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Influence of Rock Watering on Post-Seismic Activity: A Study on the Khibiny Massif

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Abstract: The article is devoted to the study of the influence of watering of the rock environment on post-seismic activity in the deposits of the Khibiny mountains. Initial data are the results of long-term monitoring of seismicity and observations of water inflows. At a qualitative level, the influence of watering of the environment on the *b*-value of the Gutenberg – Richter distribution of magnitudes of triggered events, as well as on the parameters of the Omori – Utsu law, which describes the post-seismic activity decay rate over time, was studied.

Keywords: Khibiny massif, watering, post-seismic activity, Gutenberg – Richter distribution, Omori – Utsu law.

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Introduction

Presently, the issue of the influence of watering of the rock on seismicity can be considered well-studied. There are experimental [*Board et al.*, 1992; *Kartseva et al.*, 2022] and field data [*Hainzl et al.*, 2006, 2013; *Heinicke et al.*, 2017; *Maystrenko et al.*, 2020; *Smirnov et al.*, 2022; *Talwani*, 1997; *Vorobieva et al.*, 2020; *Zoback and Harjes*, 1997] on the influence of moisture content of the geologic material on the parameters of the seismic regime for natural (tectonic) and induced seismicity. The key result of these studies is the increase in seismicity during elevation of pore fluid pressure and the "lubrication" effect due to the increase in the amount of liquid penetrating into the medium caused either by the changes in the reservoir level [*Smirnov et al.*, 2022; *Talwani*, 1997], or by heavy rainfalls [*Hainzl et al.*, 2006, 2013; *Heinicke et al.*, 2017; *Maystrenko et al.*, 2020], or by snowmelt in spring [*Zhukova et al.*, 2023], or by direct liquid injection for extraction of hydrocarbons [*Vorobieva et al.*, 2020; *Zoback and Harjes*, 1997].

Porosity and moisture content of rock play a significant role in this process. At the same time, the increase in seismicity during the growth of moisture content is manifested in both the growth in the number of earthquakes and the reduction of the *b*-value of the Gutenberg – Richter magnitude distribution [*Smirnov et al.*, 2013, 2022; *Zhukova et al.*, 2023], which reflects an increase in the proportion of strong earthquakes.

Thus, the increase in watering of the rock, accompanied by an increase in pore pressure, is a significant factor affecting the seismic regime. Moreover, a number of Russian [*Batugin*, 2006; *Lazarevich et al.*, 2006; *Nikolaev*, 1988; *Rebetskiy*, 2007] and foreign [*Bell and Nur*, 1978; *Manga and Wang*, 2015; *Shapiro*, 2015; *Simpson*, 1986] researchers consider the hypothesis that one of the main triggers of induced earthquakes may be an increase in the pore fluid pressure.

Despite the fact that the influence of watering of the rock mass on the overall seismicity has been discussed in many research, the impact of this factor on the post-seismic activity

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arising from the stress changes caused by an earlier earthquake has been studied less (see, for example, section 1.1.3 in [*Smirnov et al.*, 2020] and references therein). A possible reason for this is that such studies encounter objective difficulties. First, the data of long-term seismic observations and regular monitoring of water inflow in a territory with both seismicity and significant fluctuations in the watering of the medium are required. Second, it is desirable for watering measurements to be carried out at depths comparable to the depths of earthquakes in order to avoid ambiguities associated with the delay in the flow of fluid into the earth's crust, as it happens, for example, in the case of seismicity of reservoirs.

The territory where such a study is possible is the Khibiny massif, located in the center of the Kola Peninsula. Due to its commercial development, seismic monitoring has been carried out at the fields of the Khibiny massif since the late 1980s, and since 2002, regular measurements of water inflow have been carried out at depths comparable to the depths of seismic events (for more details refer to the section "Research area and materials"). In addition, previous studies have revealed a significant influence of watering of the rock on the seismicity of the Khibiny fields [*Kozyrev et al.*, 2021; *Zhukova*, 2015; *Zhukova et al.*, 2023]. In particular, *Zhukova et al.* [2023] showed a significant decrease in b-value during the high watering period of the Khibiny massif, from May to October, compared to the low period from November to April. In this paper, we will find out whether watering of the rock affects the parameters of post-seismic activity.

Post-seismic activity is described by three laws of statistical seismology: Gutenberg – Richter [*Gutenberg and Richter*, 1944], Omori – Utsu [*Utsu et al.*, 1995], and earthquake productivity [*Baranov et al.*, 2022; *Shebalin et al.*, 2020]. The Gutenberg – Richter law specifies the distribution of magnitudes. The Omori – Utsu law describes the decay of triggered events over time. The law of productivity characterizes the ability of seismic events to trigger aftershocks (the number of events triggered by an earlier earthquake obeys an exponential distribution).

The physical mechanism of post-seismic activity is often described by the rate- and state-dependent friction model [*Dieterich*, 1994, 2007] (other models are briefly discussed in [*Smirnov and Ponomarev*, 2020]. Under some assumptions, this model predicts Omori's law with $p = 1$ and gives a physical interpretation of its parameters [*Cocco et al.*, 2010; *Dieterich*, 1994, 2007].

In this article, we will qualitatively study the effect of rock watering in the research area on the distribution of magnitudes of triggered events and on their decay over time.

Research Area and Materials

The Khibiny massif, located in the center of the Kola Peninsula, is the world's largest alkaline intrusion [*Arzamastsev et al.*, 2013]. The complex structure of the massif is characterized by a high level of tectonic stresses, reaching values of 40–60 MPa at depths ranging from −600 to −90 m. In some cases, these stresses exceed the gravitational forces due to the weight of the overlying rocks [*Onokhin*, 1975; *Rebetskiy*, 2007].

Here and further the depths are relative to the zero of the Kronstadt footstock, corresponding to the average level of the Baltic Sea, towards the center of the Earth. Negative value means that the depth is above the reference level.

There are many annular and radial faults in the massif, some of which intersect deposits of apatite-nepheline ores [*Arzamastsev et al.*, 2013; *Shabarov et al.*, 2021]. Because of this, the mining area is a zone of increased seismic activity, saturated with tectonic disturbances. Uplifts of the Khibiny massif at a rate of 0.5 to 2–4 mm per year and periodic earthquakes [*Kremenetskaya and Trjapitsin*, 1995] indicate modern tectonic changes in this region.

