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METHODOLOGICAL APPROACHES TO ASSESSING THE STATE OF IRRIGATED LANDS IN THE DRY STEPPE ZONE OF THE VOLGOGRAD REGION USING SATELLITE IMAGES

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In this article we present the materials of studies that were carried out in the Volgograd Region. They can be used as the basis for methodological recommendations to map and determine the area and condition of irrigated lands using satellite images. They were obtained during the long-term researches in the irrigated lands in the Volgograd Region that took place on solonetz complexes in the dry steppe. Satellite imagery will help to map and determine 1) the areas of irrigated lands, 2) the areas and age of fallow lands in irrigated territories, 3) the state of irrigated soils and factors that limit their fertility. Crops growing in different hydrogeological conditions react differently to those limiting factors. Therefore, to compile a map it is recommended to adhere to such stages as identifying fields with different crops and fallow lands; highlighting patches in the images with sparse or absent crops; on the basis of field researches and analyzed soil samples, establishing the cause of the patchiness; selecting an algorithm for processing satellite images based on the results of field researches. The patchiness of irrigated fields, reflected in the images, can have a different origin, so their interpretation requires a mandatory study of the characteristics of the chosen area. Patchiness associated with secondary and residual salinization of soils is determined by the state of vegetation; therefore, the pictures should be taken during the period of high vegetative activity of plants. Among other things, it is necessary to obtain data on the level of groundwater, because its critical level is the main cause of secondary salinization. For deeply saline soils, it is necessary to build a salt map using interpolation of point data that was obtained in the field and laboratory. Patchiness associated with the carbonate content in the surface horizon does not depend on the level of groundwater and is best seen on the images showing an open soil surface. The accuracy of the map is checked by comparing it with maps of a larger scale and field observations, as well as by evaluating the accuracy of the classification of the image by determining the verification indexes. The materials presented in our article are intended for a wide range of specialists who use space information in their work, as well as for soil scientists, agronomists and chemists who work in agriculture in the southern regions of Russia.

Keywords: dry steppe zone, irrigated lands, saline soils, satellite imagery, mapping of irrigated soils.
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The Volgograd Region is the largest agricultural region in Russia. According to the Ministry of Agriculture (Report on the state ..., 2022), the total area of arable lands in this region as of January 1, 2021 was about 5794 thousand hectares, of which 178.840 thousand hectares were irrigated.

Irrigation in the Volgograd Region began long before the revolution, and by the 19th century the area of irrigated land was 8.7 thousand ha (Prikhodko, 2012). Widespread and regular irrigation began to develop around the 50-60s and reached its peak in 1989, with 345.2 thousand ha of irrigated territory, which was 4.6% of all agricultural land in the region (Pankova, Novikova, 2004). In the 1990s, due to the difficult economic situation in the country, the irrigated area sharply decreased. In 2001, they amounted to 259.4 thousand ha, i.e. 3.2% of the area, and by 2015 only about 179 thousand ha remained (Pankova, Novikova, 2004; Gorohova et al., 2019). In 2021, the area was almost the same, about 178.840 thousand ha.

The lands of the dry steppe of the Volgograd Region are actively used for arable lands, hayfields and pastures. The local soil cover is made of various combinations, including chestnut non-solonetzic and solonetzic soils of the well-drained watersheds; chestnut solonetzic complexes with different percentage of solonetzes in automorphic, semi-hydromorphic and hydromorphic conditions; combinations and patches of meadow-chestnut and meadow soils of different salination and alkalinity; and alluvial soils in river valleys. Many Soviet and Russian researchers established the main patterns of the natural soil state for the dry steppe zone under the virgin conditions, at the early and following stages of the active agricultural development (Antipov-Karataev, 1953; Ivanova, 1928; Ivanova, Fridland, 1954; Kovda, 1937; Rode, Polsky, 1961; Friedland, 1964; Minashina, 1978; Zimovets, 1991).

From the 60s of the 20th century, the classical methods for studying soils of solonetz complexes have been actively expanding, eventually adding remote sensing (aerial and satellite imagery) to the list. So, these days, the satellite method is among the main ones for studying and mapping the condition of irrigated lands. Those images are high-precision spatio-temporal models that provide data on the dynamics of the land use degradation and patterns for long periods of time. Interpretation of satellite imagery helps to determine the diverse natural features of irrigated lands and important elements of agricultural activities, such as crop rotations, irrigation methods and reclamation measures. It is also possible to determine many dynamic states of natural complexes in the natural and anthropogenic conditions.

In Russia, satellite data is actively used for mapping fallow lands, because significant areas of abandoned land is a serious problem of the country (Kurbanov, 2010; Kanatieva, 2013; Fazylova, 2014; Aldoshin et al., 2015; Rukhovich, Shapovalov, 2015). Besides that, salinity of irrigated soils is also studied (Novikova et al., 2009; Savin et al., 2014; Konyushkova, 2014).

An opportunity to assess the current state of irrigated soils remotely is especially important for hard-to-reach areas, because it improves the management strategy of the entire irrigated complex as a whole, allowing to reduce time and cost required for ground and laboratory researches.

However, the interpretation of remote data requires a mandatory study of every feature specific for the study area using the field work and analysis of soil samples. Many years of our experience confirm the need for joint use of ground and remote methods.

The purpose of this article is to present the experience and materials of long-term studies that were conducted in the irrigated lands in the Volgograd Region using the remote sensing data which shows the features of the studied region and provides necessary information for the further development of methodological recommendations.

Study methods. We used satellite data and modern methods required to process it, as well as field studies of soils and laboratory methods for determining the composition of soluble salts: usage of water extract (1:5) to determine the amount of toxic salts (%); measurement of Ca^{2+}, Na^{+} and Cl^{-} activity in soil pastes with a constant moisture content of 40%, using ion-selective electrodes (mmol/l); determination of $CaCO_3$ (%) in soil profile (Arinushkina, 1970; Khitrov, Ponizovsky, 1990).

1. Satellite Data for Assessing the State of Irrigated Lands in the Dry Steppe Zone of the Volgograd Region

1.1. Requirements for Satellite Imagery

Over recent decades, satellite imagery has been helping to obtain objective information about many objects, their homogeneity/heterogeneity, anthropogenic disturbance, and the way to use them.

The main characteristic of those images is their type, because they can be panchromatic and multispectral in the visible, infrared or radio range of the electromagnetic spectrum. Aside from that, their spatial resolution is important, together with the season and time when the images are taken. Certain characteristics help with certain kind of research and depend on the features of the study area.

Satellite imagery resolution. Today there is a wide selection of high spatial resolution images (up to 15 m) and ultra-high (up to 1 m) images that can be purchased for further study. To solve the problems of surveying irrigated lands, satellite multispectral open-access images of the Landsat Survey System have proven themselves quite well, having a resolution of 30 m in the multispectral range, and 15 m in the panchromatic range per 1 pixel, as well as the images of Sentinel-2, because they have a resolution of 10 m per 1 pixel in the multispectral range.

Satellite imagery type. A series of zonal images is a spectral summary of the studied object. Based on our experience, it is recommended to use multispectral (with RGB and infrared ranges) and panchromatic images for irrigated soils, because the red and infrared zones of the spectrum are the most informative for the analysis of the state of crops and soils, and the panchromatic images are required to increase the overall resolution.

When working with digital images, it is necessary to use those that have passed such processing stages as spatial referencing to a coordinate system (i.e. geocoding), conversion to a standard projection type, and orthorectification. When the Landsat and Sentinel images are downloaded, it should be noted that they undergo two levels of processing, which are the primary radiometric or geometric correction and geocoding or conversion to the WGS-84 standard. Table 1 below shows the most commonly used projections in Russia.

Table 1. Main geodetic coordinate systems and projections.

Geodetic coordinate systems	Projection	Ellipsoid
SK-42 (Pulkovo)	Gauss–Krüger transverse Mercator	Krasovsky 1940
WGS-84	Universal transverse Mercator	WGS-84

Satellite images from the foreign distributors come pre-converted to the WGS-84 coordinate system, but Russian topographic maps are compiled in the local SK-42 system. The difference between coordinates in these systems can reach 2 km along the Y axis in WGS-84 (or X in SK-42 system), and several 100 meters along the X axis (Labutina, Baldina, 2011). Therefore, when sharing (i.e. overlaying) foreign satellite images and Russian maps, it is necessary to convert them all into the same system.

