

## Determining locations of sublacustrine springs by remote sensing: the Skadar Lake case example Montenegro

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### ABSTRACT

Locating zones of submarine or sublacustrine groundwater discharge often presents the most important part of a costal hydrogeological research. These zones are most commonly unobservable from the surface, so their determination requires complex research of large areas (the measurement of water temperature and salinity from craft vehicles, diving explorations, etc.). Analyzing of satellite and aerial images represents a more rational way for locating of sublacustrine and submarine springs (*vruljas*). Application of remote sensing for these purposes can include two techniques: determination of temperature anomalies from the thermal infrared satellite images and identification of faults which control groundwater flow. The Landsat 7 ETM+ thermal bands for the area of Skadar Lake are used for the determination of the temperature anomalies, i.e. the locations where colder groundwater outflow below the warmer lake water. For the identification of faults, color composite image (Landsat bands 4, 5, 7) are used, and after a selection of potential zones, detailed aerial images are also analyzed. Considering that the main sublacustrine springs of the southwest cost of Skadar Lake were known by previous complex researches, this area was used as a pilot area for the testing these remote sensing techniques. It has been concluded that the application of remote sensing can be very useful for the focusing the hydrogeological investigations to potential discharge zones which can significantly reduce the cost and time of a research..

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## Introduction

Determining positions of submarine and sublacustrine springs (*vruljas*) always represents a complex task. The biggest problem is unavailability for direct observations, considering that these hydrogeological phenomenon outflow under the lake or sea level. When discharge of groundwater is concentrated, sublacustrine springs can be recognized at the water surface (they are manifested as the circular zones), but the cases where groundwater discharge is invisible are more frequent. Mostly, the difference in a temperature between groundwater and surface water is significant, so that the temperature anomalies occur on the locations of springs. Thus, the temperature presents one of the parameters that can be used to detect zones of groundwater discharge, but these locations can be also assessed based on geological, geomorphological and tectonic analysis of coastal terrain.

Using remote sensing, i.e. appropriate satellite scanners for the thermal infrared region of the electromagnetic spectrum, is possible to detect relative values of temperature on water surface. Also, satellite and aerial images can be used for analysis of geological, tectonic and geomorphological characteristics of a terrain. Therefore, it raises question whether it is possible to determine the locations of sublacustrine or submarine springs using the remote sensing, and thus avoid the complex research of large areas (the measurement of water temperature and salinity from craft vehicles, diving explorations along the whole coast, etc.)?

Techniques described in this paper are partially successfully applied at the Boka bay area (Radulović and Matović 2010), but additional test of more complete methodology is performed at the southwest edge of Skadar Lake. This area presents an appropriate pilote area for the methodology testing and giving the answer to forementioned question, considering that location of the two largest sublacustrine springs (Raduš spring and Krnjice spring) are known from previous hydrogeological, hydrological, bathymetric and diving research (Radulović 1989; Avdagić 1991, Radulović 2000, Szerszen 2008; Čvorović 2009). Hence, the aim of this research is to test whether without any fieldwork (only by using satellite and aerial images) is possible to determine the locations of these two karst springs [1-36].

### 1. Physical-geographical characteristics

Skadar Lake is situated at southeast part of Dinarides, where they represent one of the biggest natural reservoirs of fresh water.

The pilot site is represented by the catchment area of sublacustrine springs of southwest edge of Skadar Lake (figure 1). This catchment area occupies 185 km<sup>2</sup>, out of which 173 km<sup>2</sup> (93.5 %) belongs to the territory of Montenegro, while 12 km<sup>2</sup> (6.5%) belongs to territory of Albania.

The wider area of Skadar Lake has a modified Mediterranean climate. Average annual air temperature is around 12 °C, and average annual precipitation is approximately 2,500 mm. The temperature of the lake water varies temporal and spatial, and it is usually within the range from 6 to 30 °C.

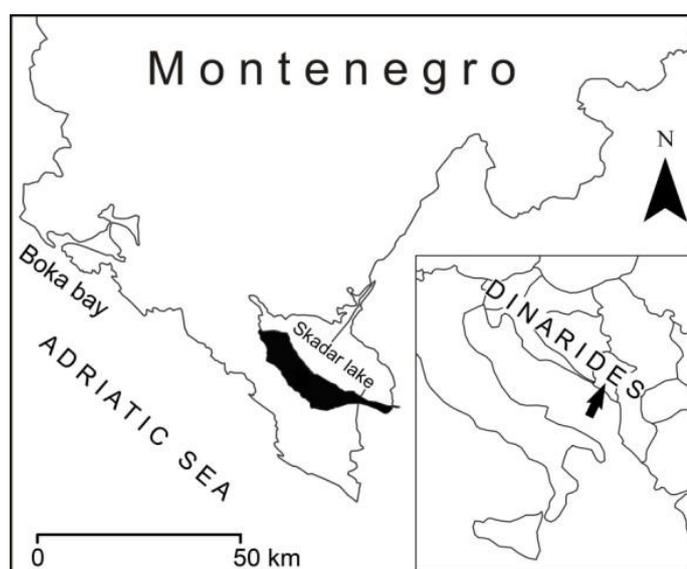


Figure 1. Geographical position of the pilot area (black area)

## 2. Geological and hydrogeological characteristics

Studying the geological structure of this region have dealt with many domestic and foreign researchers (Tietze 1884; Baldacci 1886; Hassert 1895; Cvijić 1899; Nopcsa 1916; Bourcart 1926; Waisse 1948; Milovanović 1965; Besšić 1969; Grubić 1975; Mirković et al. 1985). The main base for exploring the geology of this area is a Geologic map of Montenegro 1:200,000 (Mirković et al. 1985) and Regional geological map of sheet "Bar" 1:100,000 (Mirković et al. 1978).

Skadar Lake area belongs to the tectonic unit of the "Visoki krs". Carbonate rocks (limestone and dolomite) have a dominant distribution on this area. Total thickness of carbonate rocks can be over 3,000 m. A strike of strata on the pilot area is generally northwest-southeast, and dip toward Skadar Lake, with angle of 20-50 degrees. In the research area, there are a great number of faults which spreading in various directions (Fig. 4).