For decades, in the course of mining operations, new systems of cracks and cavities are formed in the Khibiny massif, which have a direct impact on the distribution of natural stress fields. This, in turn, leads to the destabilization of the block structure of the massif. The impact of technology and tectonics creates annealing zones, which gradually contribute to the destruction of individual areas of the massif, generally activating seismicity [*Kozyrev* *et al.*, 2022]. Thus, the seismicity of the Khibiny massif is the result of the impact of both tectonic and mining activity.

The study used a catalog of seismic events recorded by the seismic network of Kirovsk Branch (KB) of "Apatit" JSC for 2002–2022. Currently, the network consists of 60 3-component seismic sensors located at the Kirovsk and Rasvumchorr mines with a sampling rate of 1000 Hz (Figure 1). The network determines the hypocenters of seismic events with energy $E \geq 10^3$ J with an accuracy of up to 25 m in the area of increased accuracy and up to 100 m in the area of confident registration [*Korchak et al.*, 2014]. The magnitude of the completeness $M_c = 0$. The epicenters of earthquakes with $M \geq 1.5$ are shown in Figure 2.

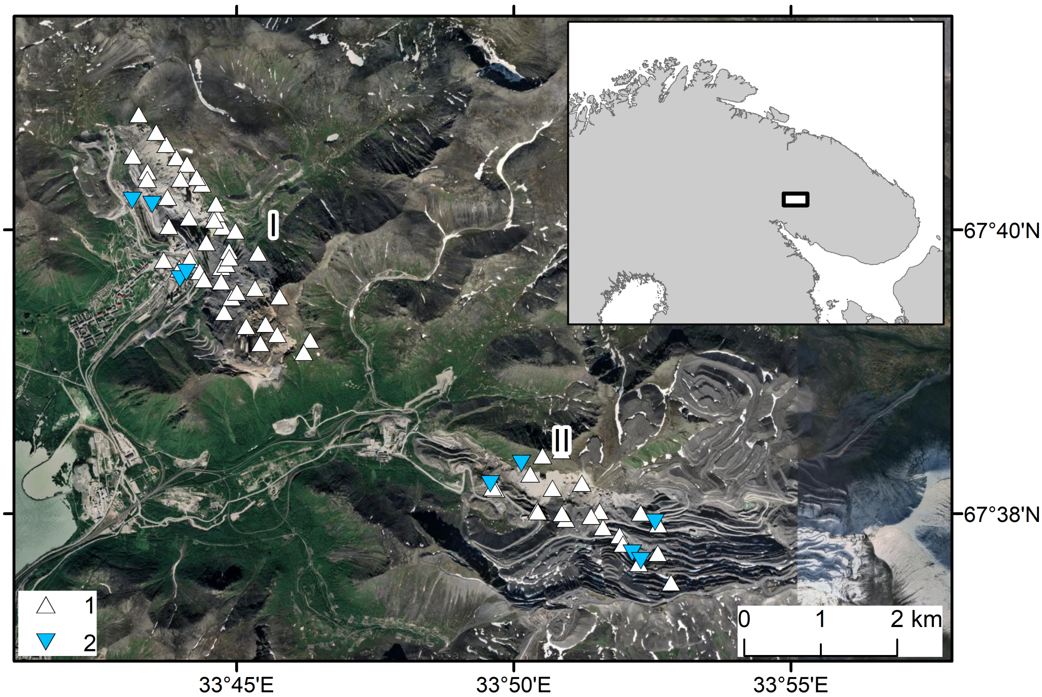

Figure 1. Location of seismic sensors (1) and water inflow measurement points (2). Roman numerals show the territories of the Kirov (I) and Rasvumchorr (II) mines. The rectangle on the insert indicates the location of the area under study.

Data on water inflows at the fields of the Khibiny massif for 2002–2022 were provided by the geological service of the KB "Apatit" JSC. Measurements of water inflow are carried out at underground mines once a day in water collectors located on production levels. Measurements of the volume of water channels at the Central quarry are carried out in ore passes in special dewatering grooves twice a day. The location of the water inflow measurement points is shown in the Figure 1. The depths at which water inflows are measured (Table 1) are comparable to the depths of earthquakes (the average depth of representative seismic events is about −450 m, 95% of them occur at depths from −725 to −100 m).

For the purposes of this article, watering refers to the total water inflow to the mine horizons where measurements are made. This characteristic is actually equivalent to infiltration, which characterizes the amount of water that penetrates into the massif.

The study area (Figures 1, 2) is in the basin of the Bolshoy Vudyavr lake in the highest and well-drained southwestern part of the massif, characterized by high runoff values, unstable seasonal changes in water outflows, as well as mutually close location of water sources, such as the Yuksporyok and Vudyavryok river systems and their tributaries. Fault zones filled with oxidized and crushed rocks have the highest degree of water saturation, their width varies from 2 to 30 meters. Groundwater is replenished by precipitation [*Gimmelfarb et al.*, 1965]. Thus, long-term series of observations of seismicity and water inflows, as well as the unstable and zonal nature of water inflow in the study area, allow us to study the impact of watering of the rock on post-seismic activity.

