Focus Article

The changing water cycle: Burabay National Nature Park, Northern Kazakhstan

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Water resources in Central Asia are scarce, so complicated issues arise from this. Kazakhstan is a Central Asian landlocked country, which has mostly closed drainage basins, characterized by endorheic lakes that do not drain to the oceans. These endorheic lakes are very sensitive to climate change and anthropogenic influences. Very few studies have been conducted on the hydrological cycle of the small endorheic lakes. This work reviews the endorheic lakes within Burabay National Nature Park (BNNP), Northern Kazakhstan. BNNP is a small ecozone consisting of terminal lakes watersheds covered by mixed forests and grasslands. These endorheic lakes have been drying out during the last one hundred years or so with the water level decrease accelerated in the past few decades. According to historical observations (1935–2014), on the one hand precipitation amounts did not significantly change, while on the other hand, air temperature steadily increased. The lake level decrease is most probably caused by a water budget deficit, with evaporation exceeding the precipitation inputs in the long term. The direct anthropogenic impact (water abstraction) plays a minor role in the deterioration of water levels, with most significant impacts through localized land-use changes such as road and building construction in the catchments. The future of the park's sensitive ecosystems in a changing climate is uncertain; therefore, BNNP requires modern ecohydrological monitoring methods and analysis tools to improve our understanding of its hydrological cycle variability, and to enable us to develop adequate adaptation and mitigation measures.

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INTRODUCTION

Kazakhstan is an inland country of the Eurasian continent with scarce water resources. Thus far, the hydrological cycle of the semi-arid Northern Kazakhstan region has not been researched extensively. According to the available literature, the last comprehensive water resources research campaigns were conducted more than 50 years ago.[1,2]

Kazakhstan has mostly endorheic watersheds, which are closed basins with drainage to isolated lakes, without outflow to neither large rivers nor oceans.[3] Because of the lack of hydrological verification data, and the complexity of the system, global climate and hydrology models often poorly represent the hydroclimatological behavior of Central Asian and Kazakhstani territory.[4–6] The water inflow to the endorheic lakes comes from precipitation and small rivers. The major loss is through evaporation, human water consumption, and to a lesser extent, groundwater recharge. The absence of regulating outlets leads to evaporative concentration of solutes and subsequent deterioration of water quality. Most endorheic lakes are located in drylands with limited precipitation and are quick to react to global climate change.[5] Recently published research[7] on global surface water, and its changes during the past 30 years based on Landsat imagery, documented an overall net increase in permanent terrestrial water extents. However, Pekel et al.[7] reported that worldwide more than 70% of permanent water loss took place in the Middle East and Central Asia, mostly in relation to dry spells and human activities.

The geographical focus of this review is Kazakhstan's Burabay National Nature Park (BNNP), a relatively small unique ecological zone located in the northern part of Kazakhstan. It consists of several small terminal lakes within catchments with a dominant land cover of temperate semiarid mixed forest and grassland. The park is located on the southern edge of Northern Eurasia where energy-limited boreal forests transcend into water-limited steppe. BNNP is one of the most famous and popular tourist attractions in Kazakhstan attracting visitors from all over Kazakhstan and neighboring regions.[8] The water levels of these lakes have experienced dramatic fluctuations during the past century (Figure 1 and Table 1) and the lakes have a tendency to dry up,[2,9,12,14] which has detrimental ecological consequences but also adversely affects tourism in the area. Unfortunately, the components of the hydrological cycle for these watersheds have not been properly monitored and quantified.

This paper is an overview of the main hydrological processes and the current state of water resources of BNNP, and a discussion of the potential ecosystem responses to climate change and anthropogenic impact of this economically and ecologically significant part of northern Kazakhstan.

The review specifically focuses on:

1. The primary characteristics of BNNP, in particular those related to the hydrological cycle and its connections to local ecosystem functions, scaled up to the regional level of Northern Central Asia;
2. Ecohydrological feedbacks to climate change within BNNP and their relative significance; and
3. Identification of gaps in knowledge of the hydrological cycle of BNNP basins that need to be addressed in order to predict the future changes in important ecosystem services.

GEOGRAPHIC LOCATION

BNNP is located in the Akmola province, in the northern part of Kazakhstan (53°N 70°E) (Figure 2). The park was established in August 2000 by a State Decree[15] with the aim to preserve and restore this unique natural complex which has important ecological, scientific, cultural, and recreational value. The total area of the BNNP is 1296 km^2, of which 141 km^2 are in a zone with special conservation conditions.[8] The main purpose of the park is to preserve its unique ecosystems, as well as its historical and cultural heritage sites.

CHARACTERISTICS OF BNNP

Climate

The Northern part of Central Asia (NCA) is considered to have the world's strongest degree of continental climate,[4] with the maximum winter–summer temperature range (difference between the absolute summer maximum and absolute winter minimum) approaching 100°C[9] and a negligible direct oceanic influence. Based on climatological data recorded from 1935 to 2014 at the Shuchinsk meteorological station located within the park, the mean annual precipitation has fluctuated between 200 and 400 mm (long-term average is 336 mm) without a significant trend (see Figures 3(a) and 4(a)). The mean monthly temperatures in July were between 18.0 and 20.5°C, and in January they were between −16.0 and −19.0°C. The mean annual air temperature was 2.3 and 1.4°C at Burabay (1980–2014) and Shuchinsk (1935–2014), respectively.[16] In BNNP, the seasonal cycles of both temperature and precipitation peak prominently in July, which is typical for NCA (Figure 3). The period of actively growing vegetation, when the temperature is higher than 5°C, is about 200 days year^{-1}. There are no long-term evaporation measurements available for the region. Local long-term mean precipitation and temperature observations are within the range of regional climatological averages of NCA. The regional mean annual air temperature is 2.6°C, and the regional mean annual precipitation is 346 mm for the period of 1971–2000.[4]