At Skadar Lake basin, the numerous hydrogeology researches have been performed (Torbarov and Radulović 1966; Radulović 1989, 2000, 2012; Radulović et al. 1989, 1998, 2013; Zogović 1992; Burić 1993; Radulović and Radulović 2004; Stevanović et al. 2008; Dević 2011; Sekulić and Bushati 2013).

Karst aquifer has dominant distribution in the wider area of Skadar Lake. Groundwater recharge occurs primarily by direct infiltration of rainwater. Karst aquifer, which is formed within karstified carbonate rocks, has high hydraulic conductivity. Groundwater flows mainly through privileged directions which are marked with faults and joints.

Sublacustrine springs (*vruljas*) that occur along coastal part of the lake are actually underwater dolines through which karst aquifer discharges. In the Skadar Lake is registered about 40 sublacustrine springs. The depth of the underwater dolines is relatively high and it ranges from 10 to 70 m. Groundwater quality is relatively good, with high content of calcium and hydrocarbons.

## 3. Methodology

Analysis of satellite and aerial images can be performed with the purpose of gathering of necessary data that refer to geology, tectonics, groundwater flow directions and groundwater discharge points. Application of remote sensing in hydrogeology is usually made at the initial research phases, so that they can timely be focused to selected potential locations.

Application of remote sensing on this research area was implemented in three phases:

1. *Mapping of Skadar Lake surface temperature* – by creating this map, zones where colder groundwater outflow were detected;
2. *Regional mapping of the fault lines*–this map is made for the catchment area of the southwest edge of the lake, with the purpose of identifying faults that could direct groundwater flow to the discharge zone.
3. *Detailed map of fault lines for the selected potential zones*–maps were made for two discharge zones in the local scale; on these maps, the faults which direct groundwater to the karst springs, were precisely identified.

### 4.1. Mapping of Skadar Lake surface temperature by remote sensing

In this section, a remote sensing technique for the mapping of the water temperature is described. As it was mentioned previously, the purpose of this technique is to detect the temperature anomalies, i.e. the locations of sublacustrine springs which occur below the lake level. This technique cannot give the real temperature values without the calibration with field measurements, but only give the approximated values which are sufficiently precise for this purpose.

Spectrum of electromagnetic energy which can be registered by satellite sensors is divided into separated regions, from which one is infrared region. According to the source of radiation in infrared range, there are reflected and emitted (thermal) unit. In emitted or thermal part, there is infrared radiation constantly emitted by atmosphere, water surface, ground and objects. The wavelengths of this radiation vary from 3 to 1,000  $\mu\text{m}$ , although maximum radiation appears in ranges 3–10  $\mu\text{m}$  and 3–20  $\mu\text{m}$ .

Satellite Landsat 7 is equipped with enhanced multispectral scanner (ETM+), which, beside other things, registers thermal part of infrared area with wavelengths from 10.4 to 12.5  $\mu\text{m}$  (band 6). Resolution of images obtained is 60 m.

The first step in process of creating temperature map of lake surface is obtaining appropriately processed satellite image. The Landsat 7 ETM+ images are suggested because they are still fabricating in better resolution for thermal-infrared region than the images obtained from other satellites. Also, it is required to obtain images from the period of year when the yields of springs are hedge and at the same time there is a significant difference in groundwater and lake water temperatures (e.g. April, May or June).

Every pixel (cell) of a satellite image possesses its own digital number (DN), which can vary in a range 0–255 for images of 8 bits. These values of digital numbers need to be converted into units of spectral radiation registered with sensor ( $W/m^2 \text{ sr } \mu\text{m}$ ), via following formula (LPSO 2009):

$$L_{\lambda} = \left( \frac{LMAX_{\lambda} - LMIN_{\lambda}}{QCALMAX - QCALMIN} \right) \times (QCAL - QCALMIN) + LMIN_{\lambda} \quad (1)$$

where is:

$L_{\lambda}$  – spectral radiation registered by satellite sensor in  $W/m^2 \text{ sr } \mu\text{m}$ ,

QCAL – pixel value on an image expressed via DN (can be between 0 and 255),

$LMIN_{\lambda}$  – spectral radiation for QCALMIN in  $W/m^2 \text{ sr } \mu\text{m}$  (for Landsat 7 ETM+, *Band 6, Low Gain*,  $LMIN_{\lambda} = 0 \text{ W/m}^2 \text{ sr } \mu\text{m}$ ),

$LMAX_{\lambda}$  – spectral radiation for QCALMAX in  $W/m^2 \text{ sr } \mu\text{m}$  (for Landsat 7 ETM+, *Band 6, Low Gain*,  $LMAX_{\lambda} = 17.04 \text{ W/m}^2 \text{ sr } \mu\text{m}$ ),

QCALMIN – minimum pixel value expressed via DN (= 0 or 1),

QCALMAX – maximum pixel value expressed via DN (= 255).

Furthermore, spectral radiation values for every pixel of an image (band 6) should be translated into the relative temperature values ( $^{\circ}\text{K}$ ) registered by satellite sensor (LPSO 2009), which can be obtained via following formula:

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_{\lambda}} + 1\right)} \quad (2)$$

where is:

$T$  – relative temperature registered by satellite sensor ( $^{\circ}\text{K}$ ),

$K_2$  – calibration constant 2 (for Landsat 7 shots  $K_2 = 1282.71 \text{ }^{\circ}\text{K}$ ),

$K_1$  – calibration constant 1 (for Landsat 7 shots  $K_1 = 666.09 \text{ W/m}^2 \text{ sr } \mu\text{m}$ ).

Converting temperature values from  $^{\circ}\text{K}$  into  $^{\circ}\text{C}$  is made according to formula:  $T^{\circ}\text{C} = T^{\circ}\text{K} - 273.15$ . Calculating estimation with image pixel values can be facilitated by using GIS software like ERDAS IMAGINE, ArcGIS etc.

