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Snow coverage changes monitoring in Caucasus based on Remote Sensing data

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1. Introduction

Snow coverage is one of the necessary factors for the hydrological cycle in highland areas, is the major principle for the greenery and production and as well as, is the primary assessment for the climate change (Ranco, De, M., & P., 2016). Surface water flows take starting from mountain watersheds are mainly based on snow coverage of the higher altitudes, that supply the river basin with water (Marsh & Woo, 1985).

Snow quality and quantity in Northern Hemisphere is anticipated to transform according to the continuous global climate change. Contrary to the tendency, snow indicators have differentiated throughout the regions (Räisänen & Dyn, 2012).

Nowadays, traditional snow monitoring methods with point data set had lost its effectiveness by the invention of the wide range of Remote Sensing techniques. Remote sensing contains high-resolution and low cost itself which enables better snow parameters in various scales all over the world (Wang, et al., 2018).

Snow Area Mapping with Remote Sensing was used to classify snow cover of Alpine Region, Northern Italy, using MERIS and AATSR satellite data (Tampellini, Brivio, Ober, & Pepe, 2012). Within the mentioned research, some deficiencies occurred in datasets, for instance, the range of the wavelength was not in the capable of discrimination of snow from clouds and the second, satellite-derived dataset was not well-suited to the target area.

Another snow-cover classification has been accomplished at Treeline, Canada by using C-Band RADARSAT-1, ERS-2 images and Ground Penetrating Radar (GPR) surveys. The research exposed that the C-band backscatter in dry snow become visible if the frost spread vertically until 20 cm inside the soil (Pivot, 2012).

Similarly, the snow cover area changes monitoring for Southern macroslope of the Greater Caucasus range will be covered under the research during the spring period of 2015, 2016 and 2017. Temperature and snowmelt correlation over the northern and southern watersheds, namely Akhty and Shaki, will be examined by using Sentinel-1 radar images.

2. Study Area

2.1 Greater Caucasus Range

The watershed of the Greater Caucasus connects Europe and Asia continents over the Alpine geosynclinal belt and lies between Taman and Absheron peninsulas approximately 1300 kilometers along (from 44°06′19″ N, 39°04′48″ E to 40°22′39″ N, 49°53′31″ E). Black and Caspian Seas surround the range from north-west and south-east coasts respectively (Tielidze & D.Wheate, 2018). The Greater Caucasus range is also referred as Northern and Southern Caucasus according to the massive slopes. Altitude range of the ridge varies around 4500 - 5600 m.a.s.l. with the highest peak, namely Elbrus (5642 m) (Solomina, et al., 2016).

Caucasus mountains situated inside Russia, Georgia and Azerbaijan countries' border administratively. Modern climate of the Caucasus is under the effect of Siberian and North Atlantic Anticyclone in winter and summer periods respectively (Borisov, Halstead, & Ledward, 1965) (Lydolph, 1977). The former prevents the arctic weather mass to enter the region from the higher latitudes. Hence, the dominant rainfall source of the Caucasus forms over the Black and Mediterranean Seas which gradually decline in proportion towards the East (Lydolph, 1977). According to the climate variety of the range, precipitation per annum changes between 200 mm and 3000 mm from semi-arid to extra-humid conditions respectively. As Greater Caucasus Range covered by glaciers approximately 1600 km^2, glacier and snow coverage of the highland areas are the necessary source for river nourishment, agricultural productivity, energy supply, recreational and even economical point of view (Shahgedanova, Hagg, Hassell, Stokes, & Popovnin, 2009).

In recent years, Southern Caucasus macroslope glaciers responded to the temperature rise with the most significant shrinkage in their volume comparing to the Northern Caucasus glaciers. In the basins of Samur, Agrichai and Kusarchai rivers, glaciated area reduced its size by 849 km^2 (52.6%) between the period of 1895-2011 due to global warming (Tielidze & D.Wheate, 2018).

