Investigation of the conditions for the formation of moisture deficiency in Northern Kazakhstan using the method of hydrological and climatic calculations

Aisulu Kusainova[1*], *Olga* Mezentseva[2], and *Zhanbolat* Tusupbekov[3]

[1]Abylkas Saginov Karaganda technical University, 56, Nursultan Nazarbayev Avenue, Karaganda, 100027, Kazakhstan
[2]Omsk state pedagogical University, 14, Tukhachevsky quay, Omsk, 644099, Russia
[3]P. A. Stolypin Omsk state agrarian University, 1, Institutskaya square, Omsk, 644008, Russia

Abstract. The article investigated the conditions for the formation of moisture deficiency in the forest-steppe and steppe zones of northern Kazakhstan. The growth of moisture deficiencies affects the yield of grain crops. The work used statistical, cartographic, analytical, and analogy methods. The hydrological and climatic calculation method developed by V.S. Mezentsev and tested in Western Siberia and adjacent territories of Kazakhstan was used as the main method for obtaining the calculated heat and water balance characteristics of the studied territory. Meteorological data obtained at meteorological stations in agricultural areas was used as initial data. Using the regression equation, the dependence of cereal crop yield on humidification in the Akmola region and the estimated yield schedule for 2024 were built. On the territory of Northern Kazakhstan, quite close dependencies between the yield and the degree of humidification have been identified. The yield of grain crops in the Akmola region was influenced by a lack of moisture for 54%. In general, during the warm period of the average year, the soil moisture resources of the studied area are not able to provide favorable conditions for the appropriate growth and development of crops.

1 Introduction

Moisture deficiency is used as an absolute complex indicator characterizing the conditions of natural moisture (precipitation minus evaporation), affecting the moisture content in the soil on a regional scale and, as a result, affecting the yield of grain crops during a short time interval, for example, during the growing season. Moisture deficits were studied using indices that consider the phenomenon as a result of lack of precipitation and deficiency of soil moisture, as well as using indicators that take into account the components of the water balance: moisture transfer in the soil, soil moisture, and its deviations from the norm.

* Corresponding author: aimarh@mail.ru

https://doi.org/10.1051/e3sconf/202452403015

Moisture deficiency is characterized as a result of the interaction of natural processes, causing a decrease in moisture content below the normative value due to the space-time variability of climate characteristics and water demand for geosystem life. Moisture deficiency can be observed in various natural zones at any amount of precipitation in them, depending on heat resources. In areas with low rainfall and high evaporation, long-term moisture deficits become one of the factors in their aridization, which, in turn, leads to climate desiccation, desertification, and land degradation [1].

Since the increase in moisture deficiency due to its impact on crop productivity is associated with the problem of the country's food security, research in this direction has continued for many years by different scientists.

The republic has a well-developed agro-industrial complex that generally specializes in the production of grain and products for pasturable livestock. The majority of grain farms in the republic are located in a northern part where the main acreage of crops is concentrated.

2 Materials and methods

In order to assess the quantitative parameters of heat and moisture supply in the territory, various methods have been proposed by scientists to date. The works of V.S. Mezentsev, I.V. Karnatsevich, O.V. Mezentseva [2], G.V. Belonenko, and Zh.A. Tusupbekova [3] studied in detail the heat and moisture supply of Western Siberia and adjacent territories [4].

M.I. Budyko and A.A. Grigoriev substantiated the classification of climatic zones on the ratio of heat and moisture, determined by the ratio of the annual radiation balance of the underlying surface to the amount of heat required to evaporate the annual amount of precipitation. They called this annual humidification indicator the radiation dryness index. However, the above characteristics and the zoning of the territory carried out with their application according to the conditions of natural heat and water supply cannot be considered perfect [5].