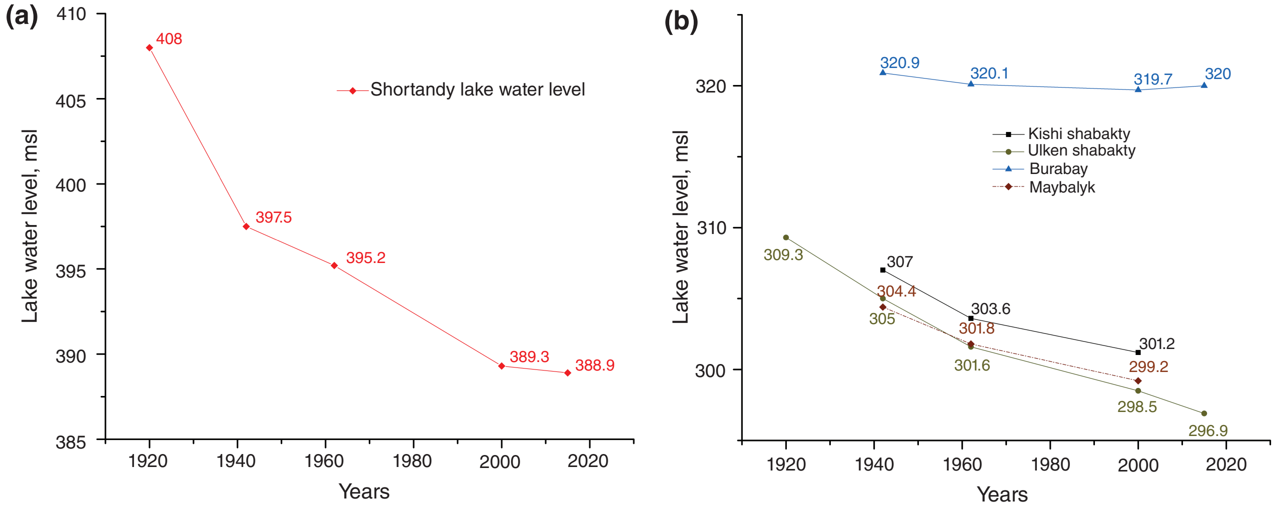

FIGURE 1 | The reconstructed long-term lake levels for main lakes of Burabay National Nature Park: (a) Shortandy (red line), (b) Burabay (blue line), Ulken Shabakty (green line), Kishi Shabakty (black line), Maybalyk (brown dash-dotted line). For sources of data and additional information, see Table 1.

Geology and Soils

The contemporary landscape of Burabay consists of hilly terrain that has been modified by geological processes along with anthropogenic activity and related land use. The most distinctive features of the landscape are mountains with afforested steep and gentle slopes with lakes in the lower areas (see Figure 2).

This part of Northern Kazakhstan is determined by two large geomorphologic structures: the West Siberian Plain in the north and the Kazakhstan Uplands in the south. BNNP has terrain that is typical of both kinds of structures, i.e., flat steppe and forested hills.[17]

North Kazakhstan is characterized by erosive-tectonic and denudation highlands and mounded hills. Hilly and mountainous terrain surrounds Burabay's granite and intrusive massif that is located in the middle part of the park. An arched rocky ledge of mounded hills, consisting of a strip of about 20 km in length with an average width of 2.5 km, extends north of Shuchinsk town (Figure 2). The highest peak of the area is Kokshetau Mountain, which is 947 m above mean sea level (msl) towering between lakes Ulken Shabakty and Burabay (Figure 2). The terrain forms were developed during the early-middle Pleistocene period, and it is believed that the formation process still continues due to the overall tectonic activity of the territory.[17]

Erosive-tectonic depressions exist mainly in the western part of the park. At their lowest points, we encounter small but relatively deep lakes. Most of them have developed as a result of tectonically lowered blocks and at fault zone intersections. Shortandy (23 m deep) and Ulken Shabakty (33 m deep) are the deepest lakes of the National Park (Table 2). Some lakes have rocky islands and peninsulas.

TABLE 1 | Historical Water Levels (m) of the Main Lakes of Burabay National Nature Park, above Mean Sea Level (msl)[1]

Lake	1900–1920[2]	1942[3]	1962[3]	2000[2]	2015[4]	Change (m), First Half of 20th Century to 2000–2015
Kishi Shabakty		307.0	303.6	301.2		–5.8
Ulken Shabakty	309.3[5]	305.0	301.6	298.5	296.9	–12.4
Burabay		320.9	320.1	319.7	320.0	–0.9
Shortandy	408.0[6]	397.5	395.2	389.3	388.9	–19.1
Maybalyk		304.4	301.8	299.2		–5.2

[1] WGS-84 c Baltic normal height system zero-mark of the Kronstadt tide gauge.
[2] Ref 9.
[3] Ref 10.
[4] Ref 13.
[5] The period of highest water level of Ulken Shabakty (1900–1920) is defined approximately by Refs 10,12,13.
[6] Korde[12] reported the level of Shortandy Lake dropped below a discharge threshold to Kylshakty river (408.0 msl; Ref 9) in 1920.