Adjustment of coordinate systems is necessary for the ground work as well, when the coordinates are determined by a global navigation satellite system, such as GPS or GLONASS. However, many modern GPS receivers can already transit from WGS-84 to SK-42 (Pulkovo).

The third stage of image processing is orthorectification, which can be either ordered to be performed by the specialists or carried out personally. It is a necessary stage for mountainous terrain due to distortions caused by the deviation of the optical axis of the satellite camera from the vertical position in the moment when a picture is taken, as well as by the translocation due to the relief. To make the contours that were selected on the image fit the map exactly, it is necessary to transform them, because even for flat terrains, the error in the planned location of points can be up to several meters. In Table 2 below we show the points on the plan deviating from the average height of the area depending on the angle that the images were taken at.

Besides, orthotransformation is carried out taking into account various relief models. The most commonly used modern digital model is the Shuttle Radar Topography Mission (SRTM), which was created on the basis of a radar survey from the Shuttle space shuttle made in 2000. SRTM is an international project that is used to form a digital elevation model of a part of the globe (from S56° to N60°). Originally, its grid was about 30 m; later, the public version was released with the grid up to 90 m. The latest version of this model (released in 2009) provides an absolute height accuracy of 16 m and a relative height accuracy of 10 m (Labutina, Baldina, 2011).

Table 2. The error severity on the plan/map depending on the terrain and angle of deviation from the nadir (ENVI User Manual …, 2014).

Angle of deviation from the nadir (°)	**Height deviation on the plan from the average value of the relief on the ground (m)**				
	2	**10**	**50**	**100**	**500**
5	0	1	4	9	44
15	0.5	3	13	27	134
25	1	5	23	47	233

Period and season for satellite imagery. It is recommended that the year of shooting be consistent with the year of research. The season should correspond to the period when the studied objects (such as irrigated lands) are at their peak contrast in the images. To identify irrigated lands, it is better to use images for the spring-summer period (from Mat to early June), because they clearly show which lands are cultivated and which are not. In addition, during that period, different crops (ripened winter cereals, fodder) and fallows are well distinguished (Fig. 1).

1.2. Pre-processing

Satellite images are processed with the help of special programs that often provide the extraction of information along with the integration of images with GIS data. Those programs are quite numerous and vary in complexity. ENVI, ERDAS Imagine and PCI Geomatica are the most popular among the high-level ones, carrying out a full processing of all currently existing types of remote surveys.

There are also freely distributed programs that can be used to perform basic image processing. For example, MultiSpec can open, view and process multispectral and hyperspectral images; ILWIS and QGIS can process images, including their geometric transformations and coordinate referencing, and work with vector maps, providing import and export of commonly used raster and vector data formats.

Most GIS packages (AutoCADMap, MapInfo, ArcGISDesktop/Workstation and its most common modules Arc/Info and ArcView) can create vector maps from a raster background, but cannot carry out various classification and index calculations. However, they can create vector maps based on images that were obtained after a preliminary processing in special software packages.

Image preparation. Image processing includes a many brightness transformations, which improve the overall quality both for visual interpretation on the screen and for subsequent automated processing. Among the most commonly used transformations are contrast enhancement, filtering, synthesis of different channels, creation of index images and image classification by brightness.

Filtering is a necessary step in the imagery pre-processing for the further analysis. Often it is needed to find out the changes that the spectral properties of soils and vegetation go through over time, or to analyze the brightness characteristics in the images of different sensors. In this case, satellite images should be comparable. It is also necessary to exclude the influence of the atmosphere on the image. Making appropriate corrections is called radiometric calibration and atmospheric correction. Radiometric calibration is designed to eliminate the system interference of sensors, and atmospheric correction is required to eliminate the atmospheric influence (Fig. 2).

Another image enhancing technique is to increase the geometric size of a pixel, usually a multispectral one (30 m for Landsat OLI-8), by combining it with an image of a higher spatial resolution, usually a panchromatic one (15 m for Landsat OLI-8). In order to do this, all images must be obtained by one sensor only or be in the same coordinate system and projection. The specialized programs listed above have special options for combining images of different resolutions (Fig. 3).

A) 01/05/2016.

B) 08/07/2016.

Fig. 1 A, B. Irrigated lands and crops on the Landsat OLI-8 images for different months: A (01/05/2016) – in the early May winter cereals and fodder are well defined, B (08/07/2016) – in June winter cereals have been harvested, but fodder is still well defined.

C) 08/09/2016.

Fig. 1 C. Irrigated lands and crops on the Landsat OLI-8 images for different months: C (08/09/2016) – in September crops are already harvested, but the harvested fields where the winter cereals were and the plowed fields are well defined.

1.3. Pre-field Study of Irrigated Lands

To study the irrigated lands, the irrigation systems should be preliminary identified based on satellite imagery. Unlike rainfed lands, irrigated ones have their own deciphering features, the main ones being as follows below.

1. The irrigated fields are usually smaller than rainfed crop fields;
2. The irrigated fields are fed by a head irrigation canal and smaller distribution canals that can be seen on the image;
3. The irrigated fields can be usually defined by their round shape (Fig. 4).

It is recommended to study the irrigation systems on topographic maps, so that the obtained information could be used later to analyze the image. The map helps to accurately identify the irrigation systems that functioned in the Soviet period, while the satellite image helps to understand what is happening to them these days. Figure 5 shows irrigation systems located along the Volga-Don Canal. When comparing the images on the topographic map of 1984 and the satellite image of 2016, it can be noted that not all systems are currently functioning, and the configuration of some irrigated areas has changed due to the cultivation of additional areas.

According to the cadastral registration, many lands are registered as irrigated, but in fact they are used for dry farming, therefore it is not entirely correct to classify them as irrigated. Unfortunately, even with the satellite images and field studies available, only the land owners can tell whether their lands are irrigated or used for dry farming.

Allocating the cultivated and fallow lands. A preliminary visual analysis of the satellite RGB-image makes it possible to establish if the irrigation system is partially or completely abandoned and has turned into a perennial fallow. A blurred pattern and an absence of crops distinguish the perennial fallow land from crop fields during the active growing season. Sometimes the image shows that the distribution canals have no water or are filled up with soil.

To separate irrigated and non-irrigated fields on multispectral space images, we select and use a combination of different channels (Fig. 6, 7).

A) Original image. B) Image after radiometric calibration.

C) Image after atmospheric correction based on the MODTRAN model.

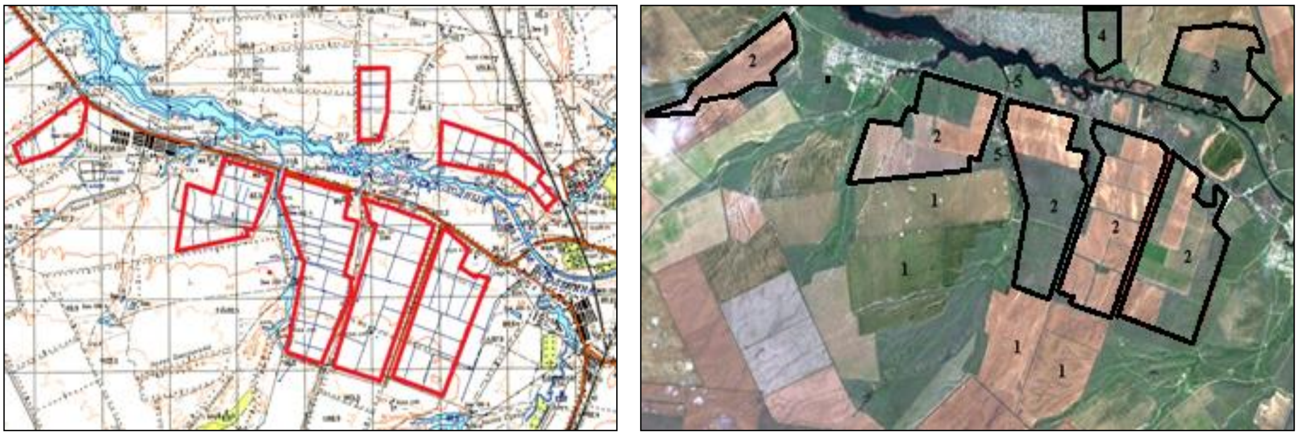
Fig. 2. Filtered Landsat OLI-8 images (09/06/2015).

