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PATTERNS OF ENERGY EXCHANGE AND HEAT RESOURCES OF SOILS IN NORTHERN KAZAKHSTAN

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Abstract

The study of the heat balance of a site, land, and a river basin is of national economic importance and has attracted the attention of climatologists and hydrologists, who sought to quantify the ratio and interrelationship of individual components of the heat and energy resources of the soil surface and the surface air layer. The heat balance equation based on the universal law of conservation of energy serves as a scientific basis for the study of heat and power processes. Based on the analysis of the short-wave arrival of solar radiation on the earth’s surface and its further transformation, taking into account the characteristics of the underlying surface, the article performed calculations of heat and power resources at the soil level. The heat and power resources calculated according to the radiation balance equation most closely correspond to the zonal conditions for the formation of the components of the heat and moisture exchange of the active surface and the surface layer of the atmosphere. The study of heat resources is of great relevance in the context of the ever-increasing impact of human economic activity on the environment. The performed calculations of Northern Kazakhstan for the network of actinometric stations made it possible to determine the heat turnover in the soil and the heat consumption for snow melting. The values obtained are of value in determining the features of the heat and moisture circulation of lands in the agro-industrial development of territories.

Keywords: Albedo, heat and power resources, heat circulation in soils, radiation balance, short-wave radiation

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1. Introduction

Solar radiation, which enters the earth’s surface, is the only form of energy input, due to which the heat and energy resources of the planet’s climates are formed (Rodkina & Ershova, 2019; Kozhagalieva, 2020). All other types of energy coming to the Earth, in total, are less than 0.003% of solar radiation (Kondratiev, 1987) and do not have a noticeable effect on the thermal processes occurring on the Earth.

Due to the sphericity of the Earth, the influx of solar radiation to the horizontal area of the outer boundary of the atmosphere depends on the latitude of the area. Of the total amount of solar energy that enters the outer boundary of the atmosphere, only a certain part of it reaches the earth’s surface, both in the form of a beam of parallel rays and in the form of solar radiation that has undergone scattering in the atmosphere. The rest of the energy is absorbed and dissipated in the atmosphere by dust, ozone, carbon dioxide, water vapor, and is also lost, reflected back into outer space. Thus, solar radiation arriving at the upper boundary of the atmosphere reaches the earth’s surface in a transformed form (Crueger & Stevens, 2015).

Reaching the earth’s surface in the short-wave range, solar radiation partially turns into long-wave radiation, which has a significant effect on the temperature distribution in the soil (Sukhanov, 2020). The process of energy conversion within the day surface is described by the radiation balance.

2. Problem Statement

Understanding the heat balance of a site, land, and river basin is crucial for economic development and environmental sustainability. The quantification of the components of heat and energy resources is important for climatologists and hydrologists to better understand the interrelationship between the soil surface and the surface air layer. Human activity has a significant impact on the environment, making it necessary to study the heat resources to manage the agro-industrial development of territories.

3. Research Questions

The topic discussed in this study raises several research questions that require further investigation: What is the heat balance equation, and how does it serve as a scientific basis for studying the heat and power processes? How can we calculate the heat and power resources at the soil level based on the short-wave arrival of solar radiation on the earth's surface? What are the components of the heat and moisture exchange of the active surface and the surface layer of the atmosphere, and how do they relate to the zonal conditions? What are the features of the heat and moisture circulation of lands in the agro-industrial development of territories, and how can we use the values obtained from actinometric stations to determine them?

4. Purpose of the Study

The purpose of this study is to investigate the heat balance of a site, land, and river basin using the heat balance equation based on the universal law of conservation of energy. The research aims to quantify the components of heat and energy resources and their interrelationship between the soil surface and the

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surface air layer. The calculations performed for Northern Kazakhstan's network of actinometric stations provide valuable information about the heat turnover in the soil and the heat consumption for snow melting. The findings offer insights into the features of the heat and moisture circulation of lands, which can help manage the agro-industrial development of territories and ensure environmental sustainability.

5. Research Methods

The radiation balance of the earth's surface R is the difference between the absorbed flux of short-wave radiation Rk and the effective radiation E, R = Rк – E.

Short-wave radiation Rk is the energy of the Sun, which enters the earth's surface in the form of direct S and scattered D radiation and depends significantly on the albedo (reflection coefficient) of the underlying surface, Rк = (S + D) · (1 - A), где S + D = Q - total radiation, A - albedo.