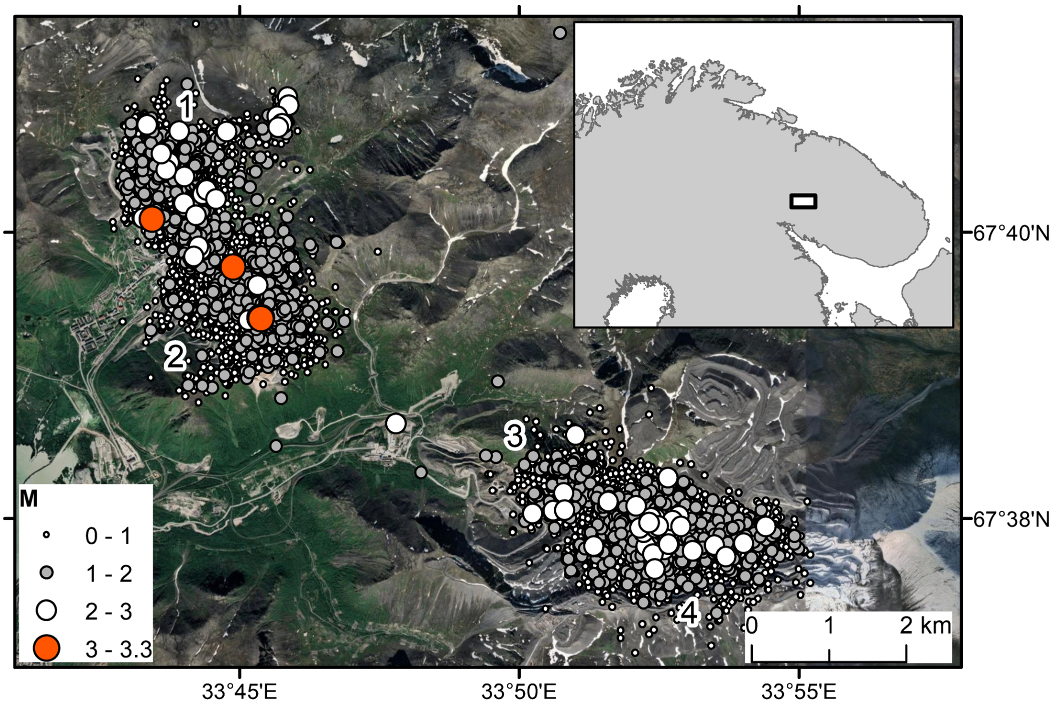

Figure 2. Epicenters of seismic events with $M \geq 1.5$ recorded in the fields of the Khibiny massif during 2002–2022. The figures indicate the following deposits: 1 – Mt. Kukisvumchorr, 2 – Mt. Yukspor (developed by the Kirov Mine); 3 – Apatitovyi Tsirk (Rasvumchorr Mine); 4 – Mt. Rasvumchorr (until 2014 Central, currently Eastern Mine). The rectangle on the insert indicates the location of the area under study.

Table 1. Coordinates and depths (m) of the points at which water inflows are measured (negative values correspond to depths above the average level of the Baltic Sea, chosen as the reference level)

Latitude	Longitude	Depth (m)
	Kirovsk Mine	
67.6616	33.7349	−320
67.6701	33.7187	−90
67.6696	33.7247	−170
67.6609	33.7330	−170
67.6616	33.7349	−252
	Rasvumchorr Mine	
67.6368	33.8263	−310
67.6392	33.8357	−425
67.6323	33.8759	−530
67.6287	33.8690	−430
67.6278	33.8716	−430

Methods

Triggering and triggered events were identified using the nearest neighbor method [*Zaliapin and Ben-Zion*, 2016]. The method is based on application of a proximity function for the space, time, and magnitude [*Baiesi and Paczuski*, 2004]

$$\eta_{ij} = \begin{cases} t_{ij}(r_{ij})^{d_f} 10^{-bm_i}, & t_{ij} > 0, \\ +\infty, & t_{ij} \leq 0, \end{cases} \tag{1}$$

where $t_{ij} = t_j - t_i$ is the time between events, which is positive if the event j occurs after the event i and negative otherwise; $r_{ij} \geq 0$ is the spatial distance between the hypocenters of the events; m_i is the magnitude of the ith event; b is the parameter of the Gutenberg – Richter law [*Gutenberg and Richter*, 1944]; d_f is the fractal dimension of the hypocenter distribution.

For each event in the catalog, its trigger is determined by the minimum value of the proximity function (1), calculated from all previous events relative to the one considered. If this value is less than the specified threshold η_0, then the event in question is considered to have been triggered by a trigger event at which the minimum of the function (1) is reached. Otherwise, the link is broken, and it turns out that the event is background (does not have a trigger). A trigger event can trigger multiple events, while any event can only be triggered by a single trigger.

The η_0 threshold can be determined in a variety of ways (for more details, see [*Bayliss et al.*, 2019; *Shebalin et al.*, 2020; *Zaliapin and Ben-Zion*, 2016]), developed to decluster catalogs of tectonic earthquakes. Here we used the model-independent method [*Shebalin et al.*, 2020] since it is preferable in the case of mining-induced seismicity.

The nearest neighbor method, unlike, for example, the method of *Molchan and Dmitrieva* [1992], does not impose any restrictions on the temporal behavior of triggered shocks (conformance to the Omori – Utsu law). *Pisarenko and Rodkin* [2019] demonstrated that efficiency of the nearest neighbor method for catalog declustering is higher than that of window methods.

The application of the nearest neighbor method to the conditions of mining-induced seismicity of the Khibiny massif is considered in detail in the paper [*Baranov et al.*, 2020], where the following estimates of the seismic regime parameters were obtained: $b = 1.25$, $d_f = 1.5$; threshold estimate $\lg \eta_0 = -6.25$. Using these estimates, for each earthquake with a magnitude $M \geq 1.5$ we will find events triggered by it. The triggered events found in this way represents the post-seismic activity of the area under study.

In order to assess the parameters of post-seismic activity, we will use the approach of [*Baranov and Shebalin*, 2019; *Shebalin and Narteau*, 2017] and stack the triggered events, replacing the magnitudes with the differences $M_\mathrm{a} = M - M_\mathrm{m}$ (M is the magnitude of the triggered event, M_m is the magnitude of its trigger), and arrange events in ascending order of time after the main shock. The use of relative magnitudes M_a brings the triggered events to a comparable form with respect to their triggers.

The use of the stack of triggered events to estimate the parameters of post-seismic activity is more correct compared to averaging the estimates obtained for individual series (this approach was used by *Reasenberg and Jones* [1989], since the distributions of parameters are generally asymmetrical. In addition, the parameters p and c of the Omori – Utsu law are correlated. For example, during fracturing along the formed fault, the relaxation parameter p increases with the increase of axial stresses; the delay in the onset of power-law decay (the parameter c in the Omori – Utsu law) decreases with an increase in axial stresses and increases with an increase in comprehensive compression pressure [*Smirnov et al.*, 2019]. In addition, a number of laboratory and field studies revealed a correlation between the Omori – Utsu and Gutenberg – Richter parameters, indicating implementation of various relaxation mechanisms [*Sharma et al.*, 2023; *Smirnov et al.*, 2019, 2020].

Estimation of the parameter b of the Gutenberg – Richter law using relative magnitudes from the stack has the advantage that the value is estimated for all the series in the range of large magnitudes, which minimizes the influence of the possible inflection of the repeatability graph that occurs due to possible post-seismic plastic deformations at the earthquake source [*Vorobieva et al.*, 2016].

The parameters of post-seismic activity were estimated based on a set of initiated events at the time interval [$t_\mathrm{start} = 0.005$, $t_\mathrm{stop} = 30$] days. The delay after the moment of the trigger event (t_start) is necessary to eliminate the distortion of parameter estimates due to the deficit of weak aftershocks at the beginning of the series [*Holschneider et al.*, 2012; *Narteau et al.*, 2009; *Smirnov et al.*, 2010]. The value $t_{stop} = 30$ days was chosen because during this time the dependence of the total number of triggered events on time (cumulative curve) has a regular form and is well described by the Omori – Utsu law.