A B

Fig. 3. A – multispectral image of irrigated lands obtained from Landsat OLI-8 on 01/05/2016, B – combination of a multispectral image and a panchromatic channel.

A B

Fig. 4. Irrigation canals on satellite images: A – mail canal, B – pivot irrigation and temporary sprinklers on the satellite images obtained from Yandex.ru and Pliedas on 18/04/2019 for the irrigated lands of the Volgograd Region.



A B

Fig. 5. Irrigation systems along the Volga-Don Canal. *Legend:* A – on a topographic map of 1984 (scale 1:100,000), B – on a satellite image (RGB; obtained from the Landsat OLI-8 on 01/05/2016; 1 – lands for dry farming, 2 – irrigated lands, 3 – irrigated areas with an increased area, 4 – abandoned irrigated lands (Gorokhova et al., 2020), 5 – irrigation canal.

When allocating a perennial fallow in the Landsat-8 satellite image (04/04/2020) using a combination of channels 7, 5 and 4 (short-wave infrared, near infrared and red), a younger fallow (up to 5 years old) is showed in bright pink, while the more mature one is paler (Fig. 6).

The irrigated lands are well distinguished on the Sentinel-2 satellite image (27/07/2020) in the 2, 3 and 4 channels (green, red and near infrared) as the bright purple patches (Fig. 7).

During the survey of irrigated lands from May to June, mature winter cereals are well distinguished in the image from forage fields (Fig. 8).

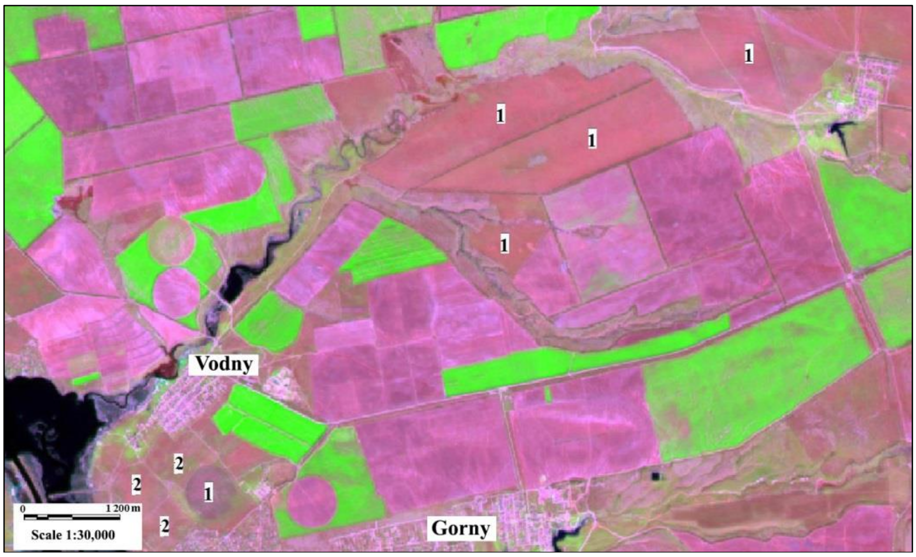


Fig. 6. Long-term fallow lands on a Landsat-8 image obtained on 04/04/2020 for the central part of the Volga-Don irrigation system, channels 7, 5 and 4 (short-wave, infrared, near infrared and red; Gorokhova et al., 2021). *Legend:* 1 – fallows up to 5 years old, 2 – fallows over 5 years old.

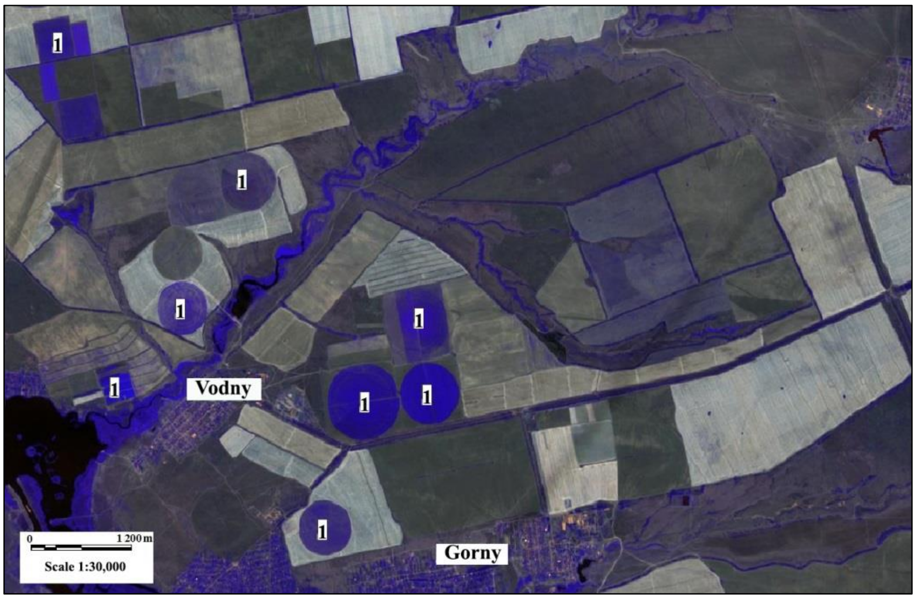


Fig. 7. Irrigated areas (1) on a Sentinel-2 image obtained on 27/07/2020, channels 2, 3 and 4 (green, red and near infrared; Gorokhova et al., 2021).

The result of automatic crops allocation in the irrigated lands during the Pliedas multi-zonal ultra-high resolution satellite image (0.5 m) processing is shown in Figure 9. It was necessary to separate fields with different crops, for which the ISODATA unsupervised classification algorithm was used (i.e. image classification without training). The main parameter set before processing was the number of classes (3) that we wanted to obtain in the end. As a result of automatic image processing, fields with mature winter cereals, harvested winter crops and forage grasses were identified (Fig. 9).

After a visual or programmed vectorization of the irrigated lands, different crop fields and fallow lands, it is possible to automatically calculate the areas of each object (Fig. 10, 11).

Determining the soil properties in the irrigated lands. The surface of irrigated fields is often characterized by heterogeneity, i.e. patchiness, which can be clearly seen on the materials of remote sensing. Depending on the soil properties, the images of the fields vary.

Fig. 8. Fields with different crops and perennial fallow lands on the Landsat OLI-8 RGB-image obtained on 01/05/2016 (Gorokhova et al., 2020). *Legend:* 1 – winter cereals, 2 – fodder field, 3 – mown fodder field, 4 – fallow arable land, 5 – perennial fallow.

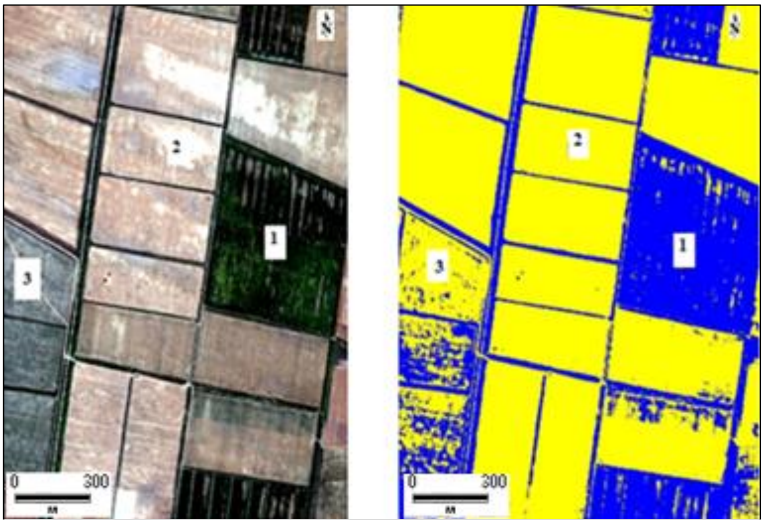
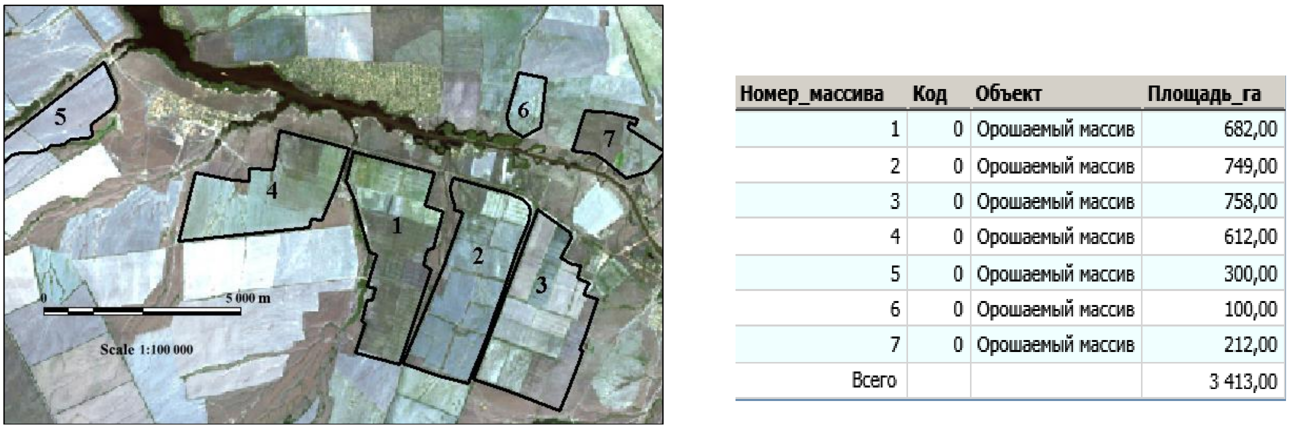