The method of hydraulic and climatic calculations (HCC), developed in 1957 by V.S. Mezentsev, is today the most physically justified since it assumes the determination of the humidification coefficient and other characteristics of heat and moisture supply according to ordinary meteorological data, taking into account amendments to the underestimation of precipitation measuring devices for periods of different duration as well as differences in providing precipitation in intervals within a particular year and between years.

This work proposes solving problems in relation to the territory of Northern Kazakhstan on the basis of studying natural heat and water supply. The work used statistical, cartographic, analytical, and analogy methods widely used in modern geoecology. The method of hydrological-climatic calculations developed by V.S. Mezentsev and tested in Western Siberia and adjacent territories of Kazakhstan [6] was used as the main method for obtaining the calculated heat-balance characteristics of the study area.

The object of research is the forest-steppe and steppe zones of Northern Kazakhstan

Geomorphologically, the surface of the studied area is represented by the Kazakh shallow hills passing in its northern part into the West Siberian plain. A feature of the natural-territorial complex is the zonal distribution of landscapes in the form of latitudinal geographical zones: forest-steppe (southern and stake forest-steppe) and steppe.

To determine the dependence of the yield of crops grown in the territory of Northern Kazakhstan on fluctuations in climatic conditions, over the past decades, the materials of observations at several meteorological stations have been used. Observation points were selected taking into account the coverage of terrain-specific features of the areas of the study area and, if they correspond to the locations of grain farms. For the estimated period, the period 1999–2020 was adopted.

As initial data, the indicators of the average monthly air temperature and the average monthly values of atmospheric precipitation for the warm period of the year, from April to August [7] were used. To determine the influence of meteorological characteristics on the yield of grain crops, the moisture coefficients of the territory were determined.

The degree of influence of climatic fluctuations over a long period on the productivity of crops in the landscape zones of Northern Kazakhstan was determined by establishing correlations between these indicators. The results of the research can be used for further planning of measures to increase crop yields.

3 Results and Discussion

According to the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, the largest sown areas of grain crops are concentrated in four regions of Kazakhstan: Akmola, Kostanay, North Kazakhstan, and Pavlodar. In 2021, these regions will account for 70%, or 16.2 million hectares, of the total sown area (22.9 million hectares) of the republic [8].

This distribution of acreage determines the main direction of the socio-economic policy of the northern part of the Republic of Kazakhstan, which consists of the development of the agro-industrial complex and agriculture. The conduct of economic activity with a predominant grain direction, to a greater extent, depends on natural and climatic factors [9, 10].

The territory of Northern Kazakhstan, in terms of geographical location, is located in a zone of insufficient soil moisture. This factor is the reason for the slowdown of biological processes occurring in plant communities, as a result of which the conditions for self-restoration of geosystems are difficult. Natural complexes that develop under such "flawed" conditions have low external resistance potential and are susceptible to degradation.

The climatic conditions of Northern Kazakhstan are characterized by continental, cold, and long winters and hot summers. About 10–15% of the thermal energy is spent on heating meltwater and melting snow, ice, and soil permafrost. The territory is poorly provided with atmospheric precipitation. The largest amount of annual precipitation of 350–400 mm/year is observed in the northern part, decreasing to the south. Low rainfall with sufficient heat supply is a determining factor in risky farming and aridization. Under such conditions, the assessment of heat and water supply conditions is the basis for planning water reclamation development and the rational use of water and land resources in the region.

The amount of moisture reserves in soils has a significant effect on the runoff and evaporation modes. The largest reserves of soil moisture are confined to the forest-steppe zone, the smallest to semi-desert areas. In the intra-annual context, the lowest values of soil moisture are observed in August–September, when in the northern part of the territory the relative humidity in the proportions of the lowest moisture capacity drops to 0.6, in the central to 0.4, and in the southern to 0.2. In September, due to a decrease in heat and energy resources, the drying capacity of the air decreases, and the humidity of the soil cover increases slightly.