The magnitudes of earthquakes follow the Gutenberg – Richter [*Gutenberg and Richter*, 1944] distribution:

$$P(M_a < m) = F(m) = 1 - 10^{-b_a m}.$$

Hereinafter, the notation $b = b_a$ is used to denote the parameter b of the magnitude distribution of triggered events from the stack. The estimation was performed using the maximum likelihood method according to the Aki's formula adapted for discrete magnitudes [*Marzocchi and Sandri*, 2009]:

$$b_a = \frac{\lg_{10} e}{E[M_a] - M_{ca} + \frac{\Delta M}{2}}.$$

Here $M_{ca} = -1.5$ is the magnitude of completeness for the stack of triggered events; $E[M_a]$ is the average sampling magnitude at $M_a \geq M_{ca}$; ΔM is the binning magnitude width of the catalog.

The distribution of estimation error of b-value and its standard deviation σ were calculated using the bootstrap method. The evaluation of the parameter b_a for the stack of triggered events is provided in Figure 3; the resulting b-value $b_a \pm \sigma = 1.21 \pm 0.048$.

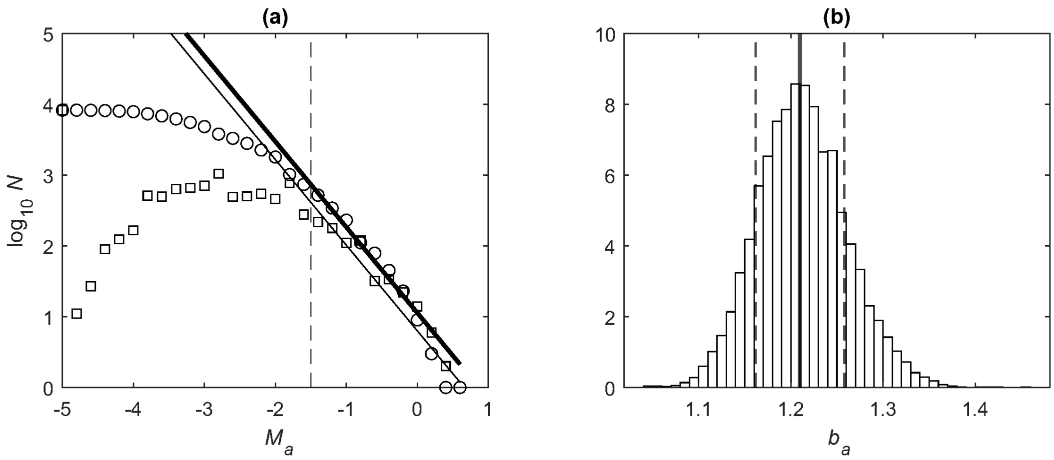

Figure 3. Estimate of b_a-value of the Gutenberg – Richter law for the stack of triggered events. (a) Cumulative (bold line) and differential (thin line) magnitude–frequency curves for the $M_a = M - M_m$; circles denote cumulative values, squares – differential ones; dashed line denotes the level of representative relative magnitude. (b) Probability density of the error; solid vertical line denotes estimation of $b_a = 1.21$; dashed vertical lines are values $b_a \pm \sigma = 1.21 \pm 0.048$ (σ is standard error).

The time decay of post-seismic activity is described by the Omori – Utsu law [*Utsu et al.*, 1995]:

$$n(t) = \frac{K}{(t+c)^p}, \tag{2}$$

where t is the time after the main shock; $n(t)$ is the rate of triggered events (the number of events per unit of time); c is the time delay of power-law decay rate of the triggered events; p is the relaxation parameter, the higher the p, the faster the triggered events decay in time; K is the productivity parameter of the stack (not to be mistaken with the parameter of the law of earthquake productivity). [*Shebalin and Narteau*, 2017] using the data on seismicity in California showed that the value $-\log(c)$ approximates the difference between the maximum and minimum stresses.

The parameters of the Omori – Utsu law were estimated using the Bayes method [*Holschneider et al.*, 2012] in the time interval $t_{start} = 0.005$ to $t_{stop} = 30$ days with uniform prior distribution of parameters c in the interval $[t_{\text{start}}2,\ 2t_{\text{stop}}]$ and p in the interval $[0.5, 2.5]$. Figure 4 demonstrates posterior distributions of the K, c, and p estimates, as well as the empirical and theoretical distribution of the times of the triggered events from the stack. The resulting values given the 95% confidence interval are: $c = 0.012(0.006, 0.018)$, $p = 1.27(1.209, 1.332)$, $K = 74.9(69.97, 79.95)$. The proximity of theoretical and empirical cumulative curves of the aftershock number (Figure 4b) indicates that post-seismic activity in the area under study obeys the Omori – Utsu law. To measure the error of estimating the parameters of the Omori – Utsu law, we use 95% confidence intervals instead of the standard error, since the posterior distribution of Bayesian estimates of parameters is generally asymmetrical.

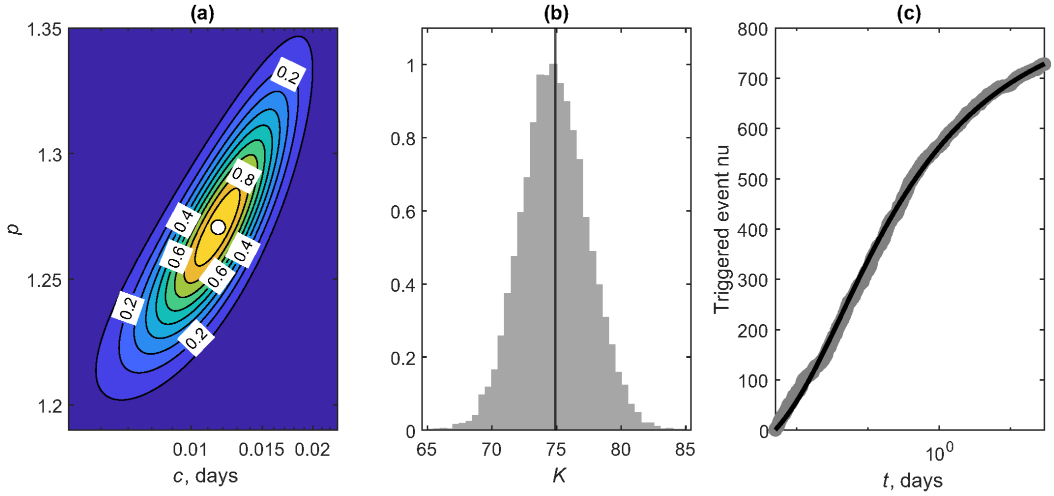

Figure 4. Estimation of the parameters of the Omori – Utsu law for the stack of triggered events. (a) Posterior probabilities of the joint distribution of estimated parameters c and p, white circle denotes the maximum likelihood. (b) Posterior probabilities of the K estimate (gray rectangles), vertical line denotes the maximum likelihood. (c) Distribution of the times of triggered events, gray line denotes the empirical distribution within the triggered aftershock stack, the black line denotes the distribution according to the Omori – Utsu law with estimated values: $c = 0.012(0.006, 0.018)$, $p = 1.27(1.209, 1.332)$, $K = 74.9(69.97, 79.95)$, 95% confidence interval is indicated in the parentheses.