Fig. 9. Part of a multispectral Pliedas image (20/05/2015) after an unsupervised classification (ISODATA) to identify the fields with different crops in the Volgograd Region (Gorokhova et al., 2018). *Legend:* 1 – fodder field, 2 – ripe winter cereals, 3 – harvested winter cereals.

The objects of our study were the irrigated lands of the Svetloyarsk Irrigation System in the Volgograd Region, located in different natural regions: the “Chervlenoe” is located in the north of the Yergeni Upland; the Svetloyarsky and Raigorodsky irrigated massifs are located in the Northern Sarpinsky Lowland of the Caspian Lowland (Doskach, 1979). Further below we discuss the natural features of this study areas and the state of its irrigated massifs in the past and at the present.

The entire Volgograd Region has extremely poor and uneven soil moisture due to heavy rainfall, the main source of moisture being the melted snow.

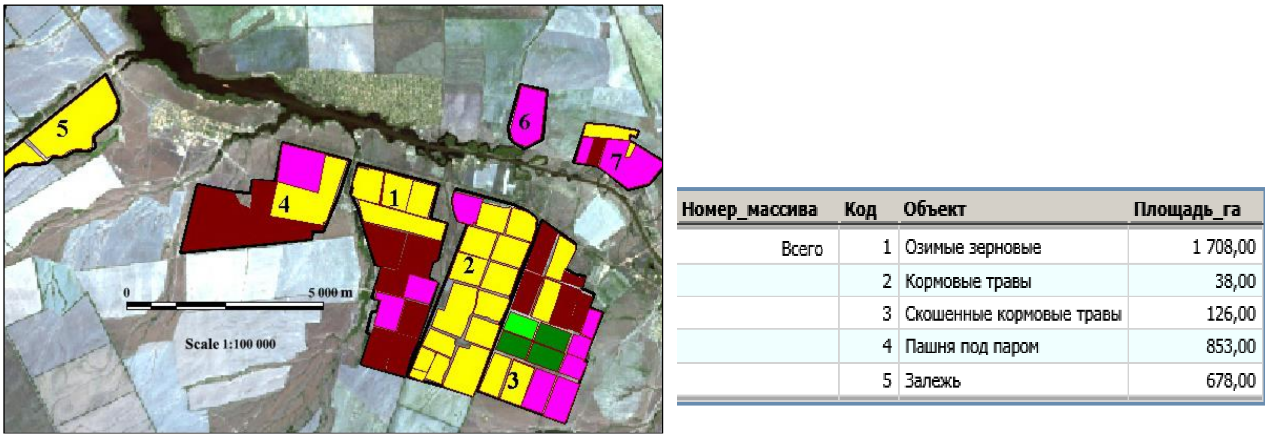
Only the northern part of the Yergeni Upland enters the Volgograd Region. Its elevation values do not exceed 150-180 m, with watersheds and slopes of river valleys and gullies being the dominant type of relief. Before irrigation groundwater on its watersheds was as deep as 18-20 m, and down to 5 m in depressions. The water mineralization was 1-10 g/l, varying from chloride-sodium-magnesium to sulfate-calcium composition.



Номер_массива	Код	Объект	Площадь_га
1	0	Орошаемый массив	682,00
2	0	Орошаемый массив	749,00
3	0	Орошаемый массив	758,00
4	0	Орошаемый массив	612,00
5	0	Орошаемый массив	300,00
6	0	Орошаемый массив	100,00
7	0	Орошаемый массив	212,00
Всего			3 413,00

A B

Fig. 10. Irrigated territory along the Volga-Don Canal (A) and its area (B), marked and calculated on a synthesized Landsat-8 OLI RGB-image obtained on 19/06/2015 (Gorokhova et al., 2020). *Legend:* 1-7 – irrigated areas; right column – their area, ha; bottom line – total area, ha.



Номер_массива	Код	Объект	Площадь_га
Всего	1	Озимые зерновые	1 708,00
	2	Кормовые травы	38,00
	3	Скошенные кормовые травы	126,00
	4	Пашня под паром	853,00
	5	Залежь	678,00

A B

Fig. 11. Fields with different crops and fallow lands in the irrigated territory along the Volga-Don Canal (A) and their area (B), marked and calculated on a synthesized Landsat-8 OLI RGB-image obtained on 19/06/2015 (Gorokhova et al., 2020). *Legend:* 1 – winter cereals, 2 – fodder fields, 3 – harvested fodder fields, 4 – leys, 5 – fallow lands; right column – their area, ha.

Before irrigation the soil cover was a complex of light chestnut solonetzic soils and solonetzes (25-50% and >50%) with a low proportion of meadow chestnut soils. The soil-forming rocks were saline carbonate loess-like loams and clays. Solonetzes were dominated by medium and deep solonetzes, saline starting at 20-40-centimeter-depth and predominantly sulfate-magnesium, often with the participation of soda in the solonetzic horizon (Degtyareva, Zhulidova, 1970).

The beginning of the irrigated development of this area dates back to the 60s of the 20th century.

In the late 80s and early 90s, i.e. during the irrigated development, the groundwater level in the "Chervlenoe" massif reached its critical values of 3-2.5 m, and 1.5-2 m in some other areas. This caused the secondary soil salinization over a very large area. Since the mid-90s, the massif was not irrigated at all, but in the 2000s some of its fields were finally used for irrigation. Currently, its groundwater level is deeper than 5 m.

The "Chervlenoe" massif has been irrigated and continues to be irrigated from the Volga-Don Canal. The canal's mineralization is of hydrocarbonate-sodium composition, varying from 0.72 to 0.84 g/l. Initially, it was a surface irrigation, but from the 2000s the sprinkler irrigation has been used.

The Svetloyarsky and Raygorodsky massifs are located in the Northern Sarpinsky Lowland of the Caspian Lowland. The northern Sarpinsky Lowland is a marine plain of the Early Khvalynsk transgression, with its absolute heights ranging from 40-50 m in the north to 15-30 m in its center. In general, this area is poorly drained. Its main landscape type is a loamy complex plain, with well-distinguished strips of flooded and depressed meadows along the gullies. Its soils are predominantly light chestnut solonetzic, with solonetzes (25-50% and > 50%), and desalinated meadow-steppe and meadow in depressions (Doskach, 1979).

The soil-forming rocks of this plain are the sediments of the Khvalynsk Sea: clays, loams with a high concentration of soluble salts, with the highly saline chocolate-colored clays underneath. If the chocolate clays are located a bit closer, they become soil-forming rocks (Degtyareva, Zhulidova, 1970).

The Svetloyarsky and Raygorodsky massifs have been irrigated and continue to be irrigated from the Volga River. Its composition is hydrocarbonate-calcium and mineralization is 0.4-0.5 g/l.