In general, over the summer period, the soil moisture resources of the territory are not able to provide favorable conditions for the normal growth and development of crops. At the beginning of summer, soil moisture everywhere in Kazakhstan is at a level below the moisture of the capillary rupture, and in semi-desert areas, below the moisture content. Thus, in the territory of Northern Kazakhstan, in order to achieve optimal conditions of heat and moisture supply and the highest possible productivity of crops, there is a need to artificially increase the moisture content of soils [11-12].

Due to the different provision of humidification conditions, the grain yield index has a large scope; for example, in wet 2011, in the North Kazakhstan and Kostanay regions, the grain yield reached 20.4 and 18.4 c/ha, respectively. In dry years, in some regions there was a low yield of cultivated grain crops, in particular in 2010 in Akmola region (5.2 c/ha) and in 2008 and 2012 in Pavlodar region (3.5 and 3.7 c/ha, respectively).

The assessment of the average yield of grain crops for 1999–2020 showed that the best productivity of grain crops has been achieved in the North Kazakhstan region (13.5 c/ha).

Regression analysis showed that the tightness of the effect of moisture deficiency on yield (multiple correlation coefficient R) is greatest in the Akmola region (Yesil), and in the Pavlodar, Kostanay, and North Kazakhstan regions, the effect of moisture deficiency is less (Table 1). Based on the results, we can conclude that from 10 to 54% of the variability in yield in the territory of Northern Kazakhstan occurs under the influence of moisture deficiency.

The amount of yield depends directly on the moisture content of the territory. As a moisture supply, consider the effect of the wetting factor on the yield of grain crops. In the works of V.S. Mezentsev [2], the structure of the relationships between heat and moisture resources is determined by the level of humidification (natural or anthropogenic); therefore, the indicator of humidification of the territory over any annual period of time is the ratio of atmospheric precipitation (corrected for the underestimation of measuring devices) to the water equivalent of heat and energy evaporation resources.

Table 1. Regression statistics to estimate crop yield (c/ha) versus humidity deficiency.

Meteorological station	R	R^2	Normalized R-square	Standard error	The regression equation
Pavlodar (Pavlodar region)	0.56	0.31	0.28	2.37	$U = 18.2 + 0.02_{\Delta}KX$
Ruzaevka (on the border with Kostanay region)	0.50	0.25	0.21	2.45	$U = 18.5 + 0.02_{\Delta}KX$
Blagoveshchenka (North Kazakhstan region)	0.32	0.10	0.06	2.63	$U = 18.1 + 0.01_{\Delta}KX$
Yesil (Akmola region)	0.74	0.54	0.52	1.63	$U = 22.2 + 0.03_{\Delta}KX$

Note: R − multiple correlation coefficient; R^2 − variance factor (variability); ${}_{\Delta}KX$ – value of moisture deficiency of growing season (V-VIII months).

According to the method of hydrological-climatic calculations by V.S. Mezentsev, in the event of an inequality of atmospheric humidification with an optimal value equal to the water equivalent of heat and energy evaporation resources, their difference expresses the amount of moisture deficits (or excesses) [1]. Thus, the moisture deficiency index of the territory *(ΔKX)* can be obtained as a difference between the amount of atmospheric precipitation *(KX)* and the water equivalent of heat and energy resources *(Zm)*.

As a result of calculations using the method of hydrological-climatic calculations, humidification coefficients and humidification deficiency values in the territory of Northern Kazakhstan for the growing season (May–August) for 1999–2020 were calculated using the sum of air temperatures above 0 °C and the sum of precipitation corrected for the underestimation of measuring instruments of the characteristic meteorological station Yesil (Akmola region). The results were compared with the yield of grain crops (Figures. 1-4).

As you can see from the graph in Figure 1, in years with a high moisture deficiency in the growing season, a low yield is observed, and in years with a low moisture deficiency, an increase in yield indicators is noticeable.