For induced seismicity, estimates of p-value are usually believed to be from 0.5 to 0.8 [*Gupta*, 2002; *Mekkawi*, 2004; *Rastogi et al.*, 1997]. Here we obtained a significantly larger value of $p = 1.27(1.209, 1.332)$. It is possible that the reason for this discrepancy is in geological conditions. The cited papers studied post-seismic activity in reservoir areas in India and Egypt. Here we are considering post-seismic activity that occurs during mining in a tectonically loaded crystalline rock mass (Khibiny Mountains), tectonic (horizontal) stresses significantly exceed gravitational (vertical) ones.

To demonstrate the influence of watering of the rock on the parameters of post-seismic activity, we estimated the monthly variations of the the b_{a} of the Gutenberg – Richter distribution and the K, c, and p of the Omori – Utsu law. By comparing the parameter estimates with the average monthly values of water inflow, we will be able to conclude whether the watering of the rock affects the post-seismic activity.

Results

The period of increased watering in the study area (water inflow above the average value) occurs in May to October (Figure 5a), while from November to April low watering is observed. The increase in watering in May and June is caused by the intense melting of the snow accumulated during the winter. From July to October, the elevated watering of the massif is maintained due to atmospheric precipitation. Approximately from the second half of October, the air temperature in the Khibiny becomes negative and the watering of the massif starts to decrease.

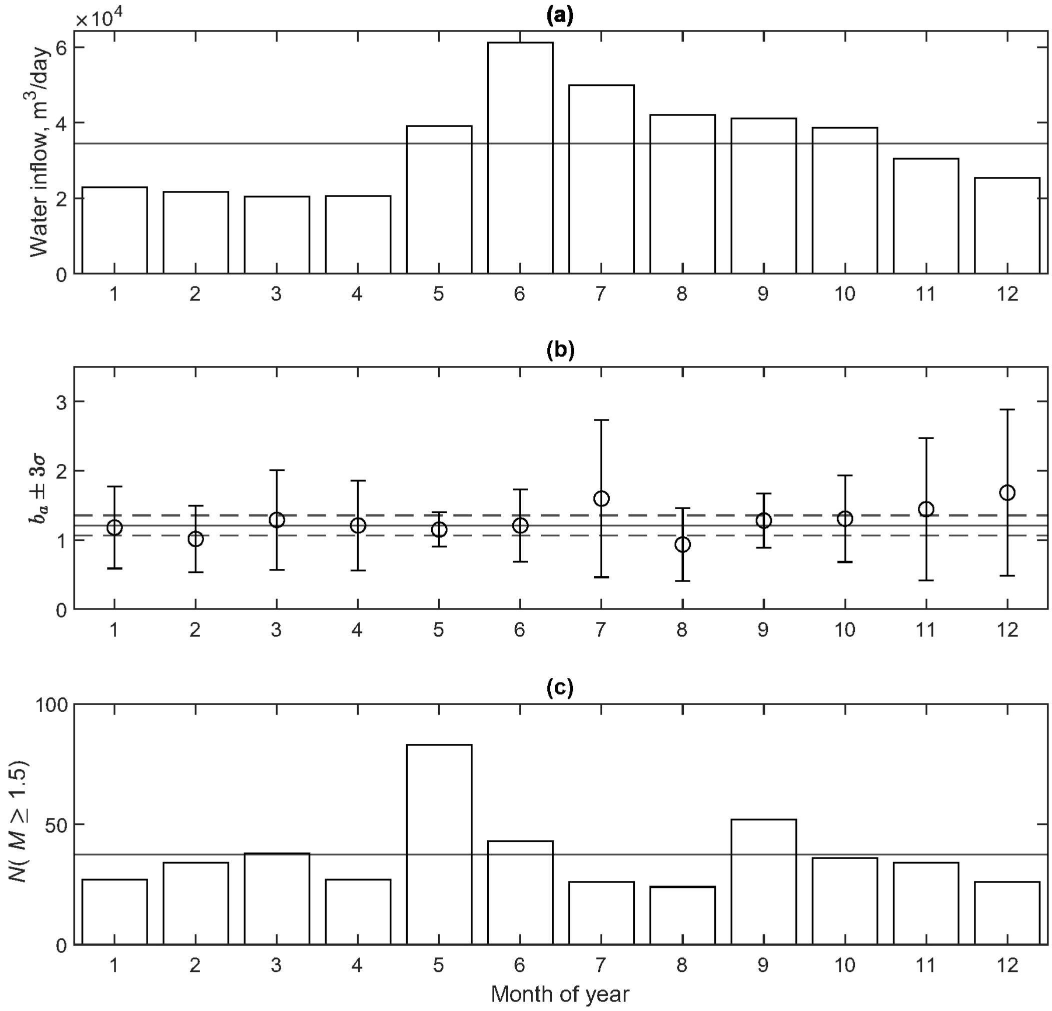

Figure 5. Monthly average variation in the rock watering level and b_{a}-values for the stack of triggered events at the fields of the Khibiny massif. (a) The average water inflow (m^3/day), the horizontal line denotes the average value; (b) The $b_{\mathrm{a}} \pm 3\sigma$ (the error bars denote triple standard errors σ), horizontal line denotes the b_{a}, estimated from all the data, dashed lines are $b_{\mathrm{a}} \pm 3\sigma$; (c) The number of earthquakes with $M \geq 1.5$ considered as triggers, horizontal line denotes the monthly average value (37.5).

