Approaches to assessing the effectiveness of earthquake predictions using the LURR (load-unload response ratio) method on Sakhalin

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Abstract. A retrospective analysis of the seismicity of Sakhalin from 1997 to 2019 was performed to demonstrate the possibilities of the LURR technique recently in previous our work. The following results were obtained: 84% of earthquakes (16 out of 19, with M ≥ 5) are predicted, 25% alarms (4 out of 15 predicted areas) were false. This paper proposes an analytical dependence to describe the forecast effectiveness (Ke) for this research. The extremes of Ke were found at the value of the alarm period of 12 and 24 months. At the same time, Ke is significantly higher for the alarm period of 24 months and decreases after a two-year alarm period. Another way to prove the results obtained is the random spatio-temporal distributions of the predicted objects (19 earthquakes with M ≥ 5). 10 such random sets have been assigned to 15 predicted areas, the result shows a significant advantage of a real sample over random ones, and also practically confirms the reliability of the algorithm for using the LURR technique. The methodology and results of this work can serve as practical recommendations for working with the LURR method for seismologists.

1. Introduction
In 2021, the paper [1] was published in the journal “Geosystems of Transition Zones”, in which the LURR (Load-Unload Response Ratio) [2] earthquake prediction method was retrospectively applied for Sakhalin seismicity. For the first time for Sakhalin, such a detailed analysis was made for a continuous time period (1997–2019) and on the territory of the entire island. It is very important that after a number of works on this topic [3–5] the authors have systematized the materials, bringing all the calculations to a single database of seismological data according to the catalog of the Sakhalin branch of the Geophysical Survey of the Russian Academy of Sciences. It should be noted that this study aroused a great interest not only among the predictors, a theoretical review of the LURR method, for example, was published almost immediately [6]. So, in the study [1], the Sakhalin territory was scanned with calculated areas in the form of circles with a radius of one degree, but unlike previous works, this was done with a high resolution (number of areas). The entire territory was covered by such zones in increments of 0.5 degrees in latitude and longitude, and the grid was detailed to 0.1 degrees in the three most dangerous seismic zones. A total of 323 calculated samples were processed on the territory of the island (of which 119 were basic and 204 were detailed). The number of earthquakes satisfactory for calculation contained 36 main and all detailed samples. In total, 77 anomalies in the LURR parameter were revealed in 36 main areas over 22 years (1997–2019). Additional calculations (step is 0.1°) helped to identify 5 more anomalies. After identifying the
anomalies of 2019 (it is impossible to retrospectively close the alarm period for them), 69 anomalies were grouped as follows. The calculated areas with anomalies that appeared with small time difference from each other were combined into the forecast zone. The beginning of the alarm period was determined for each forecast zone (from the moment of appearance of the first anomaly in the group). In total, 15 forecast zones have been established on the island for 22 years, which differ in the number of calculated areas and the area of the covered territory. For example, figure 1 shows a large alarm zone of 12 calculated areas and a small one of 2 calculated areas.

![Figure 1](image-url)

**Figure 1.** Examples of forecast zones (large and small) with a LURR parameter graph for an arbitrary calculation area.

Analysis of the data on the alarm zones for the three-year alarm period showed 17 earthquakes out of 19 with $M \geq 5$ to be retrospectively predicted. Also, 4 out of 15 periods turned out to be false, that is, for three years, no any earthquake with $M \geq 5$ occurred in these 4 zones. Thus, the result of this work turned out to be worthy of the forecast topic – 75% of the forecasts were successful for 89% of earthquakes.

Despite the good results, it should be noted that the main problem for the qualitative statistical evaluation of the results was and is the uncertainty of the forecast parameter – the alarm period. It is selected arbitrarily, but it is fixed for all forecast areas. In the work [1], a period of three years was taken as a basic level. At the same time, calculations showed that the waiting period (the time from the alarm announcement to the earthquake) was in most cases small, but alarm periods of three years or more [1] lead to their intersection in space and time. Note that the number of false alarms and missed goals depends on this value (the duration of the alarm).

