Possibility of using satellite-based monitoring for large-scale mapping and research of dynamics of mud volcanic landscapes

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Abstract. Currently Earth remote probing to study vegetation dynamics and monitor volcanic activity is of great scientific interest. The purpose of this study is to create a large-scale outline map of Yuzhno-Sakhalinsk mud volcano which will include the topography objects, mud fields of eruptions of various years and gryphons, and to perform semi-automatic classification of Yuzhno-Sakhalinsk mud volcano. Work was performed with QGIS software using the following modules: «QuickMapServices», «Freehandrastergeoreference», «LatLanTools», and «Semi-AutomaticClassificationPlugin». We developed an outline map of Yuzhno-Sakhalinsk mud volcano on a scale of 1:10000, which shows how the mud flows have changed directions over the last 70 years, as well as mud fields have been formed over the last 20 years. Using semi-automatic classification of satellite images from Sentinel-2A satellite in various color channel sets, we obtained two premaps of Yuzhno-Sakhalinsk mud volcano vegetation on a scale of 1:50 000. Satellite monitoring of YuSMV activity allows us to track the eruptive activity of the volcano, and assess its impact on vegetation.

1. Introduction
Study of vegetation dynamics and assessment of biophysical parameters of vegetation by methods of Earth remote probing (hereinafter ERP) is of interest for a range of scientific and applied tasks [1]. Analysis of current satellite images and data from multyear field observations of plants allows us to assess changes of volcanic landscapes and vegetation recovery speed. ERP was used to study the activity of a number of active magma and mud volcanos: volcanos of the Kuril Islands [2–4], volcanos such as Shinmoedake and Sakurajima (Japan) [4], Kilauea (Hawaii) [4], Saint Helen’s (USA) [5], Ol Doinyo Lengai (Tanzania) [6], etc.

Most scientific works on satellite monitoring of volcanic activity [2, 4], studying of vegetation restoration dynamics and calculation of vegetation index NDVI [3, 5–6], were made for areas up to 50 hectares. The main purpose of our research is to study potential use of ERP data for areas less than 1 hectare.

The object of this study is Yuzhno-Sakhalinsk mud volcano (hereinafter YuSMV) located 20 kilometers north-west of Yuzhno-Sakhalinsk city (N 47°04´53´´E 142°34´43´´); the volcano is listed as a natural monument [7–8]. Data on mapping of this object is very scarce. Existing maps and outline maps of YuSMV contain information on its geological structure [9], location of gryphon [9–10], and types of vegetation [7, 9].
YuSMV eruptions are quite frequent. Strong eruptions were recorded in 1959, 1979 and 2001, smaller ones between 1994 and 1996, then in 2011 and 2020. During an eruption, the volcano throws out a large amount of mud volcanic breccia (about $10^3$–$10^5$ cubic meters) and underground gas (often burning) over a short period of time. This is why mud volcanism is a dangerous geological process which must be taken into account during construction and operation of engineering structures. At gryphon stage, the volcano continually emits relatively small amounts of mud volcanic breccia and gases from gryphons (eruptive instruments on the body of a mud volcano). The total number of gryphons on a volcano remains practically unchanged from year to year and is usually from 50 to 70 [10]. Changes in the temperature mode of the gryphons are caused mostly by variation in the speed of water and mud mixture moving through the gryphon channels [11].

Mapping of YuSMV area and vegetation is necessary for assessing the multiyear dynamics of its activity and identifying additional indicators of its activity.

The purpose of this study is to develop a large-scale (1:10000) outline map of YuSMV which shows the dynamics of the mud volcano landscape, and to look for adequate methods of semi-automatic classification of YuSMV vegetation. In our understanding, the area where YuSMV is located is the current eruptive center and the adjacent medium-altitude mountainous forests with total area up to 8–10 square kilometers [12].