Comparing seasonal variations in the water inflow level (Figure 5a) and the values of the b_{a} of the Gutenberg – Richter distribution (Figure 5b) estimated based on the stack of triggered events, we can state that the observed fluctuations of b_{a} are less than the estimation errors. Thus, we cannot state that the influence of watering of the rock on the distribution of the relative magnitudes of the triggered events ($M_{\mathrm{a}} = M - M_{\mathrm{m}}$) is significant. At the same time, there is a significant increase in the number of earthquakes with a magnitude $M \geq 1.5$ in May (2.2 times higher compared to the annual average value of 37.5), when the increase in watering (Figure 5c) associated with melting of snow accumulated through the winter occurs.

Let us consider the influence of the rock watering on the parameters K, c, and p of the Omori – Utsu law, determining decay of post-seismic activity over time (Figure 6). Estimates of the K-value of the Omori – Utsu law (2) (Figure 6a) show a significant increase in May, when the melting of snow accumulated over the winter causes an increase in watering of the rock. In June, the value of K decreases, but still lingers above the average annual value.

Then the value of K decreases below the annual average and then significantly increases in September. From October until January K is lower, and from November until April it does not exceed the annual average. This means that during the period of low watering of the rock from October until April the values of the parameter K do not exceed the average annual value.

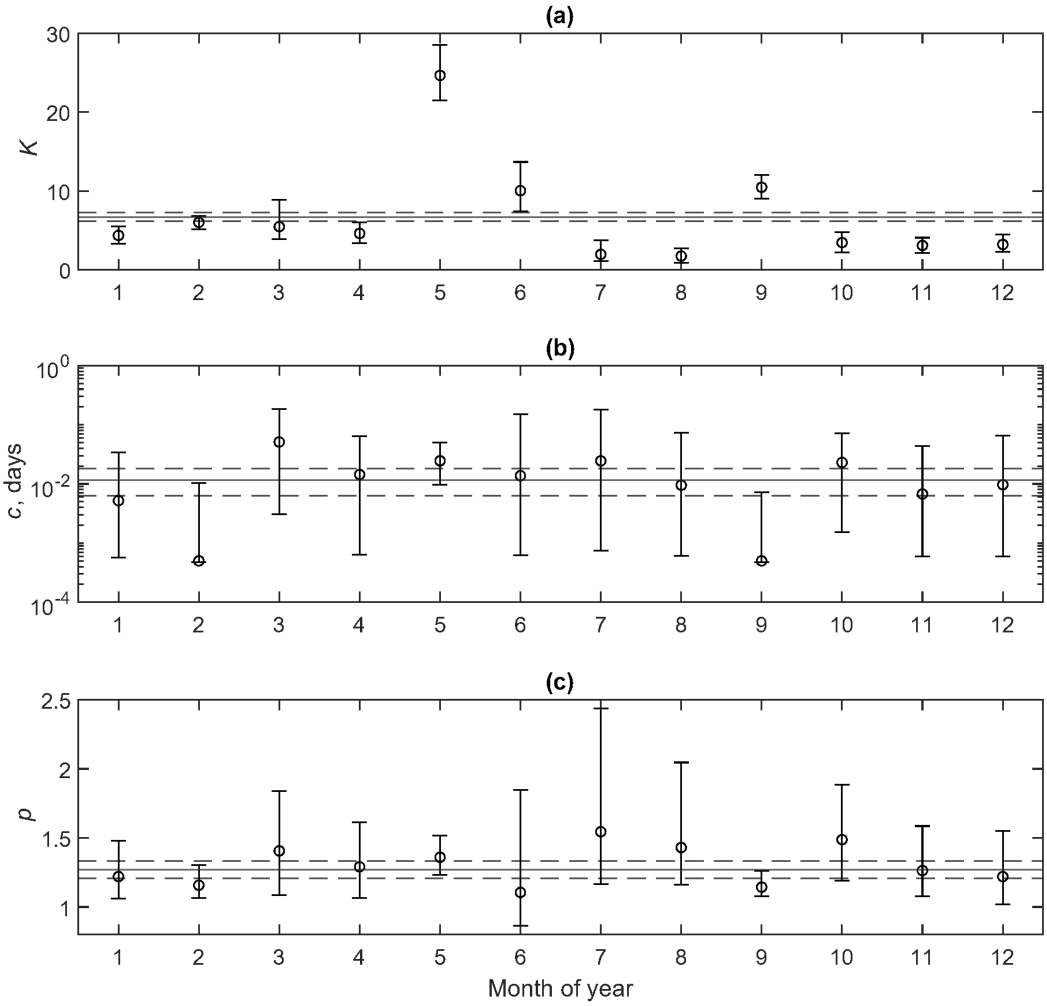

Figure 6. Estimates of the parameters of the Omori – Utsu law (error bars are the 95% confidence intervals) for triggered events at the Khibiny massif calculated by months of the year. (a) The K-values, horizontal line denotes the annual average K, dashed lines are limits of the 95% confidence interval. (b) The c-values, horizontal line denotes the c estimated using all the data, dashed lines are limits of the 95% confidence interval. (c) The p-value, horizontal line denotes the p estimated using all the data, dashed lines are limits of the 95% confidence interval.

The highest deviation of the estimates of c (Figure 6b) and p (Figure 6c) from the values obtained using all the data occur in June, when the maximum value of water inflow is observed (Figure 5a). However, these deviations do not exceed the estimation errors. In the remaining months, the variations in the estimates of these parameters are also within the 95% confidence intervals, so we cannot consider them significant. Thus, there is no significant dependence of the relaxation rate (p) and the delay in the onset of power-law decay (c) on the watering of the rock.

Discussions

Using the data of long-term monitoring of seismicity and observations of water inflows in the fields of the Khibiny massif, it was revealed that the values of the parameter b_a of the distribution of magnitudes of triggered events ($M_a = M - M_m$) virtually do not change in different periods of watering of the massif. In [*Zhukova et al.*, 2023] it was demonstrated that the influence of watering on the b-value of the distribution of magnitudes of all seismic events is significant (Figure 7). The b significantly decreases in May (the beginning of high watering period) and maintains its lowered value virtually throughout the entire high-watering period until the end of September.