### 2. Methods and results

In this paper, we will try to evaluate the effectiveness of forecasts using the LURR method, taking into account all the above aspects. To begin with, we will do this at the simplest level for predictive topics in the terminology of capturing, missing a target and false alarms, but we will get these parameters
depending on the duration of the alarm period. Recall that the alarm period is announced for the alarm area for a certain fixed period of time, while the waiting period for an earthquake may be significantly less. For alarm periods from 6 to 36 months (in increments of 3 months), we will determine the number of completed forecasts. The minimum alarm period of six months is justified, because with a sliding window of 360 days, the period for which a forecast can be made cannot be less than half of it (the window), that is, 180 days (6 months).

The analysis results of the forecasts efficiency are shown on the graph (figure 2). We will add the cases of alarm periods overlapping for several forecast zones to the indicators of capturing and missing a target and false alarms.

![Figure 2. Forecast parameters.](image)

Starting from the period of 27 months, the first cases of overlap between the alarm periods with each other appear and this progresses in the future. Thus, the maximum efficiency can be achieved within a period of 24 months, while avoiding overlaps. Such estimates are quite acceptable, but the announced forecasts have different initial conditions also for the area where anomalies are noticed. It turns out that the quality of the forecast is determined not only by the time of implementation, but also by the area of the alarm zone. For example, the M 7 Uglegorsk earthquake – one of the strongest events in the central region of Sakhalin – has occurred 6 months after the anomaly, and the anomaly was noted in only one calculated area. This is one of the best retrospective results. In order to take into account both of these parameters, for each alarm zone, we will determine the proportion of the area that is involved in the forecast from the total area where anomalies are being searched (36 calculated areas).

$$K_i = \left( \frac{N}{N_0} \right) \times \left[ \frac{S_{ai} \times n}{\sum_{i=1}^{n} S_{ai}} \right] \times \left[ \frac{N \times S_i}{N_0 \times \sum_{i=1}^{n} S_{ai}} \times X \right], \quad X = \frac{\left( \sum_{i=1}^{n} S_i \right) \times T_{ai}}{S_0 \times T_0},$$  \hspace{1cm} (1)

Where $N$ – the number of earthquakes in the alarm zones during the considered alarm period $T_{ai}$; $N_0$ – the number of objects (earthquakes) of the retrospective forecast; $S_{ai}$ – the area of the reference forecast zone (the minimum possible equal area of one ellipse); $n$ – the number of alarm zones (in our case there are 15 of them); $S_i$ – the area of the $i$-th alarm zone where the target was captured during
this alarm period $T_{al}$; $N_z$ – the number of alarm zones where a target was captured during this $T_{al}$ alarm period; $N_l$ - the number of alarm zones where there are no earthquakes with $M \geq 5$ during this alarm period $T_{al}$ (false alarms); $S_0$ – the total area of all 36 calculated areas (taking into account the zones overlap, the real area is considered); $T_0$ – total observation period (1997-2019); $T_{al}$ - alarm period

$S_{lk}$ – the area of the k-th alarm zone, where there are no earthquakes with $M \geq 5$ during this alarm period $T_{al}$; $X$ is a coefficient that indicates the degree of anxiety of the studied territory for the entire observation period, which determines the probability of an arbitrary earthquake accidentally hitting the alarm zones for a given alarm period.

Figure 3 shows two types of calculation ($K_e$), the difference of which is in the calculation of the anxiety coefficient $X$. According to the first type, the area of the alarm zone is multiplied not by the declared alarm period $T_{al}$ (except for false alarms), but by the time spent before the implementation. According to the second type, the area of all zones is multiplied by the alarm period $T_{al}$.

Figure 3. The forecast effectiveness depending on alarm period.

Note that the values of $X$, and, accordingly, the values of $K_e$ are noticeably distorted when the alarm zones massively overlap during large alarm periods. Thus, the acceptable coefficient values can only be obtained before the alarm period of 24 months. The same period turns out to be the most favorable for obtaining the best predictive statistics (figure 2). We use this result for the next check of the randomness (non-randomness) of the presented retrospective forecasts. We used a random number generator (the generator is available on the website https://randomus.ru) to get 10 sets of 19 earthquakes in the period from 1997 to 2019. Each earthquake has a date (month and year) and its location generated. Despite the fact that an earthquake could occur anywhere in Sakhalin, we will complicate our case, giving the generator a choice of 36 zones where anomalies are guaranteed to be present (table 1). This is despite the fact that a total of 119 zones were considered, but not all of them turned out to have enough earthquakes to perform the calculation using the LURR method [1].
Table 1. Calculated areas for the retrospective forecast of earthquakes M = 3.3-5 of Sakhalin Island (1997–2019).