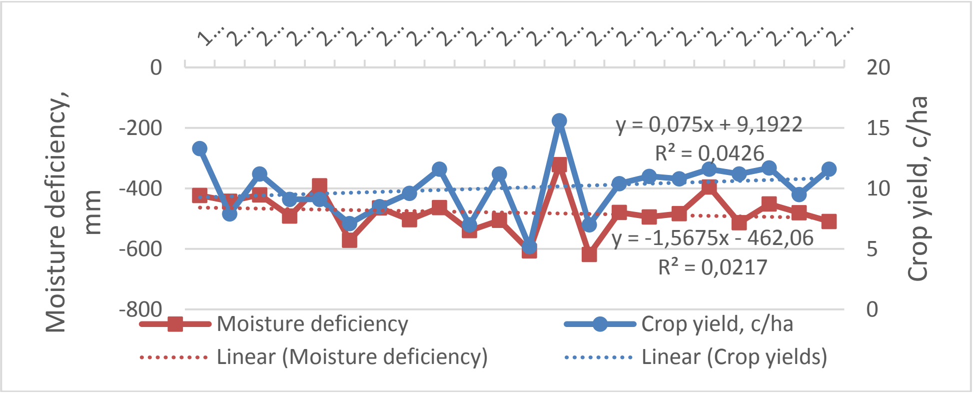

Fig. 1. Comparison of grain crop yields in the Akmola region with a moisture deficit for the growing season (May–August) for 1999–2020.

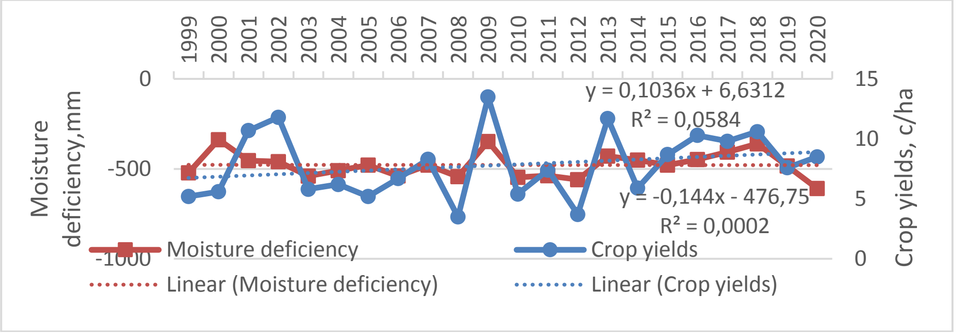

Fig. 2. Comparison of grain crop yields in the Pavlodar region with a moisture deficit for the growing season (May–August) for 1999–2020.

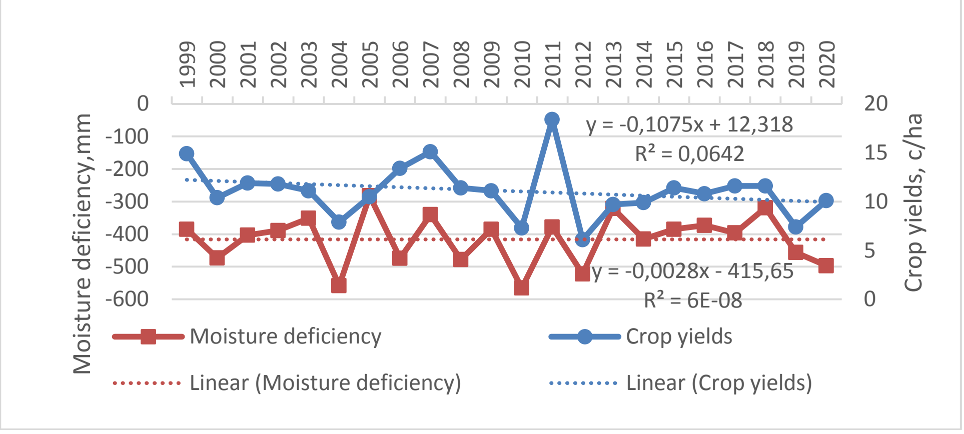

Fig. 3. Comparison of grain crop yields in the Kostanay region with a moisture deficit for the growing season (May–August) for 1999–2020.