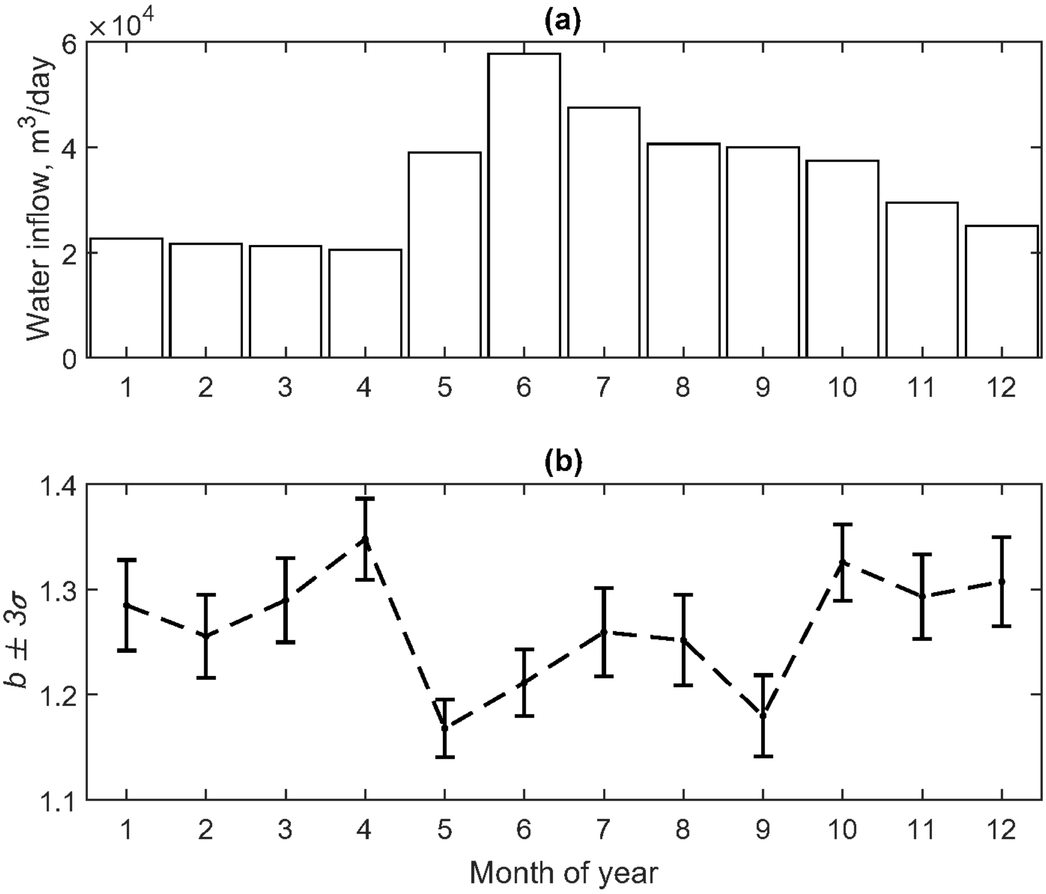

Figure 7. Monthly variations in watering and the b-value for all earthquake with $M \geq 0$ at the deposits of the Khibiny massif for 2002–2020 [*Zhukova et al.*, 2023]. (a) Average water inflow m^3/day; (b) b-values (error bars denote the values of a triple standard error 3σ).

The decrease in the b-value is illustrated even more clearly by the estimates obtained for the periods of high (May–October) and low (November–April) periods of watering of the geologic material. For the period of high watering, $b \pm 3\sigma = 1.30 \pm 0.017$ (σ is standard error); for the period of low watering, $b \pm 3\sigma = 1.22 \pm 0.014$ [*Zhukova et al.*, 2023]. These estimates are separated from each other by more than 3σ, which indicates the significance of the differences.

Despite the fact that the watering of the rock affects the distribution of the magnitudes of all seismic events, the influence of this factor on the distribution of the relative magnitudes of the triggered events ($M_a = M - M_m$) is not observed. Since b-value determines the ratio of weak and strong earthquakes, the proportion between the weak and strong events in the relative magnitudes M_a is maintained in the area under study. This allows to obtain the estimate of the parameter b_a for all the data regardless of the level of watering of the rock environment. This estimate is necessary during the assessment of post-seismic danger, for example, during the calculation of the parameters of the dynamic Bath's law [*Baranov et al.*, 2022; *Motorin and Baranov*, 2022].

As it was noted in the Introduction section, the physical mechanism of emergence of post-seismic activity is described by the *Dieterich* [1994] rate-and-state model, the key point of which is the dependence of the friction coefficient on the slip speed and the state of the fault. An increase in the moisture content of the medium directly affects the state of the fault, decreasing the friction coefficient and increasing the pore pressure. Below, we will try to explain the behavior of the parameters of the Omori – Utsu law using this model. At the same time, we are aware of the limitations of this explanation, since from rate-and-state model it follows that that the relaxation parameter $p = 1$ [*Dieterich*, 1994]. In our case, the estimates of p in most of the cases are greater than 1 (Figure 4a, Figure 6c). Moreover, according to the field [*Sharma et al.*, 2023; *Smirnov and Ponomarev*, 2020] and laboratory [*Smirnov et al.*, 2019] data, a correlation is found between the parameters of the Omori – Utsu law and changes in stresses, indicating the limitations of the model.

Assuming that the rate of tectonic deformation is the same before and after the trigger earthquake and is not equal to zero, the parameters K and c of the Omori – Utsu law using the rate- and state-dependent friction model are estimated as the following [*Cocco et al.*, 2010]

$$K = \frac{r t_a}{1 - \exp\left(-\frac{S}{A\sigma}\right)}, \tag{3}$$

$$c = \frac{t_a \exp\left(-\frac{S}{A\sigma}\right)}{1 - \exp\left(-\frac{S}{A\sigma}\right)}, \tag{4}$$

where r is the rate of background seismicity; t_a is the relaxation time, determining the duration of the aftershock series; S is the change in the Coulomb stresses due to the main shock; $A\sigma$ is the constitutive parameter of the rate- and state-dependent law governing fault friction.

According to the formula (3), productivity K depends on the stress jump, rate of background seismicity, and the value of $A\sigma$. Meanwhile, the parameters r, $A\sigma$ and t_a are strongly correlated [*Cocco et al.*, 2010]. It is difficult to understand how the increase in watering affects the K and c of the Omori – Utsu law using the equations (3) and (4) directly, because the different values $r, A\sigma$ and t_a can result in the same values of K and c. However, if it is reasonable to assume that $S \gg A\sigma$ [*Cocco et al.*, 2010], then the denominator in the formula (3) is approximately equal to 1. Then $K \sim r t_a$. It means that, as the rate of background seismicity (r) and/or relaxation time (t_a) grows, the value of K also increases.

Miller [2020] demonstrated by numerical simulation that the relaxation time has to grow with an increase in watering. A growth in the background seismicity rate during the increase in watering of the rock at the fields of Khibiny massif was also demonstrated in [*Zhukova et al.*, 2023], an illustration is provided in Figure 8. Thus, the observed increase in the parameter K of the Omori – Utsu law with an increase in the watering of the rock in May and June is explained by the rate- and state-dependent model and caused by the growth in background seismicity and relaxation time.