| Latitude (°N) | Longitude (°E) | The number of earthquakes in the region in total | M = 3.3–5 |
|---------------|---------------|-----------------------------------------------|----------|
| 1 46.0        | 141.5         | 2091                                          | 458      |
| 2 46.0        | 142.0         | 2324                                          | 520      |
| 3 46.0        | 142.5         | 1814                                          | 382      |
| 4 46.5        | 141.0         | 1588                                          | 335      |
| 5 46.5        | 141.5         | 2469                                          | 474      |
| 6 46.5        | 142.0         | 3082                                          | 569      |
| 7 46.5        | 142.5         | 3401                                          | 1683     |
| 8 46.5        | 143.0         | 640                                           | 327      |
| 9 47.0        | 141.0         | 1433                                          | 322      |
| 10 47.0       | 141.5         | 2396                                          | 420      |
| 11 47.0       | 142.0         | 3258                                          | 539      |
| 12 47.0       | 142.5         | 3241                                          | 532      |
| 13 47.5       | 141.5         | 1843                                          | 378      |
| 14 47.5       | 142.0         | 2727                                          | 486      |
| 15 47.5       | 142.5         | 2123                                          | 310      |
| 16 48.0       | 142.0         | 1378                                          | 347      |
| 17 48.0       | 142.5         | 1479                                          | 377      |
| 18 48.5       | 142.0         | 996                                           | 337      |
| 19 48.5       | 142.5         | 994                                           | 340      |
| 20 49.0       | 142.0         | 1006                                          | 370      |
| 21 49.0       | 142.5         | 1022                                          | 365      |
| 22 49.5       | 142.0         | 864                                           | 325      |
| 23 49.5       | 142.5         | 835                                           | 332      |
| 24 52.0       | 142.0         | 706                                           | 334      |
| 25 52.0       | 142.5         | 982                                           | 500      |
| 26 52.0       | 143.0         | 893                                           | 448      |
| 27 52.5       | 142.0         | 922                                           | 484      |
| 28 52.5       | 142.5         | 1170                                          | 617      |
| 29 52.5       | 143.0         | 1094                                          | 578      |
| 30 52.5       | 143.5         | 732                                           | 381      |
| 31 53.0       | 142.0         | 989                                           | 521      |
| 32 53.0       | 142.5         | 1029                                          | 535      |
| 33 53.0       | 143.0         | 933                                           | 481      |
| 34 53.0       | 143.5         | 769                                           | 419      |
| 35 53.5       | 142.5         | 880                                           | 462      |
| 36 53.5       | 143.0         | 808                                           | 433      |

Thus, if an earthquake occurs in one of the 36 zones within 2 years after the appearance of the anomaly, it is associated with a successful forecast (S), if not, then with a not successful forecast respectively (UnS). The final result for 10 sets is presented in Table 2.
Table 2. Model earthquakes obtained by a random number generator (the first sample).

| Set | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| S/UnS | 10/9 | 9/10 | 11/8 | 11/8 | 12/7 | 8/11 | 7/12 | 12/7 | 10/9 | 7/12 |

3. Conclusion

The result of modeling with random samples for Sakhalin is indicative. The ratio of successful forecasts to unsuccessful ones is close to 1 on average (the randomness of the generated samples is obvious). The most successful implementations of forecasts were 2 samples out of 10 with a 63% implementation percentage (against real sample with 89%). With such results, it already seems pointless to consider the number of false alarms, since this can only further spoil the already bad results. Such an experiment can partially prove that the predictions made using the LURR method are not random. At the same time, the proposed assessment of the LURR method efficiency remains at the qualitative level. However, the results obtained for Sakhalin Island allow us to consider it empirically reliable, especially in view of the practical implementation of two forecasts proposed in real time (for the Onor and Kriylon earthquakes). As a result of the work performed, a method for evaluating the effectiveness of the previous studies is proposed, which allows determining the optimal value of the alarm period and using this in real-time forecasting.

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