The albedo of the earth's surface, equal to the ratio of the reflected radiation flux to the total radiation flux, expressed in fractions of a unit (Bright et al., 2015). Albedo, or the reflectivity of the earth's surface, depends significantly on its state and, as observations show, ranges from 10 to 30%, excluding the surface of water and snow, for which the albedo, respectively, can vary from 40 to 90% and from 2 to 35% . The albedo value is significantly affected by soil moisture, with an increase in which it decreases.

The earth's surface, heated by short-wave radiation, itself becomes a source of long-wave VO radiation. Due to the presence of the atmosphere, the value of VO is reduced by the counterradiation of the atmosphere VA. For the most part, the effective radiation flux vector E = BO - BA is directed upward from the earth's surface, with the exception of the polar regions (Karnatsevich, 1989).

The radiation balance equation is written in the following form: R = (S + D) · (1 - A) - (BO – BA).

The radiation balance, together with the circulation of the atmosphere, has a decisive influence on the temperature distribution in the soil and the surface air layer, on the amount of total evaporation, snowmelt, and other processes occurring in the active soil layer and associated with the consumption of thermal energy (Wild, 2020).

In accordance with the law of conservation and transformation of energy on any part of the earth's surface, equality (balance) of heat input and output is ensured at every moment (Popova, 2000). Mathematically, this universal law is represented by the equation of the heat balance of a land area for a calculated period or moment of time. In general, the scheme of heat exchange of the active earth's surface with the atmosphere and underlying layers, soils is presented in Figure 1, where, in addition to the named balance items, heat flux vectors are presented:

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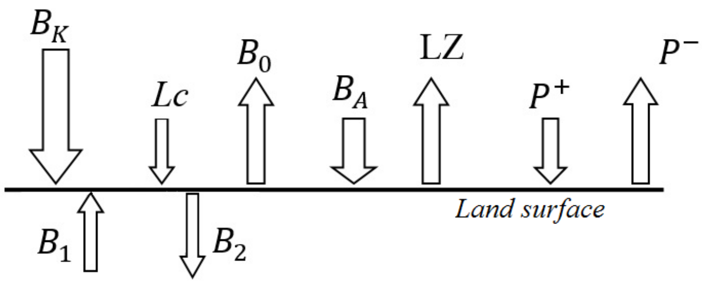

Figure 1. Scheme of heat transfer

Scheme of energy transfer flows at the level of the surface of the active layer of the Earth. LZ - heat input for the evapotranspiration process; L - latent heat of vaporization; P+ и P- - turbulent heat transfer. (P+ - directed towards the active surface, P- - in atmosphere); Lc - heat released when water vapor condenses; B1 и B2 - heat transfer in the active layer of soils, which has a two-digit daily and annual variation. In the autumn-winter and spring periods, the following balance sheet items should be added: l1h - release or consumption of heat due to freezing of soil moisture or its thawing; l1hc - heat consumption for melting, snow in the spring

In accordance with the scheme, the equation for the heat and energy balance of a land area will take the form : BK + BA + P+ + B1 + Lc ± l1h = LZ + B0 + P- + l1hc + B2, in which on the left side there are incoming, and on the right side outgoing, articles of the heat and energy balance of a land area formed over a sufficiently long time, covering a complete cycle of phase transformations of soil and atmospheric moisture.

The difference between the self-radiation of the earth’s surface and the part of the counter-radiation of the atmosphere absorbed by it is called the effective radiation of the earth’s surface. E= BO - BA, где BO и BA - respectively, the long-wave radiation of the earth’s surface and the part of the counter-radiation of the atmosphere absorbed by it.

Heat exchanges in soils are the result of radiant and turbulent heat exchange between the surface of soils and the surface layer of the atmosphere (Pavlov & Duginova, 2019; Abramov, 2022). Theoretical heat transfer schemes were proposed by geocryologists in the late 1950s. Currently, in hydrometeorology, the heat flux into soils is determined by analytical methods based on the mathematical description of the measurement of the temperature field in the upper soil layer 0.2 m thick. Analytical methods often lead to errors in determining the heat flux; the analysis of the causes of their occurrence was carried out in the works of Pavlov (Pavlov, 2003), devoted to the study of landscape thermal physics, considers the calculation and measurement of heat flux in the active layer. A great contribution to the study of heat conversion processes in the active layer was made by geocryologists V.A. Kudryavtsev, M.K. Gavrilova, A.V. Pavlov.