The behavior of the c-value of the Omori – Utsu law, characterizing the delay in the onset of power-law decay of post-seismic activity, does not depend on the level of watering of the rock (Figure 6b). According to (4), c-value depends on the Coulomb stresses jump, relaxation time and the $A\sigma$. During the increase in the rock watering, the $A\sigma$ should decrease due to the growth of the pore pressure and reduction of friction. It would be difficult to unequivocally assume what would the change in the Coulomb stresses S be in this case ($S = \Delta\tau - \mu\Delta\sigma$, $\Delta\tau(\Delta\sigma)$ is the change in the shear (effective normal) stress, μ is the effective friction coefficient). *Miller* [2020] demonstrated that t_a should increase with the increase in watering. It means that theoretically the value of c can both decrease and increase. If we assume that $S \gg A\sigma$ then we will obtain that c is positive and near 0 as it is demonstrated in the Figure 6b.

A similar interpretation of the c-value behavior can be drawn based on the paper by *Shebalin and Narteau* [2017], there they showed that $c \approx \exp[-(\sigma_1 - \sigma_3)]$ for $p = 1$ ($\sigma_1 - \sigma_3$) is the difference between the maximum and minimum stresses). In the Khibiny massif, tectonic (horizontal) stresses at the depths ranging from −600 to −90 m are 40–60 MPa and exceed gravitational (normal) stresses fivefold, and in some cases more than by an order

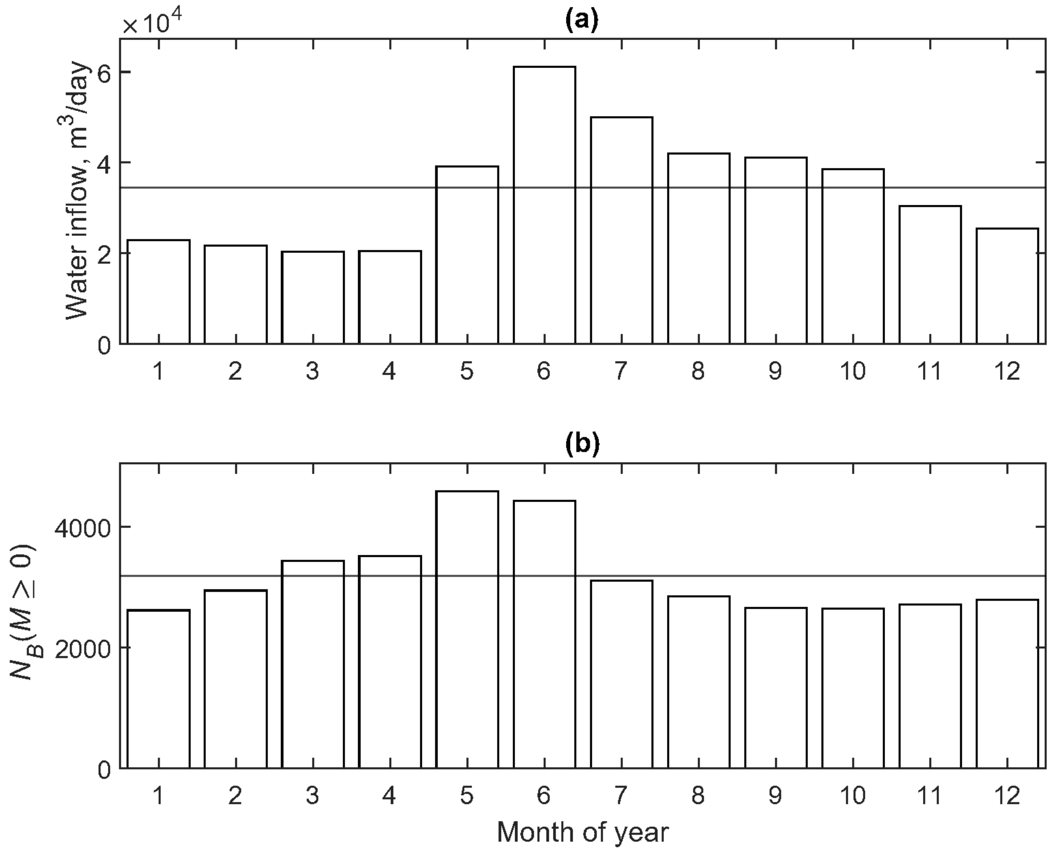

Figure 8. Monthly average variations in the level of watering of the rock environment and the total number of representative background events. (a) Average watering (m^3/day), the horizontal line represents the average value; (b) The number of background earthquakes with $M \geq 0$, the horizontal line is the average value (3188).

of magnitude [*Onokhin*, 1975; *Rebetskiy*, 2007]. (Average depth of representative seismic events in the research area is about −450 m, 95% of them occur at depths from −725 to −100 m.) This means that the c-value should be positive and close to 0. We should note that there is no reason to expand the independence of the c-value on the watering level to all the cases. It is possible that for the other values of stress differences the behavior of this parameter would be different.

We cannot apply similar reasoning to explain the behavior of the p-value of the Omori – Utsu law, characterizing the time decay of post-seismic activity, as the rate-and-state model predicts this law for $p = 1$. And in the Khibiny massif, the p-value in most of the cases is significantly higher than 1 (Figure 4a, Figure 6c).

Miller [2020] using a simple model of crustal permeability, has numerically demonstrated that the decay rate of aftershocks reflects the ability of area tectonics to re-seal cracks resulting from a trigger and triggered earthquakes. Re-sealing of the crack over time reduces the subsequent flow of fluid and therefore the formation of aftershocks. Thus, approximately the same values of p in different periods of watering of the Khibiny massif indicate that the tectonics of the Khibiny are able to quickly re-seal cracks due to earthquakes. (This property is determined by the specifics of tectonics and does not depend on the level of rock watering.) This is also supported by the high level of tectonic stresses in the massif, reaching values of 40–60 MPa at the depths of −600 to −90 m.

In conclusion, we note that the influence of the rock watering on the time decay parameters of post-seismic activity is a complex process with various relaxation mechanisms. The rate and state friction model qualitatively explains only some of the revealed effects. At the same time, the identification of patterns of the influence of watering on post-seismic activity based on field and laboratory data will allow us to obtain a universal model of post-seismic activity and broaden scientific knowledge of transient regimes of seismicity.

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