Values obtained cannot be used instead of measuring values of temperature because they can significantly differ, but they have satisfying accuracy for this purpose. By additional calibration process, the accuracy can be improved, but in this particular case that is not necessary.

The disadvantage of this method is low resolution of images, because of scanner limitations for thermal part of infrared region, so the smaller sublacustrine springs cannot be detected. Main advantage comparing to the field measuring, is temporal and financial rationalization of a research. In every case, this approach should be considered as a supporting technique which can improve hydrogeological research of groundwater discharge in costal zones.

## 4.2. Regional mapping of the fault lines

Regional mapping of fault lines can be efficiently done by interpreting Landsat 7 ETM+ colour-composite images made out of bands 4, 5 and 7, that are considered to be the most appropriate for geological researches (Won-In and Charusiri 2003). This colour-composite is chosen as base for the regional mapping of fault lines in the pilot area, in scale of 1:100,000 (Fig. 4).

Images of aforementioned bands are previously processed for the purpose of fixing their quality (image enhancement). Contrast enhancement of raw images is performed by selective linear transformation of the original pixel values. Also, spatial filtration of images is made using the process of linear elements emphasis (edge enhancement) for the purpose of enabling faults to be more visible. Colour composite making from these processed bands has enabled identification of large number of lineaments and production of the map of fault

lines. The image has been transformed into the appropriate geographical projection so that all data obtained can be combined with other maps (topographical, geological and hydrogeological).

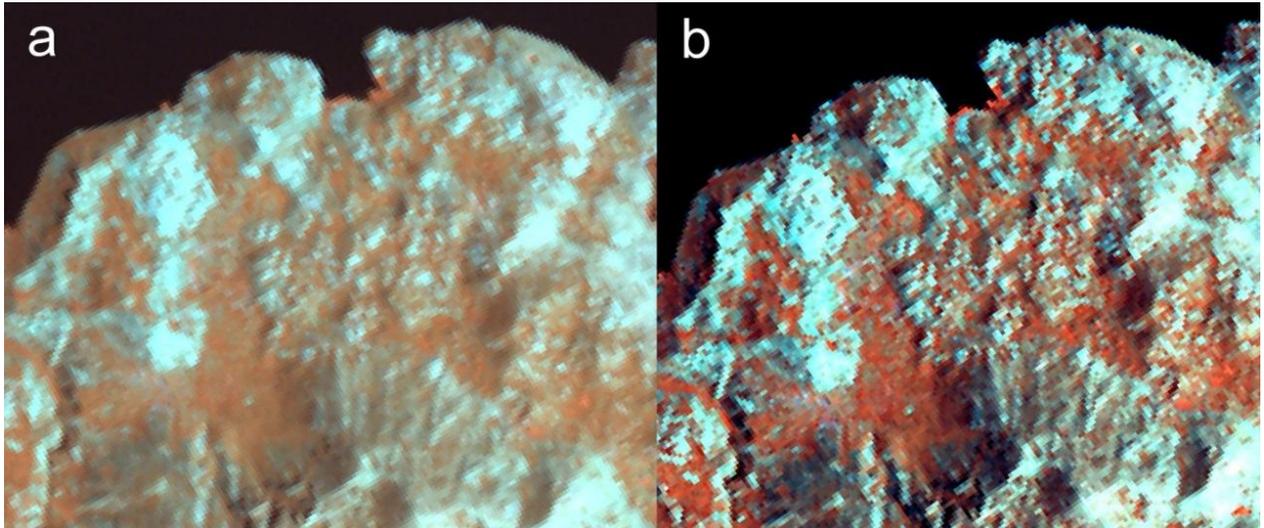


Figure 2. a) Colour-composite created of raw images; b) Colour composite created of processed images

### *4.3. Mapping of fault lines in the local scale*

The maps of fault line in the local scale can be created by stereo analysis of aerial images. Stereo view of a terrain is possible to achieve by using a stereoscope under which two oriented images are being observed. The same effect can be achieved by using special hardware (3D/Stereoscopic Monitor with specialized accessory glasses, graphics cards for hardware stereo) and software like Stereo Analyst for ERDAS IMAGINE, Stereo Analyst for ArcGIS, Leica Photogrammetry Suite (LPS). A digital stereo model (DSM) of terrain which can be created in this software obtains vertical exaggeration and better visibility of fault lines.

Generally, karst terrains are photogenic for the analysis and interpretation of images (Pavlović et al. 2001), so the subjectivity during the identification of fault lines is negligible. The analysis and interpretation should be primarily relying on direct manifestations of faults (disruption of bedding plane traces, disruption of geological boundaries), as well as onto standard criteria like: landforms, vegetation, colour and tone of ground surface. In karst terrains faults are generally manifested by elongated depressions (sinkholes) which are linearly distributed. Linear arrangement of vegetation can also indicates fault zone, but vegetation and tone features should be always considered as supporting criteria (Pavlović et al. 2001).