The change in the heat content of the active layer of the earth’s surface occurs in connection with and in accordance with the influx of short-wave radiation R+ and long-wave effective radiation E. At the same time, the largest changes in heat content are observed in the sharply continental climate of high latitudes (Tusupbekov et al., 2022). The distribution of average long-term values of heat content over the territory is determined by the value of the heat and energy resources of the climate. In the works of IV

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Karnatsevich (1989) a method for determining the process of accumulation and consumption of heat from soils based on the analysis of the radiation function was proposed. The basis of the method is the implementation of the idea of an actinometric approach to determining the heat transfer in soils and a method for calculating the heat content function using the integral curve of the radiation function, which is used in this work, is proposed.

6. Findings

On the basis of materials from actinometric stations, daily and monthly sums of nightly effective radiation were calculated for the territory of Kazakhstan. The summation was carried out for the radiation-light and radiation-dark parts of the day. Figure 3.2 shows the complete summary curve of the radiation function r(t) for the average day of June in Semipalatinsk. From point A to point B, i.e. during the radiation-light time of the day, the function has a monotonically increasing character. All the energy received during this time is spent on evaporation, heating of the soil and air, transpiration, as well as on daytime ED and night time EN = R- effective radiation. The short-wave component of the heat and energy resources of the climate during the radiation-light time of the day RD = RK – ED expressed by the difference in the ordinates of the points A and B (Figure 2). The difference between the ordinates of points B and C, is the average daily heat exchange BS = R-. On the territory of Kazakhstan, the value of VS varies within 1,3...3,0 MJ/m2 (Table 1).

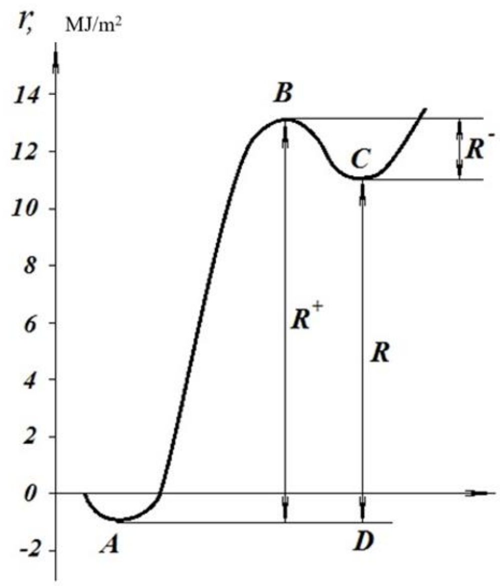

Figure 2. Total summary curve of the radiative function for the average day of June, mst. Semipalatinsk

Table 1. Night effective radiation for the average day of the month $E_N=R^-$, MJ/(m2·day)

Station	01	02	03	04	05	06	07	08	09	10	11	12	Average
Rudny	1.70	1.60	1.84	1.99	1.90	1.64	1.59	1.76	2.06	2.03	1.90	1.73	1.82
Astana	1.51	1.35	1.36	1.83	1.94	1.78	1.69	1.69	2.02	1.96	1.64	1.47	1.68
Uralsk	1.54	1.61	1.45	1.75	1.72	1.78	1.74	1.96	2.20	2.05	1.58	1.42	1.72
Dzhanybek	1.57	1.56	1.62	1.76	1.98	1.92	1.88	1.93	2.10	2.15	1.77	1.48	1.81

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Fort Shevchenko	1.99	2.01	2.01	1.95	2.10	1.99	1.98	1.13	2.33	2.49	2.37	2.10	2.04
Terekty	1.62	1.65	1.78	1.95	1.97	1.96	1.88	2.03	2.21	1.93	1.78	1.58	1.86
Balkhash	2.04	2.08	2.28	2.50	2.59	2.55	2.51	2.71	3.04	2.99	2.51	2.44	2.52
Semipalatinsk	1.71	1.61	1.75	1.93	1.88	1.67	1.64	1.76	2.05	2.16	1.98	1.88	1.53
Lakeside	1.39	1.36	1.41	1.65	1.86	1.94	1.91	2.07	2.37	2.39	2.01	1.72	1.84
Aral Sea	1.90	1.87	2.04	2.29	2.28	2.30	2.25	2.43	2.75	2.82	2.44	2.16	2.29
Alma-Ata	1.56	1.61	1.59	1.55	1.68	1.64	1.81	2.05	2.27	2.28	1.94	1.76	1.81

Table data 3.1 indicate that the nighttime effective radiation in the second half of the year is 60-80% more than in the first. The integral of deviations R- from the annual average value for any half of the year is the seasonal heat turnover BSEZ. The above approach to determining the seasonal (annual) heat turnover, strictly speaking, is applicable only under the condition of a symmetrical annual variation of R+, the absence of snow cover, and a symmetrical (with respect to the summer solstice) course of cloudiness. Table 2 analyzes the intra-annual course of deviations ΔE_N and calculated the seasonal heat exchange B_{SEZ}. Seasonal heat turnover is calculated as an integral sum $B_{SEZ} = \sum \Delta E_N$.