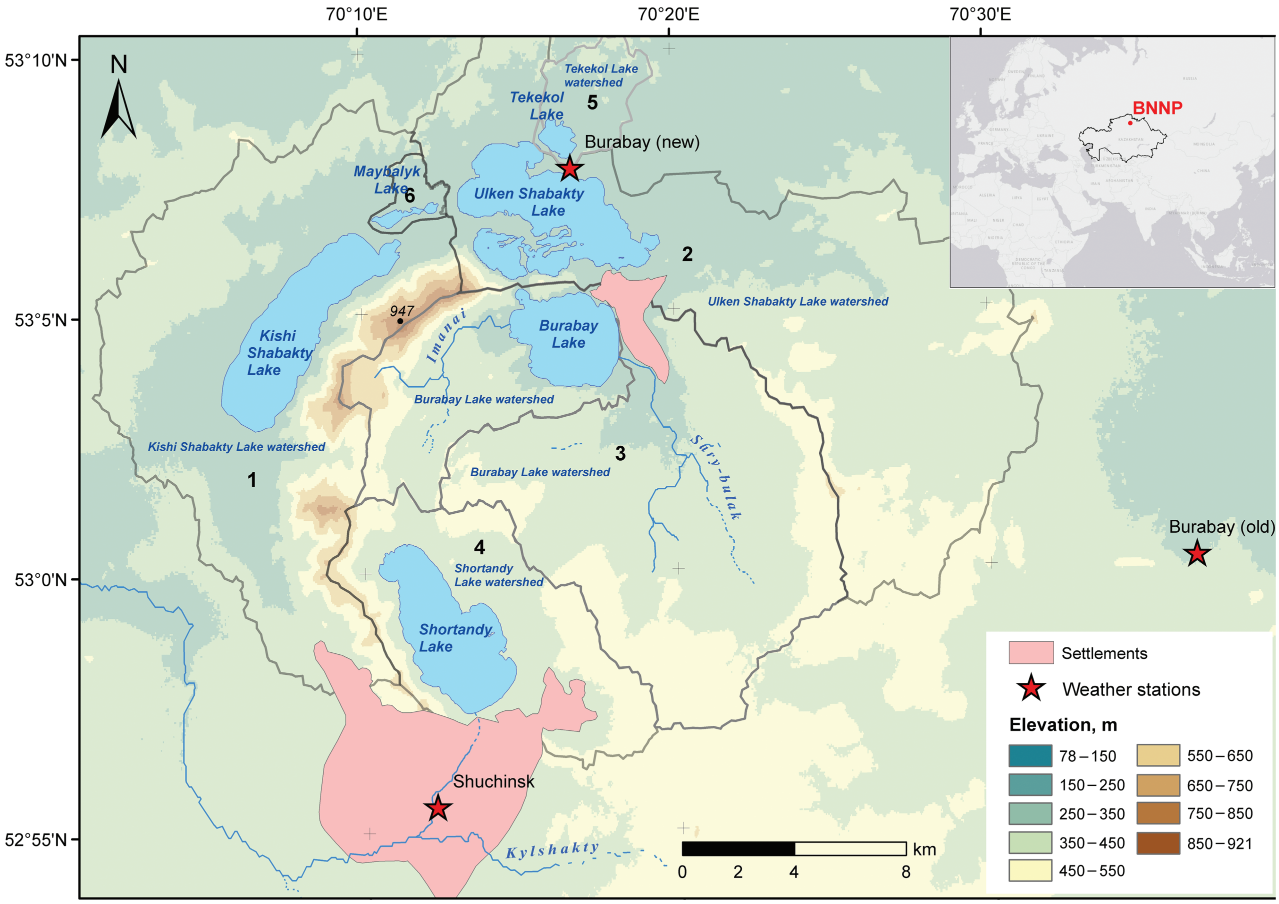

FIGURE 2 | Burabay National Nature Park location and main lake drainage basins: 1, Kishi Shabakty (Maloe Chebachie); 2, Ulken Shabakty (Bolshoe Chebachie); 3, Burabay (Borovoe); 4, Shortandy (Shuchie); 5, Tekekol; 6, Maybalyk. Former names of the lakes are given inside parentheses. Also indicated are the three main weather stations in the area (red stars), Shuchinsk town and Burabay settlement.

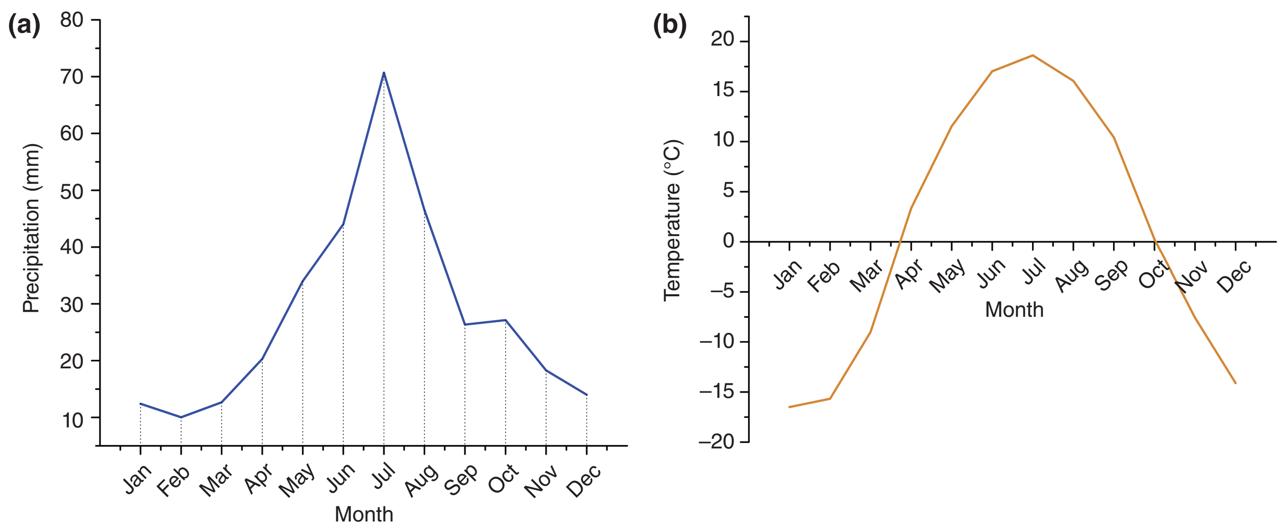

FIGURE 3 | The seasonal cycle of precipitation (a) and temperature (b), at Shuchinsk weather station (most southern station in Figure 1), for the period 1935–2014.[16]