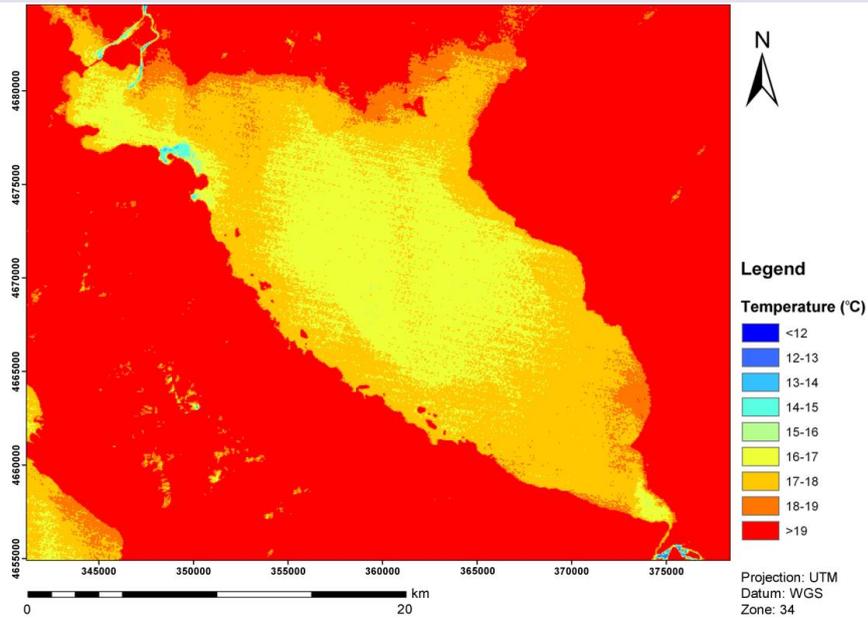
The maps of fault lines of two selected zones have been made by analysis of aerial images captured by photogrammetric camera WILD RC30 in shooting scale 1:8,500. After the interpretation, aerial images and identified lineaments were converted into orthogonal projection.

## *5. Results*

### *5.1. Map of temperature of Skadar Lake surface*

Result of applying technique described in the Section 3.1 is the map of temperature of Skadar Lake surface (figure 3). In order to register temperature anomalies, an image from spring period of year has been used, when there is appropriate temperature difference between groundwater and lake water, and at the same time the high yield of sublacustrine springs. The Landsat 7 ETM+ image (thermal-infrared band–Band 6, resolution 60 m) captured on 23rd of April 2002 is obtained.

From the temperature map (figure 3), there can be concluded that the huge influence on local change in lake water temperature has the Raduš spring. In the location of this sublacustrine spring a significant temperature anomaly, presented by blue tones on the map, has been detected. Also, the temperature anomaly, i.e. discharge zone of colder groundwater below lake level, has been detected in the Luke bay, in the location of the Krnjice spring. Further, along the coast towards southwest, temperature anomalies were not detected. The yield of other sublacustrine springs is probably not high enough to affect a greater change of lake temperature. From the temperature map (figure 3), there can also be concluded that, the Morača River (north-western part of the map) brings significantly colder waters to the lake, which is also a case with Drim River (south-eastern part of the map).

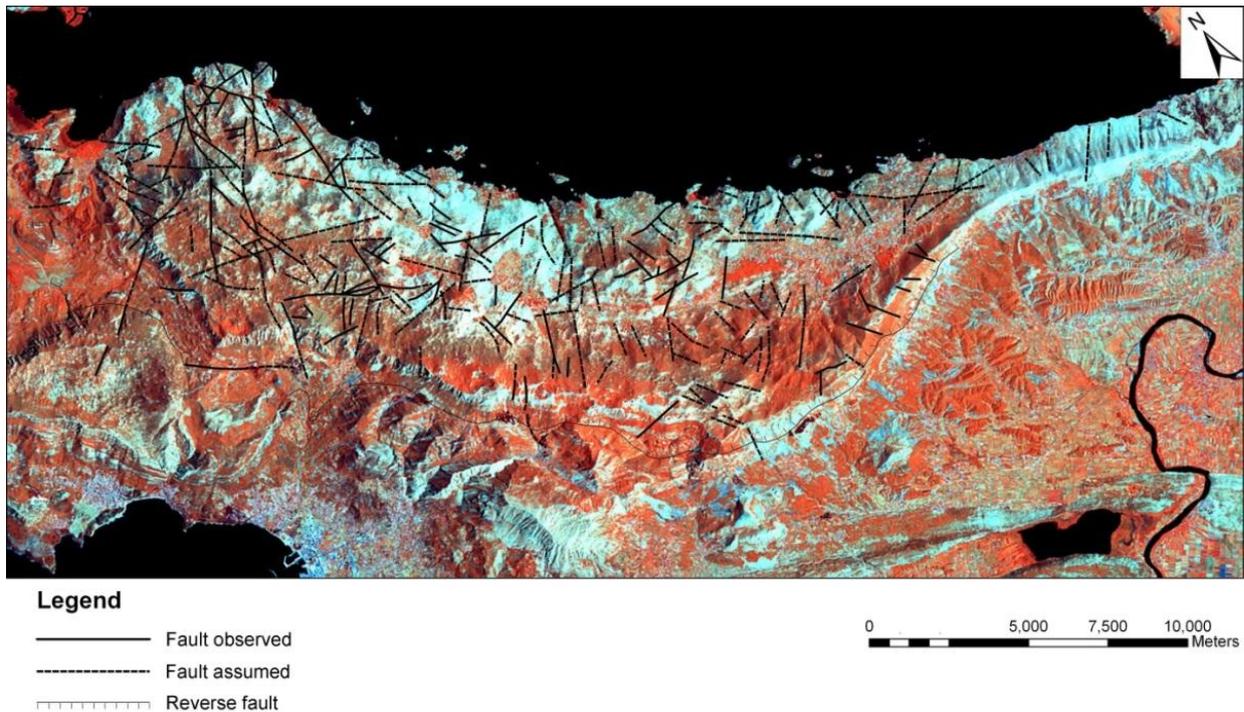


**Figure 3.** Map showing the temperature of the surface of Skadar Lake, obtained by satellite image LANDSAT 7 ETM+ (thermal infrared band—Band 6; resolution 60 m; date of capturing: 23 April 2002). The temperature anomalies (blue tones) indicate the locations of some sublacustrine springs, where colder groundwater discharges below the lake level (Radulović et al. 2015)...we must ask for the permission from the Springer

### 5.2. Regional map of the fault lines

Map of the fault lines of southwest edge of Skadar Lake (Fig. 4) has been created for the purpose of identifying the fault lines which can control the groundwater flow towards the springs.

From the map of the fault lines, there can be seen that the catchment area of the southwest coast has a significant number of faults orientated in various directions. Special attention should be paid to researching hydrogeological function of faults orientated southeast-northwest and south-north, and their possible function in transmitting groundwater towards Raduš and Krnjice springs.