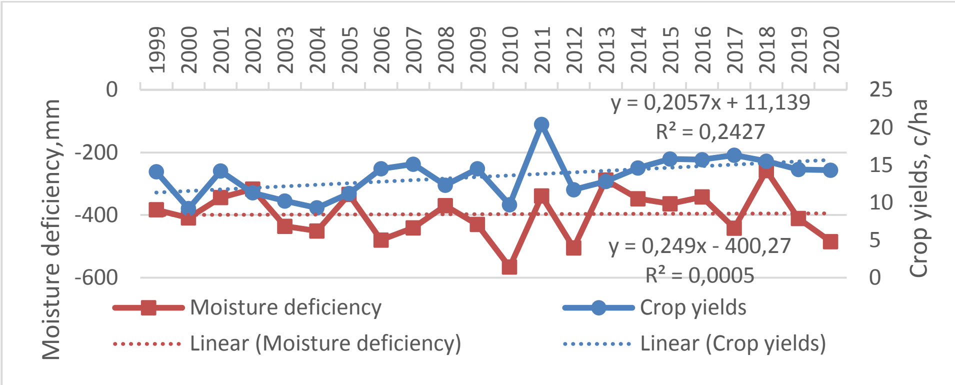

Fig. 4. Comparison of grain crop yields in the North Kazakhstan region with a moisture deficit for the growing season (May–August) for 1999–2020.

Since regression analysis has shown the closest relationship between grain yields and moisture deficiency in the Akmola region (Yesil weather station), the influence of another parameter of natural heat and moisture supply for this territory should also be considered: the moisture coefficient ($\beta_{\kappa x}$), in combination with moisture deficiency ($_{\Delta}KX$), using a multifactorial correlation regression analysis (Table 2).The multiple correlation coefficient ($R = 0.77$) shows the high tightness of the association of yield with two explanatory factors included in the model: the humidification coefficient and the humidification deficiency of the growing season. The significance of the regression equation was evaluated based on the results of the regression statistics based on the calculation of the Fisher's F-test, which is 12.8. The regression equation was tested by the F-criterion with a confidence probability of 0.95 (with v1 = k-1 = 1 and v2 = n-k-1 = 18; F = 12.8 > Fcr = 4.41) and is significant. At the 5% level of significance, the calculated values of Student's t-statistics of parameters turned out to be more than the table value of Student's t-statistics; therefore, the regression coefficients are considered significant.

Table 2. Regression statistics to estimate the yield of (c/ha) depending on the parameters of heat and moisture supply.

Meteorological station	R	R^2	Normalized R-square	Standard error	The regression equation
Yesil (Akmola region)	0.77	0.59	0.54	1.60	$U = 27.76 - 6.48\beta_x + 0.03_{\Delta}KX$

Based on the regression equations of the dependence of the yield of grain crops in the Akmola region on the parameters of natural heat and moisture supply, yield indicators were calculated (Table 3). The correlation coefficient (R = 0.77) of the calculated and actual yield values for 1999–2020 is significant.

When analyzing the graph, you can notice some inconsistencies in the relationship between these indicators, which are due to possible errors in the series of observations and the limited amount of meteorological data in these dependencies. In general, the correlation coefficient of these relationships was R = 0.74. Statistics confirm that these dependencies are related; that is, 54% of the impact on the yield of the Akmola region in the area of the Yesil meteorological station was caused by a moisture deficit, and other factors account for 45%.

Table 3. Comparison of actual and calculated yields in the Akmola region.