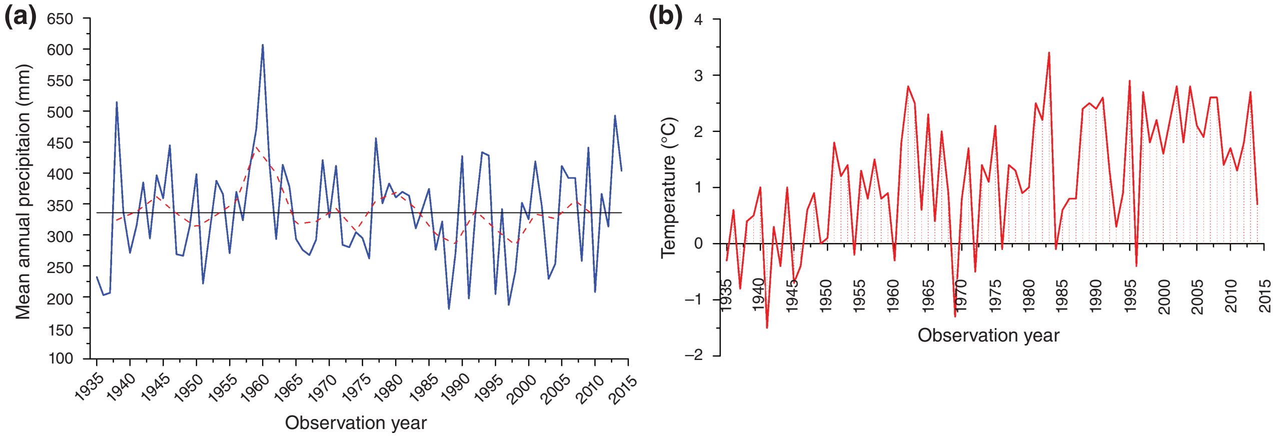

FIGURE 4 | Long-term annual precipitation (blue line) (a) with 3-year moving average (red dotted line), mean 336 mm (black line); and mean yearly air temperature (b) both at Shuchinsk Weather Station, 1935–2014.[16]

An erosive-accumulative surface landscape is common for the southern part of the territory, near the Kylshakty river watershed (Figure 2). Valleys are intersected by small rivers and temporary streams, and alluvial deposits are found in the narrow flood plains along the rivers.

In general, the territory of BNNP is composed of a denudation remnant surface which is well expressed in the terrain and landscape features. Terrain formation and its modification occurred during a general uplift of the area since the early Oligocene period which was over 36 million years ago. In contrast to the Canadian prairie lakes where the geology is determined by clay-rich glacial deposits with low water permeability inhibiting groundwater recharge,[18,19] BNNP lakes have originated from tectonic geology[9,17]and are dominated by fractured rocks.

The dominant soil type present in the BNNP area is a chernozem with a medium content of humus on evenly drained landmasses.[20] The main soil forming material consists of medium and heavy loam that lies above tertiary salt-bearing clays.[2] The average humus content is 7–9% and the soil depth is 0.15–0.3 m. In the mountainous areas, there are fragmented products of weathering, such as rubble, quartz rocks, and sand-stones. In the lake and river valley soils, alluvial deposits have been formed. The low water permeability of the loamy soils promotes surface runoff and constrains the groundwater recharge. The granite lowlands in the center of the park are lithosolic in nature and have small soil depth. Forested soils generally consist of sod-podzols underlain by coarsely fragmented weathering products, with pine-dominated areas dominated by brown forest soils.[9] The plain slopes of hilly uplands

TABLE 2 | Morphometric Characteristics of the Lakes of Burabay National Nature Park

Lake	Area (km^2)[1]	Watershed Area (km^2)	Ratio Watershed/ Lake Area	Salinity ($g\ L^{-1}$)[2]	Fluoride Content ($mg\ L^{-1}$)[2]	Max. Depth (m)	Average Depth (m)	Volume (mln. m^3)
Kishi Shabakty	17.0	139[3]	8.2	4.2–4.6	13.1	12.0[4]	6.6[4]	112
Ulken Shabakty	18.7	150[3]	8.0	0.8–0.9	15.5	33.3[3]	11.1[5]	208
Burabay	10.2	164[3]	16.1	0.1–0.2	2.4	5.7[3]	3.4[5]	35
Shortandy	15.1	70[3]	4.6	0.2–0.3	6.2	22.7[6]	11.0[6]	166
Tekekol	1.14	9.7[3]	8.5	0.7–0.8	8.7	7.5[3]	4.8[3]	5.8
Maybalyk	0.53	5.8[2]	10.9	18–27	8.5	(4.0)[2]	—	—

Maximal depth is calculated on base of a bathymetry measured in 1956.
[1] LANDSAT 8 imagery, August 2015.
[2] Ref 13.
[3] Ref 16.
[4] Ref 9.
[5] Ref 10.
[6] Own survey, 2014.

and stone-free denudation flats have undeveloped chernozems. The chernozems of BNNP have a wide range of vertical drainage properties due to their variable depth, high variability in soil structure, and considerable terrain heterogeneity.[8,10]

Vegetation and Landcover

The vegetation types of the BNNP are forest, shrub, steppe, and wetland. The total regional flora that can find an ecological niche in the national park includes more than 800 species of higher plants, with the greatest number of species concentrated in the forests.[8] The tree species in the region comprise pine (65%), birch (31%), aspen (3%), various shrubs (1%), and other species (<0.1%) such as larch, willow tree, poplar, and apple trees. Nearly 85% of the Shortandy lake watershed is mainly covered by pine forests, while almost 90% of the Burabay lake watershed is covered by pine and birch trees.[13]

The majority of forest areas are occupied by Scots pine (*Pinus sylvestris*), as well as mixed birch (*Betula pendula*, *B. pubescens*) and pine. Saucer-shaped plains are covered with birch forests, and sometimes with aspen (*Populus tremula*). In the small river and stream valleys, floodplain birch forests are formed, with an undergrowth of willows (*Salix caprea*, *S. triandra*) and shrubs (*Lonicera tatarica*, *Rosa*). The elevated plains between the forests are classified as steppes; 60–70% of the steppe area is dominated by bunchgrass.[13]

Kremenetski et al.[21] suggested that birch forests started to grow in BNNP from the early Holocene era onwards. Their findings further suggested that pine (*Pinus sylvestris*) entered the region soon after 7000 BP. The present pine forests were then formed around 5200 BP. Since then, the vegetation cover of the region has remained largely unchanged.

In a recent local investigation on tourism impacts on BNNP, Budnikova et al.[10] found that natural landcover of BNNP has only been relatively weakly disturbed during past few decades.

WATER RESOURCES AND HYDROLOGICAL PROCESSES

Brief Overview of Water Balance

The water balance equation for a general lake catchment can be expressed as:

$$P - \Delta R - \Delta G - ET = \Delta S, \quad (1)$$

where P is precipitation, ΔR is surface/streamflow runoff (inflow – outflow), ΔG is change in groundwater storage (recharge – discharge), ET is evapotranspiration (lake evaporation, bare soil evaporation, transpiration, canopy interception loss, and sublimation), and ΔS is change in water storage (lake water and soil water in the catchment).