**Figure 4.** Map of the fault lines of the site area

### 5.3. Map of fault lines in local scale

The detailed map of fault lines (figure 5) has been created for the background of Luke bay and Raduš bay (figure 5), because those two locations have been selected as potential zones of sublacustrine groundwater discharge (Sections 4.1 and 4.2). Detailed analysis of the tectonics of coastal area obtained determinations of discharge locations and local groundwater flow directions.

Area of Luke bay has got two important faults. First fault is orientated in south-north, and the second one in west-east direction. These two faults intersect not far from the coast, on a location where the groundwater discharge is assumed. The discharge point has been recognized over brighter tones on aerial image (figure 5a), what is also one of the possible indicators. The position of this karst spring (Krnjice spring) is known from the previous complex researches (Radulović 1989; Radulović et al. 1989; Szerszen 2008; Čvorović 2009), which suggest that on this location there is underwater doline, on the depth of around 20 m.

Also, on the area of Raduš bay a great number of faults have been registered. Some of this faults can important hydrogeological function, like faults along the west edge of the bay, which have a general direction southwest-northeast. The location of groundwater discharge is assumed to be on the intersection of two faults, below water surface. The exact place of sublacustrine spring is represented by brighter tones on aerial image (figure 5b). In that zone, sublacustrine spring was also reported by previous researcher (Radulović 1989; Avdagić et al. 1989; Radulović et al. 1989; Szerszen 2008; Čvorović 2009). The location of spring is presented by underwater sinkhole with diameter of around 130 m, and depth over 70 m.

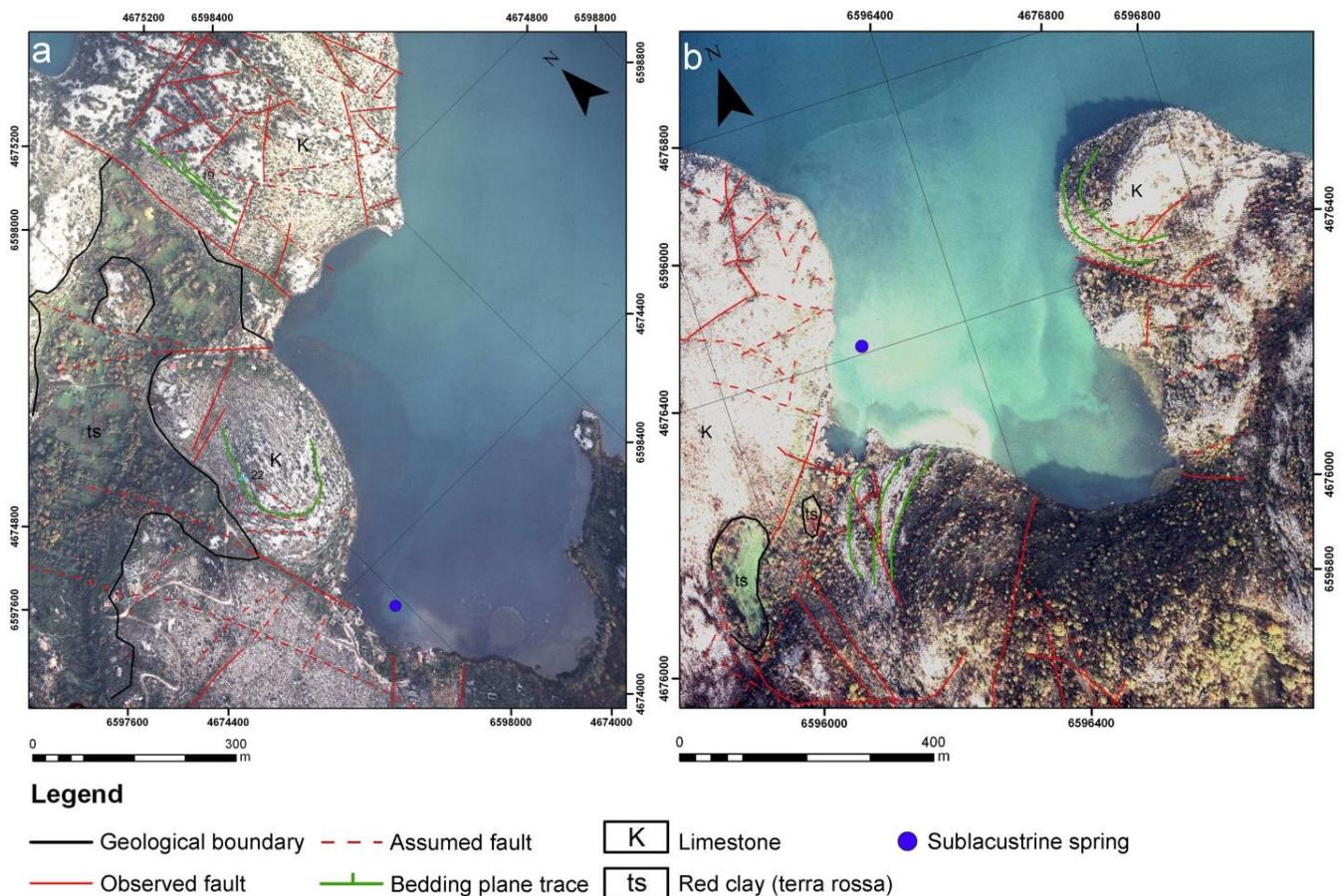


Figure 5. a) Map of fault lines of the area of Luke bay; b) Map of fault lines of the area of Raduš bay

## 6. Conclusion

The techniques presented in this paper are used for determining the locations of sublacustrine springs by applying remote sensing, i.e. by analysing and interpreting of satellite and aerial images. This approach involves creating of three types of maps:

- Temperature map of lake surface;
- Regional map of fault lines; and
- Map of fault lines for the potential zones in local scale.

At the example of southwest coast of Skadar lake, it is confirmed that approximate locating of sublacustrine springs can be performed by using remote sensing, without applying the complex fieldwork research.