The drip and sprinkling methods are currently used in the Svetloyarsky massif, although in some fields the surface irrigation is implemented. Its groundwater level never reached past the 3 m threshold throughout the entire period of irrigation; however, for the last 10 years it remains deeper than 5 m.

The groundwater level of the Raigorodsky massif reached its critical values of 3i2.5 m in the early 1990s, and 1.5-2 m in the south of the area. This caused the secondary medium and strong soil salinization in some parts of the massif in a 1 m layer. The soils of the former depressions were the first to become salinized, which, with a close location of groundwater, underwent the process of secondary salinization. From the mid-90s to the present, the massif has not been irrigated and is considered a perennial fallow.

During the construction of the irrigation system, all massifs underwent a strict field planning.

The long-term studies on the "Chervlenoe" irrigated massif helped to determine that the secondary soil salinization patchiness manifests itself whenever the groundwater level is high (2.5-1.5 m), leading to the withering of fodder grasses that looks like light spots of various sizes and characterizes a strong salinization down to 1 m regardless of the size of the spots. The dark color in the image with fodder grasses reflects low and medium salinity in the fields with large patches (100-500 m^2), as well as non-saline and slightly saline soils in the fields with small and medium patches of dead grass (< 50 m^2 and 50-100 m^2; Fig. 12).

It was also determined that the light patches of the Chervlenoe and Svetloyarsky massifs can be associated with the carbonate content of the arable horizon. There are two types of a carbonate profile formation in the study area. The first type is the removal of the humus horizon during the field planning for the irrigation system construction, followed by the filling that is carried out using a mixture of different horizons. The said filling usually contains carbonates. In some cases, during planning a large part of the soil profile was removed, including the horizon with the white lime nodules. In case of the second type, the secondary surface carbonization occurs due to the soil solutions moving up to the surface into the layer with roots. Both types were previously discussed in some earlier works (Baranovskaya, Azovtsev, 1981; Zimovets, 1991; Lyubimova, Degtyareva, 2000; Sizemskaya, 2013).

Leveling and removal off elevated areas led to the removal of solonetzic horizons from crusty and small solonetzes that used to occupy elevated forms of micro- and mesorelief. As a result, solonetzes are quite rare in irrigated fields, but sometimes the fragments of their horizons can be found there.

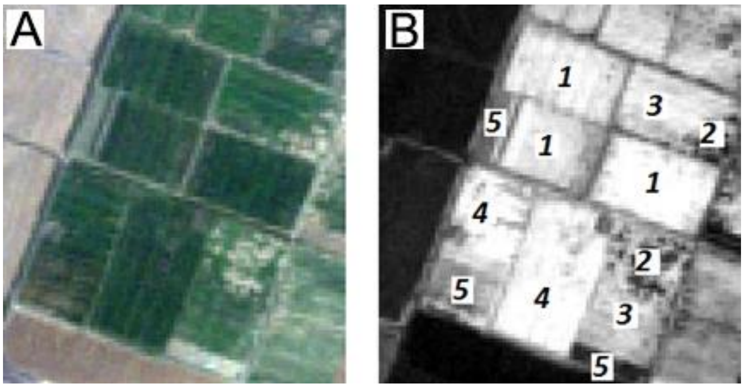


Fig. 12. Part of the "Chervlenoye" irrigated area (Svetloyarsk irrigation system, dry steppe of the Volgograd Region, Yergeni Upland). *Legend:* A – Landsat-8 OLI RGB-image obtained in August 1989, B – image of burclover fields, classified according to NDVI, with the groundwater level equal 2.5-1.5 m (Gorokhova, Pankova, 2021), 1 – nonsaline soils, fodder crop without any patches (NDVI = 0.74-0.75), 2 – bare patches of secondary heavily saline soils up to 1 m (NDVI = 0.18-0.27), 3 – weakly and averagely saline soils in the fields around large patches of absent crops (NDVI = 0.59-0.66), 4 – nonsaline and weakly saline soils in the fields around small and average patches of absent crops (NDVI = 0.65-0.71), 5 – harvested crops.

It was established that the patchiness of surface-calcareous soils is stable, does not depend on the groundwater level and is clearly visible both in the field and the images during any period, occurring together with spots of secondary saline soils. It is displayed on the open soil surface in the winter crop fields, and its area can be about 10,000-20,000 m^2. In the burclover fields with furrow irrigation the surface-carbonated soils cause crop fallout in the area of about 2,000-3,000 m^2. According to "Soil Survey Investigation for Irrigation" (1979), drying irrigated soils with a high content of carbonates (>2-4%) contribute to the formation of a crust that affects the agrophysical and agrochemical soil properties and prevents the growth of sprouts. Therefore, it is important to know the content of carbonates in the arable horizon.

In order to distinguish the surface carbonate patchiness from the secondary saline patchiness, it is necessary to analyze images with the open fields taken in the early spring, when the carbonate spots are well identified in contrast to the spots of soil salinity that are not visible on the open surface (unless it is a solonchak) and can change their boundaries from season to season under growing fodder due to the dynamic salinization process.

After finding out that the surface-calcareous soils on satellite image are shown as the light spots, it should be determined and confirmed with field studies to what extent the spotting is related to the $CaCO_3$ content in the upper horizons. We determined that the content of carbonates in the 0-25 cm layer was related to the spotting on a satellite image as follows: the average amount of $CaCO_3$ for all irrigated areas reached > 6% on the large bright spots (> 1,000 m^2), 4-6% on the small spots (from 100 m^2), and 0-4% within the rest of the background. The content of carbonates can both decrease and increase depending on the depth (Fig. 13).

The assessment of residual salinity by the patchiness of the fields was carried out in the Raigorodsky irrigated area. In the 1990s, this massif was in harsh hydrogeological conditions, because the groundwater level in its south (sulfate-sodium water) was 1.5-2 m, resulting in the formation of pockets of secondary strongly and moderately saline soils. Those were the soils of former depressions, which were quickly subjected to the process of secondary salinization due to the closeness of groundwater and a tight connection with it.

The modern images show the foci of former secondary salinization as large dark spots on a 3500 m^2 perennial fallow due to the forbs (Fig. 14). Now, when the groundwater level is deeper than 5 m, the gradual soil desalinization takes place there along the margin of the spot, while salinity remains in its center.

Fig. 13. Parts of the Landsat-8 OLI RGB-images with soils calcimorphic on the surface (0-25 cm) in different natural regions of Svetloyarsk irrigation system (dry steppe of the Volgograd Region). *Legend:* A, B – part of the “Chervlenoye” irrigated territory in the Yergeni Upland (April 2018 – open soil surface, May 1989 – fields with winter cereals), C – part of the irrigated territory in the Caspian Lowland (August 2018 – fields with winter cereals and burclover; Gorokhova, Pankova, 2021), 1 – large patches with $CaCO_3$ > 6%, 2 – small patches with $CaCO_3$ = 4-6%, 3 – field without any patches, $CaCO_3$ = 0-4%.

Soil salinization down to 50-100 cm and deeper is not always seen in satellite images. In this case, it is necessary to use the interpolation method known as Kriging to map it, since all the soils that are saline at a depth of more than 100 cm are potentially dangerous, and therefore, the information about the amount and distribution of their salts is very important.

The interpolation maps of the distribution of the weighted average sum of toxic salts (%) in the 100-200 cm of the Shervlenoye irrigated massif were built in the Surfer-13 program (Fig. 15) using the data for 2017-2018 provided by the Volgograd Hydrogeological and Reclamation Party, and our own field studies for 2017. Down to 100-200 cm the soils of both massifs have horizons of medium and strong salinity level. Only the soils in the southeast of the western massif have a weak or absent salinity 2 m below the surface. In other words, in most of the massif there is a significant amount of easily soluble salts in the 2nd meter of the profile, which can move even higher if the groundwater rises.

Based on the water extract (1: 5), the chemistry of soil salinity in the irrigated lands is predominantly chloride-sulfate, but sometimes can be sulfate and sulfate-chloride.

Thus, the present studies, as well the ones carried out in the 90s in the Svetloyarsk Irrigation System in different natural regions of the dry steppe zone of the Volgograd Region, showed that the heterogeneity of the fields reflected in satellite images can be of a diagnostic nature, but of different origins. The reason for patchiness is related to hydrogeological conditions, soil properties, field layout during the construction of the irrigation systems, and a long-term period of irrigation.