For terminal basins, two main processes, precipitation (main input) and evapotranspiration (ET, main output), normally determine the natural water balance.[5,22,23] Among BNNP lakes, only Burabay Lake has two continuous tributaries. The other lakes have no permanent surface channel inflows or outflows. As a consequence, all water inflow comes from precipitation either directly or indirectly, as a lateral flow, through shallow groundwater/baseflow. For terminal semi-arid basins, such as BNPP lakes, ET is the single largest component in the water balance.[5,22]

Precipitation: Rainfall, Snow, and Snowmelt

In BNNP, precipitation is the most important component of the hydrological cycle. In the summer season, the prevalence of latitudinal circulation allows the transfer of moist air from the west, and creates more favorable conditions for the formation of cyclones.[8] As a result of the intensification of cyclonic activity, the amount of precipitation increases sharply, compared to winter. The unique forest ecosystems of BNNP are generally considered to have formed due to a relief 'perched' above surrounding steppes allowing interception of atmospheric moisture, thereby creating higher precipitation conditions.[12,13] The park authorities report the greatest amount of precipitation (averages around 400 mm year^{-1}) falling in the western part of BNNP, on the slopes of Kokshetau Mountain, and the smallest amount (annual mean of 280 mm) to the east of the upland.[8] On the plain, rainfall decreases from north to south due to the prevalence of winds blowing from the southwest direction.[9] Taking into account the dominant wind direction, the Kokshetau ridge circling Shortandy and Burabay Lakes (Figure 2) creates a modest 'rain shadow' over Shortandy, Ulken, and Kishi Shabakty Lakes. Most of the precipitation falls in the summer season (Figure 3(a)) from June to August (40–50% of the annual amount). The annual mean precipitation varies considerably [particularly wet years were 1938 and 1960 with values up to 607 mm; dry years (e.g., 1936, 1951, 1988, 1991, 1995, 1997, 2003, and 2010) had values as low as 181 mm]. The precipitation time series does not show a significant trend (Figure 4(a)), although the occurrence of dry years appears more prevalent in the last three decades. Numaguti,[24] based on simulations by an atmospheric general circulation model and tracer data experiments, concluded that most of the summer precipitation in the northern inlands of Eurasia comes from recycling of continental evaporation, reporting that about half of all precipitation in the Central Asia region comes from the North Atlantic Ocean. Recent research of Miralles et al.,[25] who used novel satellite observations and modeling, emphasizes the importance of local evaporation for the supply of rainfall in semi-arid ecoregions where recycling ratios can reach up to 40%.

In BNNP, the extensive winters (up to 6 months in duration) are associated with the process of snowfall, snow accumulation, and subsequent snowmelt in late spring. Winters are characterized by reduced amounts of solar radiation, not only because of the reduced solar altitude but also as a result of dense clouds (55–65% cloud cover) and misty weather conditions.[9] Winter snow accumulation varies among the various landscapes of the park. In contrast to the summer months, precipitation during winter in Northern Eurasia directly originates from evaporation from the oceans.[24] The major part of this precipitation (about 80%) for Central Asia is supplied by moisture from North Atlantic Ocean and Mediterranean Sea.[24]

As temperature decreases in September and October (Figure 3(b)), precipitation mostly falls in the form of snow. Around mid-October, after the first snowfall, the thick snowpack takes 2–3 weeks to develop and a steady snowpack is generally formed by mid-November. Average amounts of snow during the winter season (from mid-December until the beginning of April), expressed in snow water equivalent (SWE), are 50–60 mm across the territory.[2,9]

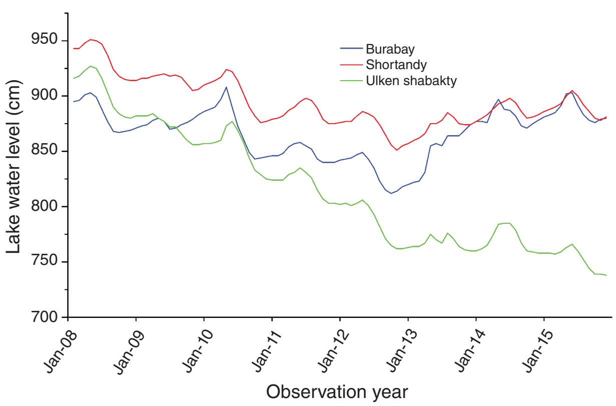

FIGURE 5 | Lake water levels 2008–2015: Shortandy Lake (brown), Burabay Lake (blue), Ulken Shabakty (green).[16] Zero datum level (msl, Baltic reference): Shortandy Lake—380.04 m; Burbabay Lake—311.23 m; Ulken Shabakty—289.5 m.

Evapotranspiration

Jung et al.[26] found modeled ET values for the cold semi-arid steppe of NCA to be around 350 mm year^{-1}. Perez-Quezada et al.[27] provided estimates of 330–360 mm for ET of the grassland steppes, for the growing period from May to October. In a recent review on the role of transpiration (T) in the global hydrological cycle, Schlesinger et al.[28] estimated T to comprise 51 ± 15% of total ET for the semi-arid ecosystems thus implying the lesser role of vegetation, in its contribution to ET, in these regions comparative to tropics. BNNP represents a diverse range of landscapes and vegetation types such as steppe, mountain pine, and pine-birch forests as well as steppe and forest lakes, which all have different ET rates. Unfortunately, there are no historical ET data available, and we are not aware of any on-going direct measurements of ET [e.g., using the eddy covariance (EC) method][29] in BNNP. However, the steady decline of long term (Figure 1) and in particular recent (between 2008 and 2012; Figure 5) BNNP lake levels are an indirect measure of increased ET rates,[16] emphasizing the need for long-term *in situ* or remote-sensing based monitoring of this important water balance component. It is interesting to note that according to observations[16] the open-water period duration of BNNP lakes has not significantly changed over the past 30 years, so there is no lengthening of the evaporation season as reported for lakes in North America.[30–32] The open-water period starts at the end of April and beginning of May, and permanent ice-cover is established around late October and beginning of November.[16] The local hydrometeorological agency provided estimates[16] of monthly open-water evaporation rates for BNNP lakes using a simple empirical model calibrated by submerged pan evaporation measurements developed by Soviet hydrologists in 1955[1] (Table 3). This model is based on monthly air temperature data and gives annual open-water evaporation totals in the range of 700–740 mm during the past 30 years.[16] It assumes that evaporation rates change linearly with changes in air temperatures (Figure 4(b)). However, calculation of open-water evaporation is not straightforward as demonstrated by Granger and Hedstrom,[33] who investigated and modeled hourly lake evaporation rates from small Canadian lakes and concluded that for periods shorter than one day, wind speed, land–water temperature, and vapor pressure contrasts are most significant drivers. The reported annual lake evaporation for similar closed-basin lakes in North America with the same climatic conditions ranges between 600 and 900 mm.[34,35]