It is essential to remark that this is a supporting approach, which has lower accuracy than detailed fieldwork researches (bathymetric survey, temperature measuring from the craft vehicle, terrestrial thermo vision recordings, speleological and diving explorations). However, applying this approach enables significant temporal and financial rationalization, so it is the most desirable to apply it at the initial phase, in order to focus the research to the potential locations.

## References

- [1]. Avdagić I, Filipović S, Mišurović A (1989) Skadar Lake as a source for the supply of fresh water. Montenegrin Academy of Science and Arts, Titograd, 284 p.
- [2]. Baldacci L (1886) Ricognizione geologica–mineraria del Montenegro. Boll R Comit Geol Ital Boll 17:9–10, 63 p.
- [3]. Bešić Z (1969) Geology of Montenegro–Karst of Montenegro (in Serbian). Geological Survey of Montenegro, Podgorica, 139 p.
- [4]. Bourcart J (1926) Nouvelles observations sur la structure des Dinarides adriatiques. In: Actas del XIV Congreso Geológico Internacional, Madrid, pp 1899–1941
- [5]. Burić M (1993) Water supply of tourist settlements of the Montenegrin coast (in Serbian). Dissertation, University of Belgrade, 274 p.
- [6]. Dević N (2011) Geochemical-environmental properties of the catchment area of the Moraca River, upstream of its mouth to the Zeta River (in Serbian). MSc thesis, University of Montenegro, 150 p.
- [7]. Cvijić J (1899) Glacial and morphological studies of the mountains of Bosnia, Herzegovina and Montenegro (in Serbian). Voice Serb Roy Acad Sci 57:1-196, 23 p.
- [8]. Čvorović M. i dr. (2009b): Atlas karata 1:10.000, Batimetrijsko i geodetsko snimanje 2007-2009, Hidrometeorološki zavod Crne Gore i GEOPROMET d.o.o., Podgorica, 145 p.
- [9]. Grubić A (1975) Tectonics of Yugoslavia. Acta Geol 41:365–384, 284 p.
- [10]. Hassert K (1895) Beiträge zur physischen Geographie von Montenegro. Petermanns Mitteilungen Ergänzungsheft, Gotha, 375 p.
- [11]. LPSO (2009) Landsat-7 science data users handbook. Landsat Project Science Office, NASA/GSFC MD. [http://ftpwww.gsfc.nasa.gov/IAS/handbook/handbook\\_toc.html](http://ftpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html)
- [12]. Milovanović B (1965) Epeirogenic and orogenic dynamics in the area of External Dinarides and the problems of paleokarstification and geological evolution of holokarst (in Serbian). J Geol Surv Serbia 4(5): pp. 5–44
- [13]. Mirković M, Kalezić M, Pajović M, Živaljević M (1978) Basic geological map of SRY 1:100,000, "Bar" sheet (in Serbian). Geological Survey of Montenegro, Titograd, 284 p.
- [14]. Mirković M, Živaljević M, Đokić V, Perović Z, Kalezić M, Pajović M (1985) Geological map of Montenegro 1:200,000. The Republic Self Managing Community of Interest for Geological Exploration of Montenegro, Titograd, 385 p.
- [15]. Nopcsa F (1916) Begleitwort zur geol. Karten von Nordalbanien, Rasien und Ostmontenegro. Földtani Közlöny 46: pp. 7–12
- [16]. Pavlović R, Čupković T, Marković M (2001) Remote sensing (in Serbian). Faculty of Mining and Geology, University of Belgrade, Belgrade, 375 p.
- [17]. Radulović M (2000) Karst hydrogeology of Montenegro (in Serbian). Geological Survey of Montenegro, Podgorica, 468 p.
- [18]. Radulović M, Radulović, V (2004) Hydrogeological map of Montenegro 1:200,000 (in Serbian). Geological Survey of Montenegro, Podgorica, 285 p.
- [19]. Radulović M, Popović Z, Vujisić M, Novaković D (1989) Basic hydrogeological map of SRY 1:100,000, "Bar" sheet (in Serbian). Geological Survey of Montenegro, Titograd, 375 p.
- [20]. Radulović M, Popović Z, Vujisić M, Novaković D (1998) Guide book for the Basic hydrogeological map of SRY 1:100,000, "Bar" sheet (in Serbian). Geological Survey of Montenegro, Titograd, 275 p.
- [21]. Radulović MM (2012) Multi-parameter analysis of groundwater recharge in karstic aquifers–case examples from Skadar Lake basin (in Serbian). Dissertation, University of Belgrade, 476 p.
- [22]. Radulović MM, Matović M: Application of remote sensing in the hydrogeological research of submarine springs in the Boka bay (in Serbian). The 3rd International Conference "Civil Engineering – Science and Practice", GNP 2010, Žabljak, 2010, Vol. 2, pp 1599-1605
- [23]. Radulović MM, Novaković D, Sekulić G (2013) Geological and hydrogeological characteristics of the Montenegrin part of the Skadar Lake catchment area (in Serbian). In: Sekulić G, Bushati S (eds) Development of hydrogeological and hydraulic study of regulation of Skadar Lake and Bojana river water regime (IPA Project)–Volume 1. Montenegrin Academy of Science and Arts, Podgorica, pp 9–115