2. Materials and methods

Outline map of YuSMV was developed with indication of topographic objects, boundaries of mud fields of eruptions of various years and gryphons, using QuantumGIS 3.16 (hereinafter QGIS) information system. The following was used as the basis for the YuSMV outline map: multispectral image of south-east part of Sakhalin as of October 19, 2020 from satellite Sentinel-2A [13], satellite image of the area of research (4x4 square kilometers) from SASPlanet software (Yandex-Sputnik section), «OpentopomapRussia» and «Topomap (marshruty.ru)» topographic maps from «QuickMapServices» module installed in QGIS. QGIS is an open-source geological information system [14]. We also used «Freehandrastergeoreference» modules to simplify loading and adjustment of bitmap images, and «LatLanTools» module to show locations on the outline map using known coordinates.

We used «Semi-AutomaticClassificationPlugin» (hereinafter «SACP») module installed in QGIS for semi-automatic classification of YuSMV vegetation (hereinafter classification).

3. Results and discussion

Topographic objects shown on the outline map of YuSMV include the railroad, a forest road, a path, rivers (the Alat and the Puta) with their outlets and tributaries, primary heights (295 m and 354 m). Using the outline provided by O. Melnikov [9], we updated our outline map of YuSMV with boundaries of mud fields which appeared in 1959, 1966, 1979, 1996, and 2001, a large gryphon mound 6–7 meters in diameter at the base and about 1 meter tall, as well as smaller gryphons (73 ea). Boundaries of the 2011 mud field were formed using the results of a field survey by V. Yershov [10]. Scopes of YuSMV emissions and their boundaries from the 2020 eruption were studied in detail by teams from the plant ecology and geocology lab and geospheres material composition research lab of the Resource Sharing Center of the Institute of Marine Geology and Geophysics of the Far East Branch of the Russian Academy of Science when the teams performed field work at the volcano in 2020.

YuSMV mapping using satellite images allowed us to identify landscape changes in its territory. In the last 60–70 years, YuSMV eruption fields have changed quite significantly since the 2001 eruption. Before 2001, mud emissions from large eruptions of 1959, 1966, and 1979 went south-east towards the outlet of the Puta River. In 2001 a large mud flow went 600 meters north-west from the supposed eruption center. It reached and blocked the outlet of the Alat River. Therefore, mud fields from the more recent eruptions have a different shape. Judging by the image from SASPlanet software (Yandex-Sputnik section), the latest YuSMV eruption of 2020 is
relatively large, but not as powerful as the 2001 one. Direction of the 2020 primary mud flow is the same as in 2001 (figure 1). Mud flows of the 2020 eruption have completely destroyed all vegetation along the 2001 flow and its boundaries, which is clearly seen on the satellite images.

Figure 1. Outline map of YuSMV: 1 – railroad; 2 – forest road; 3 – path; 4 – rivers; 5 – rivers outflows; 6 – primary heights; 7 – mud fields after the 1959 eruption; 8 – mud fields after the 1966 eruption; 9 – mud fields after the 1979 eruption; 10 – mud fields after the 1996 eruption; 11 – mud fields after the 2001 eruption; 12 – mud fields after the 2011 eruption; 13 – mud fields after the 2020 eruption; 14 – a large gryphon; 15 – smaller gryphons and salsas.

Semi-automatic classification, or controlled classification (classification with a learning curve), is placing each of the image pixels into a certain class of objects matching a certain area in the spectral properties. This type of classification is used when a learning curve can be set on the image. A learning curve is a set of sample areas which were placed into a certain class of objects based on the data of on-site inspections, detailed images or maps, and which are clearly identifiable on the image [15].

According to scientific and practical recommendations of A. Karpachev [16‒17], Landsat and Sentinel-2A satellite images can be processed and classified successfully. A. Karpachev classified the above satellite images in QGIS using «SACP» module to identify areas of dry and disturbed forest in Orlovskoye Polesye national park (Oryol Region, Russia). He found that Sentinel-2A images were clearer than Landsat images, and had a better match to the geographic data, because the parameters of visible satellite image channels for Landsat are 30 meters, while for Sentinel-2A they are 10 meters. Therefore, using Sentinel-2A satellite images seems more appropriate for small areas. Sentinel-2A satellite images allow to show the difference in the vegetation condition, including its changes over time. In our case, mud volcano monitoring covers a small area, so Sentinel-2A satellite images are more relevant for us. Visual and automatic interpretation of satellite images of YuSMV with use of on-site observations allowed us to obtain the boundaries of eruptions of 2020, 2011, 2001 (partial), the boundaries of grassland vegetation and various types of mixed and coniferous forests (figure 1, 5). We also classified the boundaries without vegetation, locations of fresh breccia and active salsas in the forest.