TABLE 3 | Water Balance Components of Major Lakes of Burabay National Nature Park during 2011–2013

Lake	Precipitation[1] (mm)	Open-Water Evaporation[2] (mm)	Watershed Inflow and Groundwater Discharge[3] (mm)	Anthropogenic Water Consumption[4] (mm)	Change in Storage in Lake[5] (mm)
Burabay	300	730	450	50	−30
Ulken Shabakty	295	740	350	30	−125
Shortandy	290	720	280	70	−220

The monthly open-water evaporation was calculated using the following equation: $E = 8.28 \times T_a + 11.3$, where T_a is mean monthly air temperature in °C and E is open-water evaporation in mm month^{-1}.
[1] Direct precipitation over the lake surface.
[2] Open-water evaporation during ice-free period.
[3] Lumped estimated discharge from watershed and groundwater.
[4] Total human water consumption from surface and groundwater sources.
[5] Calculated as a difference between water balance components (data source: Ref 16).

Gronewold et al.[32] in their synthesis on the hydrological status of the North American Great Lakes, asserted that a continual increase in lake evaporation over the past 50 years is related to a long-term change in climate which has led to the decrease in permanent water levels in the world's largest lake system, especially during the last decades. Shikano et al.[23] estimated total evaporation for Chany, a shallow endorheic lake in Southwest Siberia close to BNNP area, to amount to 714 mm (1994–1999). Two recent studies focused on North Eurasia's ET[36,37]; based on ecosystem and remote sensing modeling efforts they found open-water evaporation estimates (using the Penman model) about 800 mm year^{-1}, with around 300 mm year^{-1} terrestrial ET (growing season) for the southern part of the region. These literature values fit well with the values reported for BNNP.

Surface Water and Runoff

The water resources of the BNNP are characterized by numerous lakes and a poorly developed river network. There are 22 lakes in the park: 14 of which have a surface area larger than 1 km^2.[8,13] The biggest lakes are Ulken and Kishi Shabakty, Shortandy, and Burabay while the smaller lakes are Tekekol and hypersaline Maybalyk (Figure 2 and Table 2). The overview of the main lake watersheds is shown in Figure 2, and the morphometric and some water quality characteristics are summarized in Table 2. Burabay and Shortandy Lakes, located inside of Kokshetau arched ridge, are typical forest fresh water lakes; Ulken and Kishi Shabakty, Tekekol, and Maybalyk, located outside of the mountain range, are more characteristic of steppe lakes with various degrees of salinity (Figure 5, Table 2). It is suggested that the high salinity of Maybalyk is caused by brine groundwater discharge to the lake.[9,13]

BNNP lakes were formed by young tectonic faults and are classified as mountain lakes. Judging by the forms of the relief and the location of ancient lake terraces, it could be claimed that the Kishi and Ulken Shabakty, Tekekol, and Maybalyk lakes were formed from one big lake on the northern side of Kokshetau Ridge.[9] However, based on the differences in gyttja (peat based mud) between the adjacent Maybalyk and Ulken Shabakty lakes, any former connections between the lakes has been refuted by Korde.[12]

By using paleomorphometric analysis, it has been possible to reconstruct the hypsometric position of BNNP[38] terraces and thus to recover the maximum water levels of these lakes. It was found that the levels of the lakes were higher at the quaternary period, as the height of the fragments of terraces exceeds the present floodplain rivers by 5–7 m.[10,17]

According to Kazhydromet,[13] the recharge of these lakes is the result of snowmelt water (25–30%), the surface flow of temporary streams (60%) and groundwater (up to 15%). The river network density of the area is very low, and streams appear only during the snowmelt season. In recent years, there has been a steady drop in the lake water level (Figure 5), averaging 15–20 cm year^{-1} due to a decrease in the inflow of snowmelt, associated with an accumulation of runoff water because of artificial damming (road construction, ponding due to human influence, etc.), the enhanced role of evaporation, and an increase of water being pumped from groundwater stores due to the growing number of recreational facilities.[13,16,17] The watershed draining area of the largest lakes with the highest historical water level decline (Shortandy and Ulken Shabakty) is not sufficient to sustain high levels. The smaller long-term decrease of Lake Kishi Shabakty water levels compared to the decline in Ulken Shabakty levels can be attributed to its relatively big drainage area and higher salinity (see

Table 2). Lake levels stabilize (Ulken Shabakty Lake) or start to increase again from 2013 onwards (the other two lakes), most likely as a result of increased precipitation (Figure 5).

Groundwater and Subsurface Flow

The hydrogeology of BNNP is very complex due to its high diversity in geology, diverse types of relief, and land cover. The regional and local groundwater flows are dominated by fractured zones of Paleozoic and Archean rocks and to a lesser degree by quaternary alluvial deposits and weathering crusts.[9] Within the lake catchments, in the absence of impervious materials, all aquifers are connected into one hydraulic system controlled by a common surface level and accumulation conditions.[13]

The main source of groundwater recharge is atmospheric precipitation. However, though most precipitation falls during summer, the groundwater is mainly recharged by spring snowmelt infiltration as a result of the very thin unsaturated zone and the prevalence of fractured areas.[13] The quaternary alluvium deposits are not very developed and exist only in the valleys of old stream beds in the southern and eastern parts of BNNP, such as Kylshakty and Sarybulak rivers, and they play a minor role in subsurface flow.[13] Due to the primary recharge of groundwater by snowfall accumulated during the winter–early spring period, water is usually fresh especially in areas controlled by fractured rocks.[39] Snowmelt recharge of groundwater and lakes in BNNP is still very poorly understood and can be identified as one of the biggest knowledge gaps requiring the application of modern approaches such as, e.g., use of stable water isotopes and numerical modeling.[40]