Meanwhile its pattern depends on whether the field is cultivated, has an open surface or turned into a fallow. That is why the interpretation of remote data requires mandatory studies of the current situation in the chosen region and substantiating the causes of patchiness on the basis of field and laboratory researches.

A B

Fig. 14. Raygorod irrigated territory with a perennial fallow land (A) on a Landsat-8 image obtained on 19/06/2015 (groundwater level > 5 m), and foci of the former secondary soil salinization (B) that look like large dark spots due to the sagging surface caused by the lack of secondary planning and by the intense growth of weeds after a precipitation accumulation. Currently, the soils in this undergo a gradual desalination on the edge of the patch, while remaining weakly and averagely saline in its center (Gorokhova, Pankova, 2017).

1.4. Field Work

The purpose of field work is to study the current state of the soil cover, confirm the connection between the satellite image and the actual soils, and also answer the questions that might have arisen when a preliminary map was compiled based on satellite images.

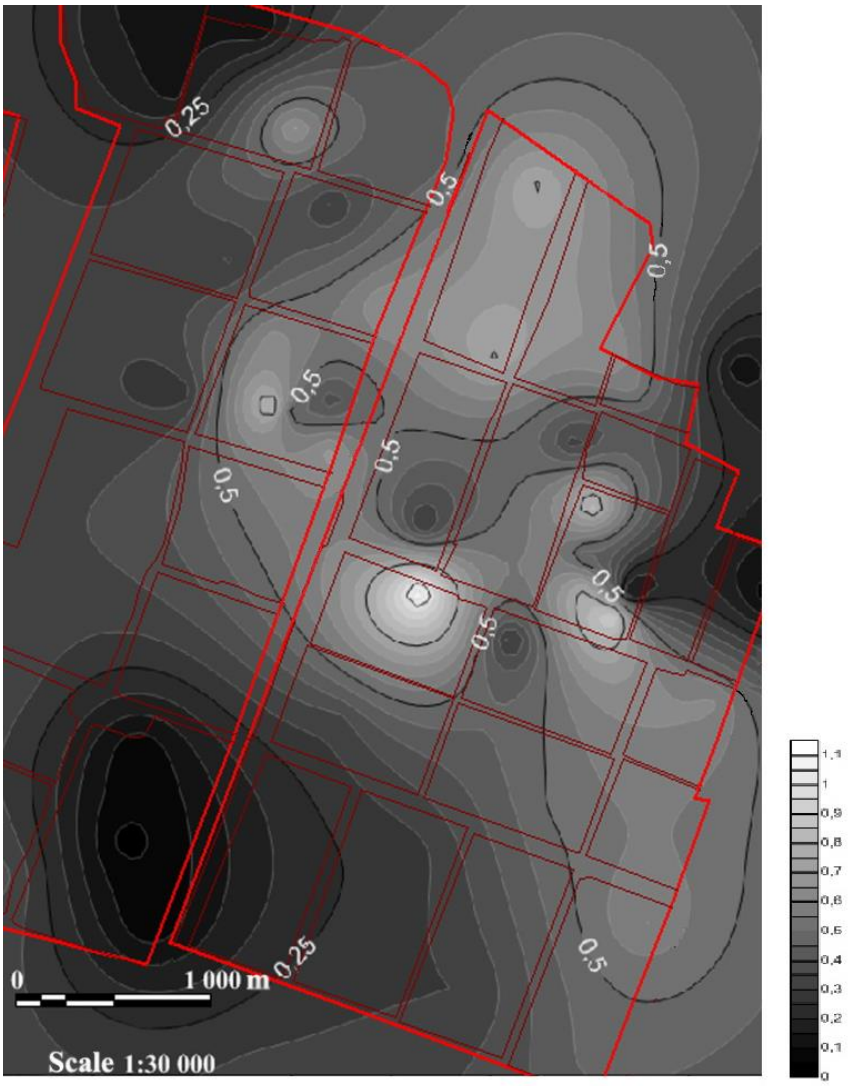
Using the preliminary map, the field work is carried out according to the plan outlined in the pre-field period. Reconnaissance routes are required to make the reference soil profiles in order to assess soils properties of various landscapes. On the routes the locations for more detailed key and profile studies are determined as well, the purpose of which is to confirm the close relationship between the satellite image and the actual soils, and to clarify the data obtained after interpreting the image. The profiles and sampling points must be linked with the help of satellite navigators. Within the mapped area, their number should approximately correspond to the approved standards, such as 1-1.5 profiles per 1 km^2 of soil survey at a scale of 1: 50,000, 2-3 profiles at a scale of 1: 25,000, and 6-7 profiles at a scale of 1: 10,000 (Table 3).

The studies provide creation of transects, i.e. the soil-geomorphological profiles that would cover all points of the current landscape. Based on these materials, the list of soils, soil complexes, soil-forming and underlying rocks are specified on the preliminary maps.

The key studies are carried out to classify soil heterogeneities and identify landscape-indicative relationships. It is necessary to cover the main types of photographic image on a satellite image. The key sites should be placed taking into account the agricultural use of the chosen territory, because it will help to analyze the relationship between soil heterogeneity and crop diversity (Sorokina, 2006).

During the field work, such sampling points as main profiles, test pits and boreholes are used.

The main profiles should be made at the most typical relief points to study the general soil profile, opening the access to all genetic soil horizons and the upper part of the parent rock. Their depth should be from 1.5 to 2.5 m.



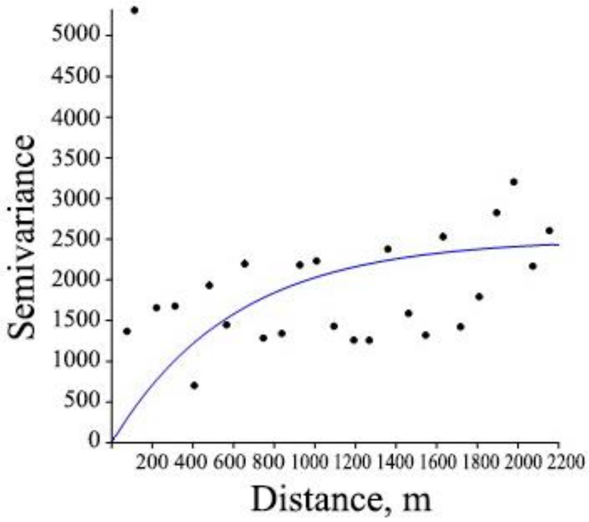


Fig. 15. Variogram and map of the spatial distribution for the concentration of the weighted mean sum of toxic salts (S_{tox}, %) in a layer of 100-200 cm depth (Gorokhova et al., 2020).

Table 3. Number of main soil profiles for the soil survey (Instructions on soil surveys …, 1975).

Scale	Soil complexity category*			1 profile per area, ha	1 profile per area, ha**
	1	2	3		
	Number of soil profiles per 1 km**				
1:200,000	0.08	0.11	0.15	1250-670	–
1:100,000	0.2	0.25	0.33	500-300	200
1:50,000	0.75	0.90	1.20	134-83	50
1:25,000	1.5	2.0	2.5	66-40	12.5
1:10,000	3.0	5.6	6.7	33-14	2
1:5,000	8.0	12.0	15.0	12-7	0.5
1:2,000	20.0	25.0	35.0	5-3	–

Notes to Table 3: * – complexity is defined by the participation percentage of heterogeneous components in the soil (category 1 – 15%, category 2 – 15-30%, category 3 – more than 30%), ** – the number of profiles is given according to “Soil Survey Investigation for Irrigation” (1979).

Test pits are laid to clarify the boundaries of the distribution of soil heterogeneities and to determine the variability of their properties, such as thickness of the humus horizon and depth of the salt, solonetz, carbonate and gypsum horizons. They are also used to identify the share of soil cover components in an inhomogeneous contour, and to interpret a photographic image by matching the test pits to different spots on a satellite image. Their depth on various soils ranges from 0.4 to 0.75 m.

The boreholes serve the same purpose as the test pits, helping to characterize soil-forming and underlying rocks, as well as to establish the groundwater level.

During the field work soil samples are collected to characterize the soil and its salinity. To assess soil salinity, samples should be taken from each profile along the genetic horizons down to 1-2 m; below, in the 50-centimeter-deep layers, the mixed samples are taken. The lithological heterogeneity of parent and underlying rocks must be considered when sampling to avoid mixing of different layers.