- [24]. Radulović MM., Radulović M, Stevanović Z, Sekulić G, Radulović V, Burić M, Novaković D, Vako E, Blagojević M, Dević N, Radojević (2015) Hydrogeology of the Skadar Lake basin (Southeast Dinarides) with an assessment of considerable subterranean inflow. *Environ Earth Sci* DOI 10.1007/s12665-015-4090-7, 265 p.
- [25]. Radulović V (1989) Hydrogeology of Skadar Lake watershed (in Serbian). Geological Survey of Montenegro, Titograd, 187 p.
- [26]. Sekulić G, Bushati S (eds) (2013) Development of hydrogeological and hydraulic study of regulation of Skadar Lake and Bojana river water regime (IPA Project)–Volume 1. Montenegrin Academy of Science and Arts, Podgorica, 274 p.
- [27]. Stevanović Z, Radulović M, Shammy Puri, Radulović MM (2008) Karstic source 'Boljesestre': Optimal solution for regional water supply of the Montenegro coastal area (in Serbian). In: Zbornik radova Odbora za kras i speleologiju (Recueil des rapports du Comite pour le karst et la speleologie), vol 9. Serbian Academy of Science and Arts, Belgrade, pp 33-64
- [28]. Szerszen A (2008) Karst Springs of Skadarsko Jezero—expedition report. Grupa Nurków Jaskiniowych, Warsaw, 385 p.
- [29]. Tietze E (1884) Geologische Uebersicht von Montenegro. Hölder, Vienna, 87 p.
- [30]. Torbarov K, Radulović V (1966) Regional hydrogeological research of Montenegro and Eastern Herzegovina (in Serbian). Geological Survey of Montenegro, Titograd, 275 p.
- [31]. Waisse JG (1948) Les bauxites de l'Europe centrale (Province dinarique et Hongrie). Dissertation, University of Lausanne, Lausanne, 138 p.
- [32]. Won-In K, Charusiri P (2003) Enhancement of thematic mapper satellite images for geological mapping of the Cho Dien area, Northern Vietnam. *Int J Appl Earth Obs* 4(3): pp. 183–193
- [33]. Zogović D (1992) Final report of hydrogeological exploration of Karuč source (in Serbian). Energoprojekt, Beograd, 128 p.
- [34]. Dauvalter V.A., Khloptseva Ye.V. *Gidrologicheskiye i gidrokhimicheskiye osobennosti ozer bolshezemelskoy tundry*. [Hydrological and hydrochemical features of lakes Bolshezemelskaya tundra] *Vestnik Murmanskogo gosudarstvennogo tekhnicheskogo universiteta*. 2008. Vol. 11. Issue 3. Pp. 407-414. (rus)
- [35]. Ostroumova L.P. *Vodno-balansovyye issledovaniya ustyevykh oblastey rek*. [Water balance studies estuarine areas of rivers] *Trudy Gosudarstvennogo okeanograficheskogo instituta*. 2013. Vol. 214. Pp. 180-199. (rus)
- [36]. Savkin V.M., Dvurechenskaya S.Ya., Saprykina Ya.V., Marusin K.V. *Osnovnyye godrologo-morfometricheskiye i gidrokhimicheskiye kharakteristiki ozera Chany*. [Main godrologo-morphometric and hydrochemical characteristics of the lake Chany] *Sibirskiy ekologicheskiy zhurnal*. 2005. Vol. 12. Issue 2. Pp. 183-192. (rus)

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## Определение местоположения вспомогательных озерных источников с помощью дистанционного зондирования на примере Скадарского озера (Черногория)

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### АННОТАЦИЯ

Расположение зон подводных источников озер часто представляет собой наиболее важную часть гидрогеологических исследований. Эти зоны наиболее часто являются ненаблюдаемыми с поверхности, поэтому их определение требует комплексного исследования больших площадей (измерение температуры и солености воды, дайвинг исследований и т.д.). Анализ спутниковых и аэрофотоснимков представляет собой более рациональный способ для поиска местонахождения подводных родников (vruljas). Применение дистанционного зондирования для этих целей, могут включать в себя два метода: определение температурных аномалий от тепловых инфракрасных спутниковых изображений и идентификации неисправностей, которые контролируют поток грунтовых вод. Landsat 7 ETM + тепловые поля для области Скадарского озера используются для определения температурных аномалий, т.е. тех мест, где холодный поток грунтовых вод отличается от теплой воды озера. Для идентификации используется цветное составное изображение (Landsat полосы 4, 5, 7), а после нахождения потенциальных зон анализируются подробные аэрофотоснимки. Учитывая, что основные озерные источники юго-западной части Скадарского озера были известны ранее комплексных исследований, эта область была использована в качестве пилотной территории для тестирования методов дистанционного зондирования. Был сделан вывод, что дистанционное зондирование может быть использовано для фокусировки гидрогеологические исследования, что может существенно снизить временные и материальные затраты на исследования.