When we interpreted and selected channels of multispectral image of YuSMV and mapped the new mud field of the 2020 eruption, we used recommendations of D. Kurbatsky [18] and the information table for channels interpretation prepared by D. Dolgopolov [19], showing comparison of channels of multispectral images from different satellites (MODISMCD43A4, Landsat 8, Sentinel-2A).

The «artificial colors» combination (8–4–3 for Sentinel 2-A, 4–3–2 for Landsat 5, 7) is widely used for studying vegetation, monitoring drainage and soil mosaic, and also for studying crop species
Vegetation is shown in shades of red, soil color varies from dark brown to light brown, clouds look white of light blue. Overall, deep shades of red are indicative of healthy vegetation of all kinds, while the lighter colors mean grass and shrubs or sparse forest [18]. In our opinion, this set of channels is not suitable, because yellow leaves are shown in blue, just like a mud field or clouds, which makes classification more difficult (figure 2).

![Figure 2. Image of YuSMV (Sentinel-2A, 19.10.2020) in the 8–4–3 color set. The red contour shows that the clouds, mud field, and yellow vegetation are all shown in the same color.](image)

When we performed classification, we tried using two sets of channels: 4–6–12, as proposed by A. Karpachev [17], and 4–3–2 («natural colors»). In the 4–6–12 channels set the colors look more natural than in the «natural colors» set. The 4–6–12 color set has a wide range of colors, areas without vegetation are shown in bright colors; the «healthy» vegetation, dry and sparse vegetation are also visualized quite well. In the 4–3–2 color set the objects on the ground look the way a human eye sees them, with less contrast, but visually telling one kind of vegetation from another is more difficult than
in the 4–6–12 set. Also, the image in the 4–3–2 color set is sharper, because channels 2, 3, and 4 have image resolution of 10 m, while for channels 6 and 12 it’s 20 m (figure 3–4).

As a result of classification performed for YuSMV (1:50000 scale), areas without vegetation are clearly visualized. We can see various versions of forest vegetation: sparse forest with bamboo, synusia of tall grass in forest communities, or forest communities (figure 5). As a result of classification in the 4–6–12 color set we mostly visualized sparse forests with bamboo and synusia of high grass in small-leaved forest communities, and classification in the 4–3–2 color set shows small-leaved forest and synusia of tall grass with bamboo in mixed small-leaved and dark coniferous forest communities. Areas shaded due to area landscape peculiarities are hard to classify. We can tell which result is more accurate and which set of colors is more suitable for further studies of YuSMV only after we compare these results to field studies results.

![Figure 5. Results of classification in 4–6–12 (a) and 4–3–2 (b) color sets. 1 – Areas without vegetation. 2 – Sparse forest with bamboo. 3 – Small-leaved forest. 4 – Synusia of tall grass in small-leaved forest communities. 5 – Synusia of tall grass and bamboo in mixed small-leaved and dark coniferous forest communities. 6 – Mixed small-leaved and fir forest. The red contour shows clouds.](image)

4. Conclusion
As a result of our work on creating an outline map of YuSMV using visual and automatic interpretation of satellite images of YuSMV and using on-site observations, we have created eruption boundaries for the last 20 years, and showed how large eruptions of a mud volcano change its landscape.

Using semi-automatic classification with «SACP» module in QGIS, we found that this method is suitable for large-scale mapping and study of dynamics of woody plants in volcanic landscapes. Further work on creating YuSMV vegetation map requires a comparison of this study results with data which will be obtained during field work.

Satellite monitoring of YuSMV activity is very important. It allows us to track the eruptive activity of the volcano, assess its impact on vegetation. Satellite monitoring also allows us to perform a more detailed analysis of the vegetation, both close to the volcano and several kilometers from the eruption center, trace the succession process, and determine the exact location of potential field work.

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