Table 2. Deviations ΔEN from the average nighttime effective radiation for the year, MJ/m2

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Sum.
Rudny	-2.56	-6.29	-0.98	5.43	2.69	-5.24	-6.77	-0.7	7.57	6.65	2.69	-2.50	25.04
Astana	-4.54	-11.53	-11.23	4.46	7.83	2.94	0.19	1.04	10.26	8.43	-1.33	-6.52	35.15
Uralsk	-5.02	-5.27	-9.99	0.61	-0.30	1.53	0.31	8.00	14.34	9.76	-4.57	-9.45	34.60
Dzhanybek	-6.41	-9.06	-7.29	-1.40	5.31	3.48	2.26	4.75	8.97	10.49	-1.10	-9.94	35.26
Fort Shevchenko	-6.42	-7.97	-4.13	2.83	3.44	3.14	0.7	6.29	10.76	2.22	-2.35	-8.45	29.32
Terekty	-2.83	-5.23	-5.23	-5.05	-0.47	-3.83	-4.13	1.53	6.54	11.42	7.76	-0.47	27.24
Balkhash	-13.45	-15.33	-9.43	-0.44	2.31	1.07	-0.13	7.32	16.03	14.51	-0.13	-2.27	41.18
Semipalatinsk	-2.82	-8.34	-4.21	3.03	1.51	-4.90	-5.81	-1.27	6.69	10.05	4.56	1.51	27.35
Lakeside	-12.94	-15.91	-14.44	-5.71	0.70	3.14	2.22	8.14	16.25	16.86	5.28	-3.58	52.59
Aral Sea	-10.92	-14.66	-9.64	0.02	-0.28	0.33	-1.20	5.51	14.05	16.19	4.60	3.34	40.64
Alma-Ata	-6.77	-7.64	-8.23	-7.86	-3.89	-5.11	0.07	8.42	14.1	14.41	4.04	1.45	40.95

In the northern and central parts of the territory of Kazakhstan, the distribution of ΔBSEZ by months has an asymmetric course. Undoubtedly, the asymmetry of distribution is influenced by snow cover, which remains on the surface of the watershed for 5–6 months and determines large values of reflected radiation in the first half of the year (Mezentseva et al., 2022).

Seasonal changes in the BSEZ heat content at high latitudes, judging by the data of thermal measurements, should be greater than at low latitudes. Based on the data in Table 2, the seasonal values of the BSEZ heat exchange were determined for a number of points in the study area (Table 3).

Table 3. Seasonal heat turnover in soils on the territory of Kazakhstan BSES, MJ/m2

Station	B_{SEZ}	Station	B_{SEZ}	Station	B_{SEZ}
Bulaevo	90	Astana	68	Akmolinsk	52
Petropavlovsk	89	Berlik	58	Irgiz	48
Yavlenka	85	Karaganda	62	Chelkar	42

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Komsomolets	78	Bes-both	60	Ayakkum	38
Kustanay	75	Leninogorsk	82	Dzhanybek	39
Kushmurun	70	Seleznevka	78	Urda	38
Dzhetygara	65	Samarka	72	Guryev	35
Krasnoarmeyka	82	Aksuat	65	Myself	32
Kokchetav	80	Ayaguz	60	Fort Shevchenko	29
Mikhailovka	92	Bakhty	56	Aral Sea	40
Pavlodar	85	Jean Arc	55	Kyzylorda	38
Bayanaul	73	Dzhezkazgan	50	Taldykurgan	46
Kazgorodok	66	Betpak-dala	45	Bakanas	44
Arkalyk	59	Chalobay	80	Almaty	40
Turgai	55	Kokpekty	70	Achisai	36
Alekseevka	75	Barshatas	59	Jambul	33
Atbasar	70	Ucharal	53	Shymkent	30

The change in seasonal heat turnover on the territory of Kazakhstan has a latitudinal character. Highest values BSEZ observed in the north of the territory 90 MJ/m2, the smallest - 30 MJ/m2 in the south.

In accordance with the change in short-wave heat input to the active surface in cold countries, there are clear time boundaries between the seasonal heat accumulation half-cycle and the cooling half-cycle (Sedelnikov & Taizhanova, 2020). Figure 3 shows the complete summary curve of the radiation function (Mst. Astana), constructed by summing the daily values of R(t) measured at actinometric stations. Curve r(t) has extrema (points A and B), where the first derivative r'(t)=0, therefore, the curve characterizes a permafrost point (Karnatsevich, 1989).