The lake beds and local groundwater have very good connectivity owing to the high permeability of the fractured zone. The low mineral content of water (200–300 mg L^{-1}) in Burabay and Shortandy lakes illustrates the high inflow of ultra-fresh snowmelt via groundwater discharge. The growing fluoride concentration in all BNNP lakes (ranging from 2 to 15 mg L^{-1})[16] indicates the evaporative enrichment of this highly mobile ion that is leached from the groundwater (Table 2). The granites of the fracture zone have fluorites and tourmaline inclusions which constantly contribute fluoride ions.[10,17] The shallow groundwater provides water for the pine forests' transpiration especially during the dry summers.[13] Further investigation is required to understand the lateral interactions between lakes and shallow groundwater as well as the role of forest transpiration in these links in BNNP.

Summary of Water Balance for BNNP Lakes

In 2012, the Government of the Republic of Kazakhstan requested the local state hydrometeorological monitoring agency (Kazhydromet) to estimate the state of the water resources of the BNNP lakes.[16] The estimated annual water balance broken down in its main components for three important BNNP lakes is presented in Table 3 (reference period 2011–2013). Although the strongest long-term decline in water level has been observed in Shortandy Lake (Figure 1 and Table 1), the biggest level drop in recent years is evident for Ulken Shabakty Lake (Figure 5). The Kazhydromet report[16] emphasized the stability of precipitation inputs into the lakes as well as the increasing role of open-water evaporation, with anthropogenic consumption playing a minor role only in the overall water budget. The main cause of lake level decline is proposed to be a steady rise of open-water evaporation rate due to rising mean air temperatures (Figure 4(b)) resulting in a growing atmospheric demand for water.

HYDROLOGICAL RESPONSES TO ANTHROPOGENIC DISTURBANCE AND CLIMATE CHANGE

Climate Change

Future climate change projections in the region show an increase of mean annual air temperature from 1°C to over 7°C depending on emission scenarios, compared to 1986–2005 reference time period.[41] At the same time, winter precipitation is predicted to increase moderately by about 10%. Precipitation in other seasons is projected to remain approximately the same. Evaporation is estimated to increase by 0.2 mm day^{-1} in all scenarios, which means that the soil moisture deficit will increase.[41]

Changes in the onset, end, and length of the vegetation growing season in BNNP will have an unknown effect on the various ecosystems in the park. On the one hand, longer growing seasons and warmer springs may strengthen the forest C sink. On the other hand, disturbances (such as fire) may increase the amount of open land relative to forests.

The evident increase in air temperature in the region (Figure 4(b)), especially in winter, spring, and autumn periods, is already having its impact by increasing evaporation and changing freeze–thaw cycles. One of the notable impacts is the change in snow precipitation with more precipitation coming as rain.[13] BNNP is a cold semi-arid hydroclimatological region where snow, though comprising only about 25% of annual precipitation, provides a significant addition of water for the soil, groundwater, and lakes. The increase in the relative contribution of liquid precipitation compared to solid precipitation will most probably decrease the net precipitation ($P - E$) inputs. There are many uncertainties connected with the total precipitation rate, as the current ground observations do not show a significant trend (Figure 4(a)).

The decline in surface winds speeds observed in Northern Hemisphere and worldwide[42,43] over the past few decades, attributed to increased surface roughness,[42] climate change, and anthropogenic activities,[43] is considered to be a major cause for the decrease in globally observed pan evaporation rates.[44] Kazakhstan is a country with the highest annual negative wind speed trends estimated to reach -0.03 ms^{-1} year^{-1}.[43] Nevertheless Brutsaert and Parlange[45] demonstrated that decreasing pan evaporation in water-limited environments can be a good indicator of increasing terrestrial evaporation caused by intensification of hydrological cycle. This conclusion was experimentally corroborated for the former USSR and the United States by comparing data for pan and actual evaporation rates.[46] Moreover, the most recent studies[26,47,48] on global terrestrial evaporation though emphasizing the high uncertainty of this component of global water and energy budget agree that land ET has a small positive trend over the past few decades.

BNNP watersheds are imbedded into the larger Esil-Tobyl river basin that drains into the Irtysh River. The drainage area of BNNP became completely isolated about 100 years ago when Shortandy lake level dropped below the threshold that allowed drainage to the Kylshakty River.[12,39] The endorheism of these basins makes them a unique proxy for climate change,[5] serving as an illustration of what may happen to neighboring areas, such as for example Siberian boreal coniferous forests .

Large hydrological research studies conducted in USSR times[2] for Virgin lands (*Tselina*) development purposes already reported the drying trends of local lakes due to higher evaporation loss. In the two most recent decades, the water levels dramatically decreased, especially those of lakes Shortandy and Ulken Shabakty (Figure 5).

Furthermore, due to water scarcity in the territory of BNNP, climate change will pose an impact on vegetation, particularly on the forests. Such disturbances in forests include fire, drought, insect outbreaks, and urban encroachment. Climate change directly and indirectly affects the growth and productivity of forests in BNNP: directly due to changes in atmospheric carbon dioxide and local climate regime and indirectly through complex interactions in forest ecosystems, also involving the hydrological cycle. The role of forests in the park is to accumulate snowfall, and to store and recycle the moisture. However, during the dry season, groundwater levels can decline as a result of water extracted for transpiration. Climate change impacts on forest productivity and tree growth are already being documented across the boreal forests of North America, and are interpreted as signals of increasing drought stress.[49] Overall, each disturbance influences the forest communities differently. However, they all impact the way forests accumulate moisture and store carbon. In water-limited regions, changes in temperature can significantly alter seasonal water amounts that will in turn influence vegetation distribution patterns and photosynthetic activity.