For a more detailed analytical characterization of soil properties, samples are taken from the basic profiles (~10-15% of the total number of profiles) to determine the content of humus, carbonates, gypsum and exchange cations. The particle size analysis is selective, taking into account its variability along the profile and within the mapped area. In the reference sections, groundwater should be sampled for further analysis.

The field stage of the study can be considered complete after the compilation of 1) a map of the actual material that reflects the entire volume of field researches, 2) a field soil map, 3) an application for the analytical work.

A complete chemical analysis of the content and composition of salts should be carried out for some (about 20%) profiles. Salinity of the rest of the samples can be estimated using the reduced water extract: the content of Na for soils with predominantly sulfate salinization, and Cl for soils with predominantly chloride salinity (Soil Salinization in Russia, 2006).

1.5. Processing the Results of Field and Laboratory Research, Finishing the Mapping

After finishing the field work and collecting results of chemical analyzes, a series of vector map layers is created to reflect the obtained data on land use, soil cover and properties at the time of the study. Then the final legend for each layer of the map is made and the calculations of areas are carried out. Then a soil report is made. Thus, at the final stage, the map is corrected based on field work, laboratory analyzes and final processing of the satellite image.

At the final stage of processing a multi-zonal image, a Supervised Classification is carried out, with software recognition of objects using training samples.

There are several methods of supervised classification, but all of them include the following steps:

1) Determining the classes of objects that will be selected as a result of the procedure (determined by a user);

2) Creating a training sample for each class of objects (created by a user);

3) Calculating the parameters of the "spectral image" for the classes that was formed on the basis of reference pixels from training samples;

4) Viewing the entire image and assigning each pixel to a certain class.

Supervised classification is performed only if each class has reference samples that are based on field work. There are many methods of trained classification, among which 3 are the most widespread:

1. Classification by the Minimum Distance: assigning a pixel to a reference class with the minimal Euclidean distance to its center in the feature space. This method is suitable for cases with limited number of classes.

2. Box Classifier is based on a statistical approach: assigning pixels to reference classes, the characteristics of which are the intervals of brightness. They are selected after analyzing a histogram of brightness distribution in the image. This method bears proper results if the spectral characteristics of objects do not intersect in the feature space.

3. The Maximum Likelihood is based on the statistical approach as well: determining the probability of a pixel falling into a particular class. This method is usually used when the spectral characteristics of object do not differ too much, a common occurrence when determining soils and plant communities.

There is also a Mahalanobis Distance method that uses statistics for each class, minimum distance, spectral angle, binary encoding, neural network classification, decision tree, and object-oriented classification (Chandra, Ghosh, 2008; Shovenberg, 2013; ENVI User Manual …, 2014). We cannot claim that one classifier is better than another since their performance is highly dependent on the source data (i.e. image).

The formation of a training sample for image processing is highly important, because the accuracy of classification depends on its quality. The quality of the training sample is evaluated by the following categories:

– representativeness of the set of brightness values in the sample, determined by the accuracy of reference to a certain class;

– homogeneity, i.e. absence of brightness values that are uncharacteristic for the class; it is estimated by the standard deviation of the brightness from the average value;

– distinguishability, i.e. noticeable difference in the spectral brightness of each class and minimal overlap of class ranges, using such parameters as, for example, Jeffries–Matusita distance (Knizhnikov, 2011; Shovenberg, 2013).

For a satisfying accuracy of image classification it is better to carry out separate processing (classification) for different categories. Such territories as villages and roads, i.e. those that are not subject to analysis, should be preliminarily excluded using masking.

Training samples can be based on brightness (spectral brightness values, NDVI), their statistical parameters and models that are used in different channels (Rouse et al., 1973; VEGA-PRO, 2022).

The map of irrigated lands, created using the image classification, should reflect the structure of the soil cover and help researchers to calculate automatically the areas of irrigated lands and the share of each component of the soil cover in the fields.

The work results in a final GIS of the study area, which includes the following cartographic, attributive and textual information.

1. Cartographic Information:

1.1. High and ultra-high resolution images for the study period;
1.2. If possible, images for different years before the study period;
1.3. Map of the actual material;
1.4. Map of land use;
1.5. Map of soils.

2. Attribute Information:

2.1. Descriptions of soil profiles (appended to the Map of the actual material);
2.2. Data of chemical analyzes (appended to the Map of the actual material);

3. Textual Information (explanatory note to the maps):

3.1. Physical and geographical conditions of the study area;
3.2. Characteristics of available cartographic materials and images;
3.3. Description of the method and image classification results in the image;
3.4. Description of the groundwater depth and mineralization, degree of salinity and salts composition; the upper boundary of the gypsum and calcareous horizons, content of gypsum and carbonates (in %) in the layers of different soil types; the depth and degree of salinity, and chemistry of soil salinity in the study area.

As an example, we provide the interpretation of the Pleiades ultra-high-resolution multispectral satellite image (20/05/2015) taken in the Svetloyarsk irrigated massif, where we used training samples based on our field work. The samples covered parts of burclover fields, both in good condition and with absence of vegetation, as well as fields with winter wheat growing in spots and depressions, but always at sampling points.

The quality of the created training samples was determined according to the following criteria (Knizhnikov et al., 2011):

1) Representativeness of the set of brightness values in the sample, for which each class was represented by several (3-5) reference areas;

2) Homogeneity, i.e. absence of brightness values that are uncharacteristic for the class, estimated by the standard deviation of the brightness from the average value; for this each soil type with a different brightness in the fields due to a harvest or overgrowing weeds, was represented by several samples, combined at the post-classification stage of image processing into 1 class; the standard deviation (%) of the average brightness, calculated for all classes in 4 channels, varied acceptably from 2.7% to 16.0%;

3) Distinguishability, i.e. noticeable difference in the spectral brightness of each class and minimal overlap of class ranges; for this we used the Jeffries–Matusita distance and the transformed divergence, the values of which should never exceed 1.7 and should tend to 2; in our samples both parameters varied within 1.76-2.0.

To classify the image we used an automatic spectral angle mapper that considered all pixels, including training samples, as vectors in the spectral feature space. For each class the maximum allowable spectral angle was specified, i.e. the angle between the reference vector and the pixel vector that is being classified. If the spectral angle is less than the maximum, then the pixel belongs to this class; if it is higher, then it does not belong to the class. The spectral angle method is fitting to classify objects with similar brightness in all spectral ranges (Schovengerdt, 2013).

After classification and generalization, we carried out the vectorization of the image contours; the results are presented in Figure 16.

1.6. Checking and Evaluating Map Accuracy

The accuracy of the map can be checked and evaluated either by comparing it with the maps of the same/larger scale that were compiled based on field observations, or by evaluating the accuracy of the image classification.

The classification reliability is assessed visually to find severe mistakes and inconsistencies. Then the quantification is carried out by comparing the classification results with test areas, such as ground-based observations, maps and large-scale images. If the classification results are not satisfying enough, the training sample can be refined, for example, by dividing large classes into smaller ones, and then the process is repeated.

Next, the classification accuracy is analyzed using a confusion matrix, with calculated overall accuracy, kappa coefficient (Cohen's kappa), omission and commission errors, user accuracy and producer accuracy.