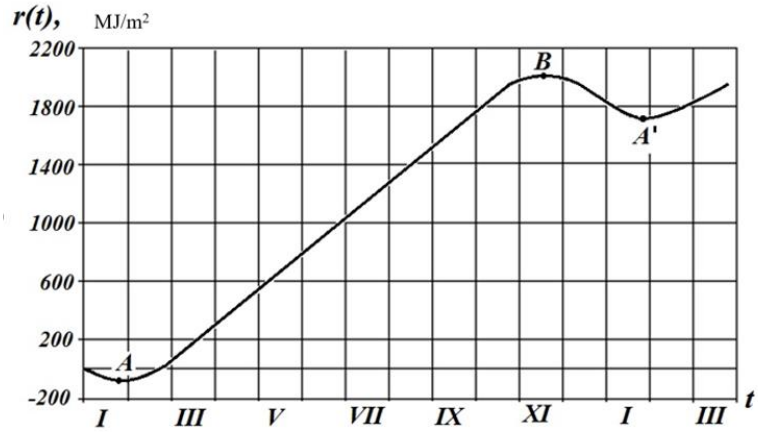

Figure 3. Complete summary curve of the daily sums of the radiation function r(t), MJ/m^2 mst. Astana

The minimum and maximum points correspond to the dates of the beginning of the increase (point A) and decrease (point B) of the heat content of the active layer. If we take into account that the curve is built for an average year, then the time interval from point A to point B characterizes the period of accumulation of HP, and the interval from point B to point A' - the period of consumption of heat TP from the active layer of soils.

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The complete summary curve of the radiative function (Figure 3) makes it possible to determine the dates of the beginning and end of the increase in the heat content of the active layer. So in the southern part of the study area, the start date falls on the beginning, and in the northern part - in mid-February. From this date, the temperature of the snow surface begins to rise. The time interval from the start of heat accumulation to the start of snow cover destruction depends on various factors - latitude, shading, snow cover thickness, and snow surface albedo (Cuntz & Haverd, 2018).

On the territory of Kazakhstan, snowmelt, from destruction to complete melting of the snow cover, occurs at the end of February in the southern regions and in mid-April - in the north. The duration of this period in Northern Kazakhstan ranges from 2 to 20 days depending on the amount of solid precipitation and weather conditions at that time of the year. On average, over a long period, the melting of the snow cover ends at the end of the second decade of April.

Distribution over the territory of heat consumption for snow melting TTS depends on the water reserves in the snow cover h_B, $T_{TS} = L \cdot h_B$, где L - specific heat of phase transition ice-water. Table 4 shows the average dates of the destruction of stable snow cover and the dates of snow cover melting, as well as the values of short-wave radiation RTC received during this period, and the heat costs for snow melting.

Table 4. The arrival of short-wave radiation RTS for the period from the beginning of destruction to the complete melting of the snow cover and the heat costs for melting snow TTS, (MJ/m^2)

Station	Date of snow cover breakdown	Snow cover date	R_{TS}, MJ/m^2	T_{TS} MJ/m^2
Bulaevo	6.IV	20.IV	133	22,4
Ore	6.IV	13.IV	72	23,5
Shchuchinsk	5.IV	24.IV	190	20
Arkalyk	2.IV	10.IV	80	26,1
Astana	9.IV	16.IV	73	22,4
Besoba	2.IV	9.IV	72	12,3
Ayaguz	1.IV	10.IV	101	28,4

The results of the analysis show that the highest TTC values are observed in the northern part of the territory and in the region of the Kokchetav mountains (up to 30 MJ/m^2). In the south of the territory and in the steppe region of the Irtysh, heat consumption for snow melting is 15-20 MJ/m^2.

7. Conclusion

Solar radiation is the only source of energy for the heat and moisture circulation of the earth's surface. In cold countries, a significant proportion of heat is annually spent on heating the air and the active layer of soil. Under these conditions, the study of the heat and power resources of the process at the level of soils is one of the urgent tasks of water-balance studies.

The performed calculations of the heat and energy resources of the surface layer on the territory of Kazakhstan for a network of actinometric stations made it possible to determine the heat exchanges in

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soils. The field of this physical quantity on a geographical basis characterizes the territory of Northern Kazakhstan with values from 50 MJ/m^2 in the south to 120 MJ/m^2 in the north.

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