Climate change will not only affect forest growth and productivity. It will also increase the length of the growing season. However, warming could also shift the geographic ranges of some tree species, simultaneously changing the habitat of some animal species. BNNP lies on the southern extent of Scots Pine (*Pinus Sylvestris*) determined by high temperature and low precipitation,[21] so rising air temperatures threaten to destroy the ecosystem forming tree species in coming decades. Increased temperatures would alter the timing of the snowmelt, affecting the seasonal availability of water. Although many trees are resilient to some degree to drought, increases in temperature could make future droughts more damaging than those experienced in the past. In addition, drought increases the risk of fire since dry trees and shrubs provide fuel for fires.

Human Disturbance

Historically, the water supply for human needs for Shuchinsk town (population of 50,000)[10] and the settlement of Burabay (population of 5000)[10] both indicated in Figure 2, came from nearby lakes and groundwater sources. Budnikova et al.(2010)[10] reported that for the period of 2006–2010 around 500,000 tourists visited BNNP annually, and their number is growing. Due to the declining lake water levels, the direct anthropogenic water abstraction from lakes was cut to almost zero by local authorities in 2008. Water was supplied to the communities by constructing a water pipeline from a reservoir located about 200 km away from BNNP.[10] However, this measure did not stop the continued decrease in lake water levels, especially for Lake Shortandy, where the biggest human settlement is situated. While direct water abstraction from lakes has been prohibited the pumping from groundwater continues especially in the areas without a centralized water supply, usually located close to the lakes.[16] These groundwater withdrawals though quite small are poorly regulated and may disturb lateral interactions with the lakes.[9]

Based on available land-use information,[10,11,50] we cannot explain the dramatic decline in lake water levels neither through a change in forest area nor by a change in surface water area. Maybe the answer to the recent decline in lake water levels can be found by looking into qualitative land-use data. A clear example is the watershed of Lake Ulken Shabakty (Figure 2) where the main portion of the forest draining area is disconnected by the development of the Burabay settlement and related asphalt road construction. Through this activity, the actual catchment has been considerably reduced. Another example is that of Lake Kishi Shabakty where by recommendations of Soviet hydrologists,[2] narrows in the North-East direction were dammed to conserve the water for agricultural purposes. In recent decades, the small ponds that developed as a result of these developments are evaporation reservoirs with no obvious use to local communities. The dense patterns of roads and paths, resorts, and villa construction sites on the lake shores have created barriers for surface and subsurface water drainage to the lakes. During the design phase of these construction projects, no water passages or bypasses were planned for. The culverts under roads exists only in the places where permanent running streams cross the roads and development sites.

Further research on landcover and land-use dynamics is needed to improve our understanding of impact of human activities on ecohydrology in BNNP both presently and historically.

CONCLUSION

One of the greatest problems of the BNNP is the decline water levels of its main lakes. All of the largest lakes in BNNP, apart from Lake Burabay, are drying out. The obvious explanation is that lake evaporation is higher than the input of water from the atmosphere directly by precipitation and through catchment basin stream runoff, and lateral groundwater flow. However, relatively little research on lake evaporation and catchment evapotranspiration has been conducted in BNNP, as the methods used for hydrological monitoring are still the same as 30 years ago. The anthropogenic influences such as impacts of groundwater pumping, construction, and other human induced land-use changes must be assessed in detail. Moreover, there is an urgent need for reliable water accounting.

It is interesting to note that the recent stabilization, and even increase of BNNP levels from 2012 onwards (Figure 5) coincides with the fastest observed rise of Lake Superior and Lake Michigan-Huron (the Great Lakes, North America) water levels in 2013–2014 after 15 years of below-average conditions.[51] Since 2013, the water levels of Burabay and Shortandy Lakes have been steadily increasing while Ulken Shabakty water levels remained approximately stable (Figure 5). There are similar trends between long-term water level changes in endorheic lakes of Canadian praries[34] and BNNP lakes. The higher lake levels a century ago in both regions are attributed to wetter conditions.[19,34] We could identify a similar lake level fluctuation evolution for Redberry Lake in Saskatchewan, Canada and Ulken Shabakty in BNNP located at the same latitude.[9,34] van der Kamp et al.[34] reported a 9-m decline for Redberry lake between 1918 and 1986,while Kazhydromet estimated the drop of Ulken Shabakty' water level to be more than 10 m since the middle of last century to 2000.[9] The decline in Canadian prairie lakes levels is associated with land-use changes leading to a decrease in runoff to the lakes, and an increase in evaporation, as a result of rising air temperatures especially in the spring-time period.[34]

Although we have data on monthly average precipitation levels over the past 70 years, we have limited knowledge of the spatial and temporal distributions of precipitation, and how these would change under climate change. The hydrometeorological observations conducted by Kazhydromet are generally based on old technologies, with an emphasis on manual collection and without implementation of modeling tools. To improve our understanding of the hydrological cycle in BNNP, modernization of monitoring methods is required. One example of such a tool is the EC method, which has led to significant scientific advances, making it a primary *in situ* technique for energy (including latent heat flux, i.e., evapotranspiration) and CO_2 flux measurements.[29]

Recent research[52] suggests that drylands, occupying almost half of the terrestrial biosphere, and semi-arid ecosystems in particular, will play an increasingly important role in the carbon cycle which has strong interdependencies with hydrological conditions.

Hydrologic connectivity between the lakes and local groundwater in BNNP is another area in need of investigation. Currently, the surface water resources and meteorology monitoring are conducted by KazHydromet, while groundwater research is conducted by the Geology and Subsurface Resources Committee. This has led to surface and groundwater resources and needs being considered separately from each other. A modern approach, using integrated water resources monitoring and management, is needed without delay. The emerging interdisciplinary field of Critical Zone Science,[53,54] that considers the complex interaction of processes occurring between the top of the vegetation and the base of groundwater offers promising methods and approaches to ask and answer the right questions in the context of the BNNP hydrological cycle.

Once improved *in situ* monitoring is implemented, these data sources can be combined with satellite observation data and integrated with models, such as hydrological or climate models that have land surface models embedded within them.[55] This will improve our understanding of key aspects of the water balance which are often intricately linked to the energy and carbon balance. Long-term measurements accumulated by EC flux towers will allow for development and validation of regional and global models that are underpinned by remote sensing. Such research developments are essential if we want to protect the unique landscape of BNNP and the ecosystem services it provides.

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