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## Литература

- [1]. Avdagić I, Filipović S, Mišurović A (1989) Skadar Lake as a source for the supply of fresh water. Montenegrin Academy of Science and Arts, Titograd, 284 p.
- [2]. Baldacci L (1886) Ricognizione geologica–mineraria del Montenegro. Boll R Comit Geol Ital Boll 17:9–10, 63 p.
- [3]. Bešić Z (1969) Geology of Montenegro–Karst of Montenegro (in Serbian). Geological Survey of Montenegro, Podgorica, 139 p.
- [4]. Bourcart J (1926) Nouvelles observations sur la structure des Dinarides adriatiques. In: Actas del XIV Congreso Geológico Internacional, Madrid, pp 1899–1941
- [5]. Burić M (1993) Water supply of tourist settlements of the Montenegrin coast (in Serbian). Dissertation, University of Belgrade, 274 p.
- [6]. Dević N (2011) Geochemical-environmental properties of the catchment area of the Moraca River, upstream of its mouth to the Zeta River (in Serbian). MSc thesis, University of Montenegro, 150 p.
- [7]. Cvijić J (1899) Glacial and morphological studies of the mountains of Bosnia, Herzegovina and Montenegro (in Serbian). Voice Serb Roy Acad Sci 57:1-196, 23 p.
- [8]. Čvorović M. i dr. (2009b): Atlas karata 1:10.000, Batimetrijsko i geodetsko snimanje 2007-2009, Hidrometeorološki zavod Crne Gore i GEOPROMET d.o.o., Podgorica, 145 p.
- [9]. Grubić A (1975) Tectonics of Yugoslavia. Acta Geol 41:365–384, 284 p.
- [10]. Hassert K (1895) Beiträge zur physischen Geographie von Montenegro. Petermanns Mitteilungen Ergänzungsheft, Gotha, 375 p.
- [11]. LPSO (2009) Landsat-7 science data users handbook. Landsat Project Science Office, NASA/GSFC MD. [http://ftpwww.gsfc.nasa.gov/IAS/handbook/handbook\\_toc.html](http://ftpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html)
- [12]. Milovanović B (1965) Epeirogenic and orogenic dynamics in the area of External Dinarides and the problems of paleokarstification and geological evolution of holokarst (in Serbian). J Geol Surv Serbia 4(5): pp. 5–44
- [13]. Mirković M, Kalezić M, Pajović M, Živaljević M (1978) Basic geological map of SRY 1:100,000, "Bar" sheet (in Serbian). Geological Survey of Montenegro, Titograd, 284 p.
- [14]. Mirković M, Žvaljević M, Đokić V, Perović Z, Kalezić M, Pajović M (1985) Geological map of Montenegro 1:200,000. The Republic Self Managing Community of Interest for Geological Exploration of Montenegro, Titograd, 385 p.
- [15]. Nopcsa F (1916) Begleitwort zur geol. Karten von Nordalbanien, Rasien und Ostmontenegro. Földtani Közlöny 46: pp. 7–12
- [16]. Pavlović R, Čupković T, Marković M (2001) Remote sensing (in Serbian). Faculty of Mining and Geology, University of Belgrade, Belgrade, 375 p.
- [17]. Radulović M (2000) Karst hydrogeology of Montenegro (in Serbian). Geological Survey of Montenegro, Podgorica, 468 p.
- [18]. Radulović M, Radulović, V (2004) Hydrogeological map of Montenegro 1:200,000 (in Serbian). Geological Survey of Montenegro, Podgorica, 285 p.
- [19]. Radulović M, Popović Z, Vujisić M, Novaković D (1989) Basic hydrogeological map of SRY 1:100,000, "Bar" sheet (in Serbian). Geological Survey of Montenegro, Titograd, 375 p.
- [20]. Radulović M, Popović Z, Vujisić M, Novaković D (1998) Guide book for the Basic hydrogeological map of SRY 1:100,000, "Bar" sheet (in Serbian). Geological Survey of Montenegro, Titograd, 275 p.
- [21]. Radulović MM (2012) Multi-parameter analysis of groundwater recharge in karstic aquifers–case examples from Skadar Lake basin (in Serbian). Dissertation, University of Belgrade, 476 p.
- [22]. Radulović MM, Matović M: Application of remote sensing in the hydrogeological research of submarine springs in the Boka bay (in Serbian). The 3rd International Conference "Civil Engineering – Science and Practice", GNP 2010, Žabljak, 2010, Vol. 2, pp 1599-1605
- [23]. Radulović MM, Novaković D, Sekulić G (2013) Geological and hydrogeological characteristics of the Montenegrin part of the Skadar Lake catchment area (in Serbian). In: Sekulić G, Bushati S (eds) Development of hydrogeological and hydraulic study of regulation of Skadar Lake and Bojana river water regime (IPA Project)–Volume 1. Montenegrin Academy of Science and Arts, Podgorica, pp 9–115

- [24]. Radulović MM., Radulović M, Stevanović Z, Sekulić G, Radulović V, Burić M, Novaković D, Vako E, Blagojević M, Dević N, Radojević (2015) Hydrogeology of the Skadar Lake basin (Southeast Dinarides) with an assessment of considerable subterranean inflow. Environ Earth Sci DOI 10.1007/s12665-015-4090-7, 265 p.
- [25]. Radulović V (1989) Hydrogeology of Skadar Lake watershed (in Serbian). Geological Survey of Montenegro, Titograd, 187 p.
- [26]. Sekulić G, Bushati S (eds) (2013) Development of hydrogeological and hydraulic study of regulation of Skadar Lake and Bojana river water regime (IPA Project)—Volume 1. Montenegrin Academy of Science and Arts, Podgorica, 274 p.
- [27]. Stevanović Z, Radulović M, Shammy Puri, Radulović MM (2008) Karstic source 'Boljesestre': Optimal solution for regional water supply of the Montenegro coastal area (in Serbian). In: Zbornik radova Odbora za kras i speleologiju (Recueil des rapports du Comite pour le karst et la speleologie), vol 9. Serbian Academy of Science and Arts, Belgrade, pp 33-64
- [28]. Szerszen A (2008) Karst Springs of Skadarsko Jezero—expedition report. Grupa Nurków Jaskiniowych, Warsaw, 385 p.
- [29]. Tietze E (1884) Geologische Uebersicht von Montenegro. Hölder, Vienna, 87 p.
- [30]. Torbarov K, Radulović V (1966) Regional hydrogeological research of Montenegro and Eastern Herzegovina (in Serbian). Geological Survey of Montenegro, Titograd, 275 p.
- [31]. Waisse JG (1948) Les bauxites de l'Europe centrale (Province dinarique et Hongrie). Dissertation, University of Lausanne, Lausanne, 138 p.
- [32]. Won-In K, Charusiri P (2003) Enhancement of thematic mapper satellite images for geological mapping of the Cho Dien area, Northern Vietnam. Int J Appl Earth Obs 4(3): pp. 183–193
- [33]. Zogović D (1992) Final report of hydrogeological exploration of Karuč source (in Serbian). Energoprojekt, Beograd, 128 p.
- [34]. Даувальтер В.А., Хлопцева Е.В. Гидрологические и гидрохимические особенности озер большеземельской тундры. Вестник Мурманского государственного технического университета. 2008. Т. 11. № 3. С. 407-414.
- [35]. Остроумова Л.П. Водно-балансовые исследования устьевых областей рек. Труды Государственного океанографического института . 2013. № 214 . С. 180-199.
- [36]. Савкин В.М., Двуреченская С.Я., Сапрыкина Я.В., Марусин К.В. Основные гидролого-морфометрические и гидрохимические характеристики озера Чаны. Сибирский экологический журнал. 2005. Т. 12. № 2. С. 183-192.

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