Years	**Actual crop yield (y),(c/ha)**	**Estimated crop yield y(x), c/ha)**	**Discrepancy y-y(x), (c/ha)**	**Years**	**Actual crop yield (y), (c/ha)**	**Estimated crop yield y(x), c/ha)**	**Discrepancy y-y(x), (c/ha)**
1999	13.3	12.9	0.4	2010	5.2	8.9	-3.7
2000	7.9	12.7	-4.8	2011	15.6	15	0.6
2001	11.2	13.1	-1.9	2012	7	8.3	-1.3
2002	9.1	11.9	-2.8	2013	10.4	11.8	-1.4
2003	9.1	13.6	-4.5	2014	11	11.6	-0.6
2004	7.1	9.7	-2.6	2015	10.8	11.8	-1
2005	8.5	12	-3.5	2016	11.6	13.5	-1.9
2006	9.6	11.3	-1.7	2017	11.2	11.1	0.1
2007	11.6	12.1	-0.5	2018	11.7	12.5	-0.8
2008	7.5	10.4	-2.9	2019	9.5	11.9	-2.4
2009	11.2	11.4	-0.2	2020	11.6	11	0.6
Correlation coefficient $R=0.77$							

Graph analysis in Figures 2–4 showed a less close association between yield and moisture deficiency in the territories of Pavlodar (R = 0.56), Kostanay (R = 0.50), and North Kazakhstan (R = 0.32). In these areas, the effect of this factor on the yield of grain crops ranges from 10 to 31%. Presumably, in these areas, other factors affect the yield in addition to moisture supply (for example, the timing of sowing, agrotechnical techniques, the composition of fertilizers, etc.).

Table 4. Elements of thermal and water balance sheets and yields in Akmola regions for 2020–2024.

Years	**Вн, mm**	**Zm, mm**	**ΔКХ, mm**	**Crop yield, c/ha**
2020	0.22	692	-542	11.6
2021	0.08	860	-794	8.7
2022	0.13	685	-596	9.0
2023	0.19	706	-570	9.4
2024 (assumed value)	0.17	712	-592	8.9

Forecasting changes in the elements of the thermal and water balances of the territory in arid natural zones is one of the necessary conditions for increasing the yield of crops.

Since the highest correlation between humidification coefficient, humidification deficiency, and yield was identified in the Akmola region, the estimated plot of yield for this territory for the next year was built based on the obtained regression equation (Table 4, Figure 5).

A limitation of prediction based on the regression equation, especially paired, is the condition of stability, or at least low variability, of other factors and conditions of the studied process that are not related to the main ones. In the case of other changes not related to the conditions of heat and moisture supply, the previous equation of regression of the effective characteristic to the factor one will lose its value. For example, changing agricultural techniques, including the composition of fertilizers, can have a significant impact on crop yields.

Judging by the data presented in Table 4 and Figure 5, in the Akmola region there is a tendency for a strong decrease in the humidification coefficient (0.08) and an increase in the humidification deficit (-794 mm) in 2021. In the same year, the yield decreased to 8.7 c/ha. The estimated yield for 2024 based on the regression equation was 8.9 c/ha, a slight decrease from previous years.

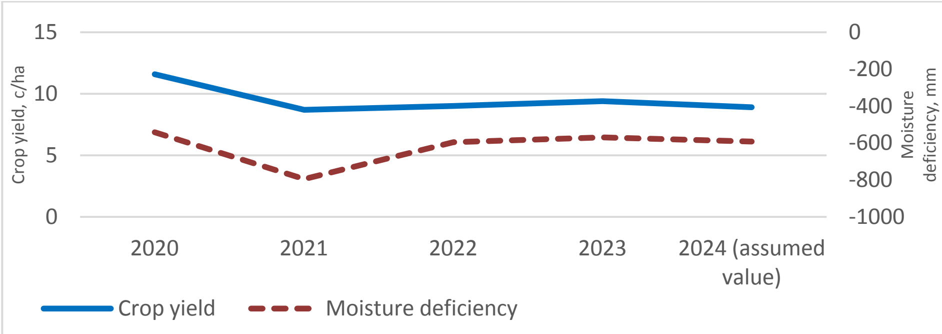

Fig. 5. Comparison of grain crop yields in Akmola region with moisture deficiency for 2020–2024.

