been increasing steadily over the past years [10]; high fluoride affects human health, e.g. causes dental fluorosis.

The application of the RCM in BNNP demonstrated that the model has difficulty reproducing current local climate variables. However, note that long-term climate observations show that mean long-term air temperature in BNNP (Shuchinsk) is about 1 ºC lower than regional air temperature (Kokshetau) [10]. This can be caused by local evaporative cooling due to substantial evaporation from lakes and forested catchments in BNNP that is not accounted for in models such as PRECIS. Despite this, the precipitation projections fit with long-term observations [10] and other studies on the region [28]:, i.e. no significant changes in rainfall in the future. The rising air temperature trend in BNNP projected by RCM is also in line with ground observations [10].

The higher air temperatures will cause increased lake surface water temperatures thus promoting lake evaporation. Also, the rising air temperatures will lead to an increase in duration of open water season for the lakes, thereby lengthening the evaporation period and hence increasing the total amount of water lost through evaporation.

This paper shows that free high-resolution satellite imagery such as Landsat can be used successfully to monitor long-term changes in lake areal extent and volume, for example for local water resources impact assessment studies. Certainly, there are uncertainties in our lake surface water area and volumes estimates as the lakes are relatively small in size. We try to use the best available high resolution remote sensing data with sufficiently long records to detect the changes in water storage. The spatial resolution of 30 meter per pixel such as Landsat and SRTM was considered high resolution until a few years ago. However, studies at a small catchment scale ideally use sub-*meter* or even *cm* resolution remote sensing data to accurately assess water balance of small water bodies, for example. Unfortunately, these ultra-high resolution data come at a significant cost and long-term records are not yet available. Hence, Landsat and similar data are still deemed very useful in many scientific and applied contexts, whether for water balance estimates, assessments of plant productivity/vegetation greenness, etc.

High-resolution remote sensing data can help understand the water balance of endorheic lakes, in particular when combined with gridded climate data such as those available from CRU and global atmospheric reanalysis products, such as ERA Interim. Open water evaporation, unlike terrestrial actual evapotranspiration cannot be directly estimated from satellite data [29]. However, relatively accurate measurements of lake surface water temperatures can be obtained from satellites [30]. The combination of such remote sensing measurements with ERA Interim data to drive mass transfer lake evaporation models would make lake evaporation assessment possible without having to rely on ground observations.

Further work in BNNP must include a detailed investigation of the lateral interactions between lakes and groundwater, with a focus on the role of snowmelt. The present lake evaporation assessment is preliminary and therefore we are currently analyzing high frequency BNNP data (including lake temperatures and evaporation), while taking into account the effects of surroundings, meteorological conditions, lake thermal behavior and heat storage.

5. Conclusions

We conducted a thirty-year analysis of changes in water storage of small endorheic lakes in semi-arid Northern Central Asia, by combining remote sensing, ground measurements such as bathymetric surveys and hydrometeorological observations, and gridded climate data (CRU and ERA Interim), utilizing GIS tools and simple micrometeorological models to estimate evaporation losses to assess impacts of climate on lake storage. We also used a regional climate model to forecast how climate (precipitation and air temperature) will alter in the next thirty years, and how this would affect lake storage via changes in inputs (precipitation) and outputs (evaporation). Furthermore, we assessed the effect of anthropogenic activities on BNNP endorheic lake storage, by studying the water abstraction for the largest lakes in BNNP.

We attribute the decline of BNNP lakes to long-term P-E deficit, i.e. lake evaporation exceeding recharge by precipitation (and from small contributions by groundwater influx, in particular after high snowfall winters). There is a trend of rising air temperatures in BNNP (causing increased E); however, the future precipitation rates are uncertain. Anthropogenic impact through water abstraction plays a minor role in the BNNP lakes water balance. However, human induced land use changes (construction of hotels and roads) in the lakes' watersheds are expected to negatively affect the recharge of the lakes. The two largest lakes (Ulken Shabakty and Shortandy), showing the highest historical water level declines, do not have sufficient water drainage basin area to sustain water levels under current and future local evaporation rates. Although the BNNP lakes' water volumes are currently relatively constant, the increasing atmospheric demand indicated by higher PET and lake evaporation rates can lead to further deterioration of lake levels and the unique ecosystems of Burabay.

Supplementary Materials: The following are available online, Figure 1: Landsat images of BNNP area (1986-2016); Table 1: List of used LandSat and KazEOSat-2 multispectral data; Table 2: **.** The surface area of BNNP lakes estimated from Landsat images (1986-2016). Lakes: (11) Ulken & Kishi Shabakty, Shortandy, Burabay, Akkol, Zhaynak, Maybalyk, Tekekol, Gornoe, Karasie, Svetloe; Table 3: The water volumes of three main BNNP lakes (1986-2016). Lakes: (3) Ulken Shabakty, Shortandy and Burabay.

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Author Contributions: Vadim Yapiyev conceived and planned the work, collected the observational data, conducted precipitation and evaporation analysis, wrote and edited the paper. Kanat Samarkhanov, Nazym Tulegenova, Saltanat Jumassultanova collected remote sensing data and conducted its analysis in GIS. Dauren Zhumabayev provided regional climate model data and analysis. Nursultan Umirov conducted water abstraction analysis. Kanat Samarkhanov, Zhanay Sagyntayev, Nazym Tulegenova and Saltanat Jumassultanova prepared the maps. Kanat Samarkhanov and Vadim Yapiyev conducted spatial rainfall interpolation. Assel Namazbayeva provided evaporation pan data. Kanat Samarkhanov, Nazym Tulegenova, Saltanat Jumassultanova, Dauren Zhumabayev, Nursultan Umirov, and Anne Verhoef helped with data-interpretation, contributed to the text and edited the paper and Assel Namazbayeva contributed to the text on evaporation and edited the paper. The authors' names are provided in the order of contribution.

Conflict of Interest: The authors declare that they have no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Appendix A

A.1. Water abstraction calculation for Burabay

Surface Area of Burabay Lake in 2000 = 9.9531 km^2 = 9.9531*10^6 m^2. The total abstraction for Burabay Lake in 2000 equals 495.5 thousands m^3/year. Watershed Area of Burabay Lake = 164 km^2 = 164*10^6 m^2. The total volume of Burabay Lake in 2000 equals 31.13738 million m^3.

1) Water abstraction in percent: Water abstraction/Volume of the lakes x 100 %

Water abstraction in percent of lake water volume = $\frac{495.5}{31137.38} \times 100\%$ = 1.59 % per year.

2) Water abstraction per lake surface area only in mm/year= $\frac{495.5\times1000\ m^3/\text{year}}{9.9531\times1000000\ m^2}$ = 0.04978 m/year = 49.78 mm/year = 50 mm/year.

3) Water abstraction per lake watershed area in mm/year= $\frac{495.5\times1000\ m^3/\text{year}}{164\times1000000\ m^2}$ = 0.003021341 m/year = 3.02 mm/year ~3 mm/year

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