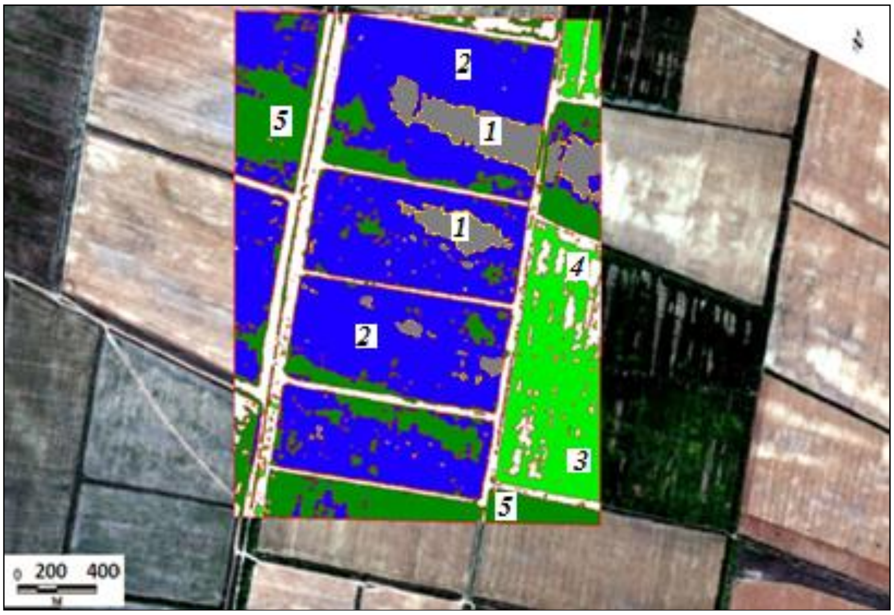


Fig. 16. Fragment of a soil map for the Svetloyarsk irrigated area (inner rectangle) with the background of an ultra-high resolution Pliedas image obtained on 20/05/2015 (Gorokhova et al., 2018). *Legend:* 1 – light chestnut calcareous (surface effervescence) deeply alkaline soils under winter cereals, 2 – light chestnut calcareous (effervescence starts at 15-20 cm) deeply alkaline soils under winter cereals, 3 – light chestnut calcareous (effervescence starts at 15-20 cm) deeply alkaline soils under burclover, 4 – light chestnut calcareous (surface effervescence) under scarce burclover, 5 – meadow-chestnut (black earth) soils of gorges and round depressions.

The confusion matrix is a square matrix with its number of rows and columns equal to the number of classes. Its diagonal elements show the values that are equal to the number of correctly classified pixels in each class. The sum of the values in the diagonal elements shows the total number of correctly classified pixels, while the ratio of this number to the total number of pixels in the matrix is called the overall classification accuracy.

To assess the overall reliability of the classification, the kappa coefficient is used that can be calculated by the following formula:

$$k = \frac{N\sum_{i=1}^{n} x_{ij} - \sum_{i=1}^{y} x_{i+} \bullet x_{+i}}{N^2 - \sum_{i=1}^{r} x_{i+} \bullet x_{+i}}$$

where x_{ij} is the diagonal elements of the error matrix; x_{i+} is the sum of pixels along the i row; x_{+i} is the sum of pixels in a column; N is the total number of pixels in the matrix; n is the number of classes.

If kappa is ≤0.5, then the results of the overall classification are not satisfactory.

Omission error is the number of pixels that were not included in this class by mistake.

Commission error is the number of pixels that were mistakenly assigned to this class.

Producer accuracy is the percentage of pixels from a certain class that were correctly classified. It is calculated by dividing each diagonal element of the confusion matrix by the total number of pixels in the corresponding column. This parameter helps to evaluate the match accuracy between the classification results for a certain class and the test data.

A similar parameter that is called user accuracy is calculated for an actual class by dividing the number of correctly classified pixels by the total number of its pixels, according to the data being tested (i.e. the total number of pixels in the corresponding rows of the matrix). It shows the probability of pixels of a class (checked image) falling into the corresponding class (test image).

To carry out this analysis, it is necessary to turn the ground-based data and maps or training samples that were created during the field work into a classified image. Then, the said image should be compared with the classified image of the samples (ENVI User Manual …, 2014).

Transformation of ground-based data into a classified image and calculation of the confusion matrix parameters can be performed in any program for high-level image processing.

Our experience shows that classification reliability of 90-95% can be achieved for 2 or 3 classes. The results are considered satisfactory, if 70-85% of the classified objects are correctly identified (Labutina, Baldina, 2011).

Conclusions

1. Irrigated soils have always been a difficult object of mapping whenever it is carried out by traditional and remote methods. The reason for that is the high anthropogenic deformation of the soil cover and changes in the natural factors of soil formation due to field planning, long-term irrigation and hydrogeological regime.
2. Crops growing in different hydrogeological conditions react differently to those limiting factors. Therefore, when compiling a map it is recommended to adhere to such stages as 1) making a land use map with marked fields with different crops and fallow lands, 2) highlighting patches in the images with sparse or absent crops, 3) on the basis of field researches and analyzed soil samples, studying the modern soil cover, the morphology and nature of the soil visualization on the images, and establishing the cause of the patchiness, 4) selecting an algorithm for processing satellite images classification based on the results of field researches and add map legends, 5) using an automated method of point data interpolation and the field research data, making a salt map for deeply saline soils.
3. It should be remembered that the deciphering signs of the current state of irrigated soils and their salinity cannot be extrapolated to map similar regions, because natural relationships in irrigated soils are significantly disrupted, the impact of anthropogenic factors is too high, and in each specific case an individual approach to mapping is required, based on the relationship between the image showing the soils and the actual soil cover.
4. The patchiness of irrigated fields, seen on satellite images, can be of different origin, and therefore the interpretation of those images requires a mandatory study of the area and substantiation of the causes of patchiness on the basis of field work and analyzed soil samples.
5. The carbonate patchiness of the surface horizon (0-25 cm) does not depend on the groundwater level and is best seen on satellite images with an open soil surface.
6. The patchiness due to the secondary and residual salinization is determined by the state of vegetation; therefore, the pictures should be taken during the period of high vegetative activity of plants. Information about the groundwater level is also required, since its critical level is the main cause of secondary soil salinization.
7. The accuracy of the map is checked and assessed by a visual comparison with other maps of a larger scale that were compiled according to field observations, and by assessing the accuracy of the image classification. The reliability of the classification is determined using the overall accuracy

matrix, kappa coefficient, omission and commission errors, user accuracy and producer accuracy. If the classification is unsatisfactory, then it is necessary to refine the training sample and repeat the process.

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МЕТОДИЧЕСКИЕ ПОДХОДЫ К ОЦЕНКЕ СОСТОЯНИЯ ОРОШАЕМЫХ ЗЕМЕЛЬ СУХОСТЕПНОЙ ЗОНЫ ВОЛГОГРАДСКОЙ ОБЛАСТИ С ИСПОЛЬЗОВАНИЕМ КОСМИЧЕСКИХ СНИМКОВ

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В статье представлены материалы исследований в Волгоградской области, которые могут быть положены в основу методических рекомендаций для картографирования, определения площадей и состояния орошаемых земель с использованием космических снимков. Эти материалы опираются на многолетний опыт, полученный при изучении орошаемых земель в зоне солонцовых комплексов сухой степи. Привлечение материалов космической съемки поможет картографировать и определить: 1) площади орошаемых земель, 2) площади и возраст залежных земель на орошаемых массивах, 3) состояние орошаемых почв и факторы, ограничивающих их плодородие. Сельскохозяйственные культуры в различных гидрогеологических условиях по-разному реагируют на лимитирующие факторы, поэтому при составление карт рекомендуется придерживаться следующих этапов картографирования: выделять поля с разными культурами и залежью; выявлять наличие пятен с разреженностью или отсутствием сельскохозяйственных культур на снимках; в полевых условиях и на базе проведенных анализов отобранных почвенных образцов устанавливать причину пятен, выявленных по изображению; используя результаты полевых исследований, подбирать алгоритм для обработки космических снимков. Пятнистость орошаемых полей, отраженная на космических снимках, имеет разную природу, поэтому интерпретация дистанционных материалов требует обязательного изучения особенностей района исследований. Пятнистость, связанная с вторичным и остаточным засолением почв, определяется по состоянию растительности, поэтому важен период проведения космической съемки, отражающий высокую вегетационную активность растений. Необходимы также сведения об уровне грунтовых вод, поскольку их критический уровень является основной причиной возникновения процесса вторичного засоления почв. Для глубокозасоленных почв стоит построить солевую карту с помощью интерполяции точечных данных, полученных в полевых условиях и на основе лабораторных анализов. Пятнистость, связанная с карбонатностью поверхностного горизонта почв, не зависит от уровня грунтовых вод и лучше всего просматривается на космических снимках с открытой поверхностью почв. Проверка и оценка точности карты может проводиться путем сравнения с картами более крупного масштаба и данными полевых наблюдений и путем оценки точности проведенной классификации космического изображения, посредством определения проверочных индексов. Представленные материалы предназначены для широкого круга специалистов, использующих космическую информацию в работе, а также для специалистов (почвоведов, агрономов, агрохимиков), работающих в аграрном секторе южных регионов России.

Ключевые слова: сухостепная зона, орошаемые земли, засоленные почвы, космические снимки, картографирование орошаемых почв.

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