The formation of crop yields begins in the fall of the previous year. The normal amount of autumn precipitation and the sufficient height of snow cover in the fields contribute to ensuring the necessary moisture in the soil. One way to ensure soil moisture is also through snow retention.In the steppe natural zone of Northern Kazakhstan, in order to achieve optimal conditions of heat and moisture supply and high productivity in agriculture, the degree of soil moisture should be increased. For these purposes, irrigation is used to artificially increase humidity, and methods of agrotechnical reclamation affect the structure of the soil, improving its physical properties.For a more detailed study of the impact of atmospheric humidification, which is the main limiting factor in the yield of grain crops in the forest-steppe and steppe regions, it is necessary to continue work on expanding the meteorological data base to improve the quality of regression models.

4 Conclusions

As a result of research in the territory of Northern Kazakhstan, a significant impact of moisture deficiency on agricultural production was revealed, and the following conclusions were made:

- The northern regions of Kazakhstan account for 70% of the total sown area of the republic. According to the indicator of grain crop yield, it has a large scale of changes; for example, in wet 2011, grain yield reached 18.4–20.4 c/ha. In dry (2008, 2010, 2012) years, 3.5–5.2 c/ha.
- Regression analysis showed that the tightness of the effect of moisture deficiency on yields is greatest in the Akmola region. Up to 54% of yield variability in this area occurs under the influence of moisture deficiency.
- The correlation coefficient (R = 0.77) between the calculated regression equations and the actual yield values for 1999–2020 is significant.
- The general trend of moisture deficiency in Pavlodar region is characterized by its increase in recent years by an average of 100 mm over 20 years, and in Kostanay and North Kazakhstan regions, the trend of increasing moisture deficiency is not observed.
- In 2021, in the territory of the Akmola region, there will be a strong decrease in the humidification coefficient (0.08) and an increase in the humidification deficit (-794 mm). In the same year, there was a decrease in yield to 8.7 c/ha. The estimated yield for 2024 based on the regression equation was 8.9 c/ha, a slight decrease from previous years.

References

1. A. Kusainova, Zh. Tusupbekov, O. Mezentseva, N. Volkovskaya, IOP Conference Series: Earth and Environmental Science, Krasnoyarsk **677**, 42078 (2021)
2. O. Mezentseva, Bulletin of the Brest State Technical University **2**, 14–18 (2009)
3. G. Belonenko, Zh. Tusupbekov, N. Ryapolova, Problems of Regional Ecology **3**, 174–179 (2015)
4. V. Paromov, V. Zemtsov, S.Kopysov, Georesources Engineering **328 (1)**, 62–74 (2017)
5. I. Karnatsevich, Omsk Scientific Bulletin, **1(118)**, 241– 246 (2013)
6. I. Karnatsevich, V. Akimova, Omsk Scientific Bulletin, **1(128)**, 193–200 (2014)
7. Meteorological information site "Kazhydromet" of the Republic of Kazakhstan, https://kazhydromet.kz/
8. Official website of the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, https://stat.gov.kz/ru/
9. I. Korolev, M. Kravchenko, E. Fedorova, N. Ozerova, N. Vasileva, E3S Web of Conferences **494**, 01024 (2024)
10. Ihssan El ouadi, Fadoua Badaoui, E3S Web of Conferences **492**, 04002 (2024)
11. S. Baisholanov, Hydrometeorology and ecology. RSE "Kazhydromet", **3**, 27–38 (2010)
12. T. Aidarbekova, A. Khussainov, G. Syzdykova, Zh. Alenov, Science and Education, **2-2(71),** 186-194 (2023)