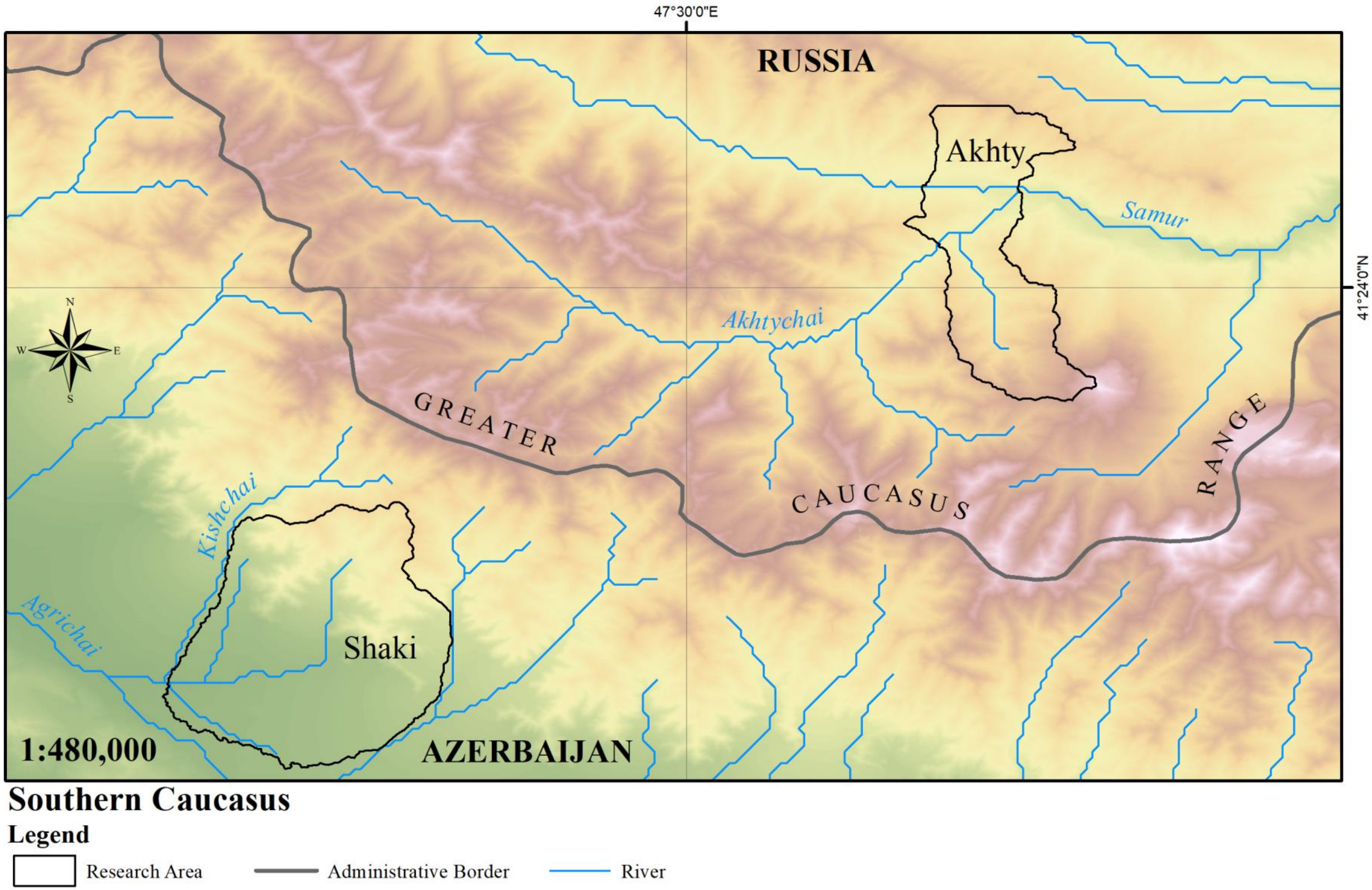
The origin of the water network within Caucasus ranges is highly relied on meteorological rainfall and snow melting. Commonly, higher precipitation occurs on highlands until 2000 m.a.s.l. and gradually decline from west to east per year. Higher precipitation area water streams are typified as high flow and originated by snow melting. Constant snow and glacier zone of the Greater Caucasus mountains hold most of the higher altitude rivers' origin itself. Active river floods are common for the area which lasts about a half of a year, as snow melting results with the rise of the water level during spring and summer periods. Contrary to the rivers which originate from highlands, lowland rivers of the Caucasus flood due to spring snow melts and autumn heavy rains. Unexpected floods happen infrequently in the case of excessive snow melt and deface the terrain which is relatively plain, especially in cropland areas (Beruchashvili, Shotadze, & Nikolaishvili, 2002).

2.1 Research Area Description

The target area of the research consists of two watersheds (*Map 1*), located on the Southern macroslope of the Greater Caucasus range which is also a separator between two parts of the interest area. The first counterpart, namely Akhty (Ахты́) watershed which includes Akhty city areas itself, is included to an administrative unit, Akhtynsky district, in the Dagestan Republic, Russia. The city was established in the middle of 1st millennium BC which was a part of Caucasian Albania and referred as Turi (Гаджиев, 1967). Geographically, Akhty is on the north part of the Greater Caucasus watershed where the Samur and Akhtychay rivers are confluence.

The other counterpart of the research area, Shaki watershed, which also contains a part of the Shaki city, situated on the southern part of the Greater Caucasus ranges. Administratively, the city located within the border of Azerbaijan Republic. As the northern and southern counterparts are close to each other from the geographical point of view, Shaki city was also a part of Caucasian Albania and was founded in the 7th century BC and named as Niqa. The most known rivers for flash floods in Shaki are Kishchai and Shinchai which are branches of Agrichai river originated from the Greater Caucasus range, about 2900 m.a.s.l. altitude (National Encyclopedia of Azerbaijan, 2007).

Due to select comparable sub-watersheds in the region, watershed analysis has been applied to the potential glaciated area within the Southern Caucasus macroslope which have been mapped into The Greater Caucasus Glacier Inventory article (Tielidze & D.Wheate, 2018). As the analysis gave us several couples of sub-watersheds from the region of interest, temperature dataset availability has been affected to select those specific watersheds. Akhty and Shaki sub-watersheds located in a short distance of an airport, which enables continuous climate dataset in any date. In order to have qualified comparisons of snow cover change impacts over the region, Akhty from the northern slope and Shaki from the southern slope of the Southern Caucasus mountains have been defined as the best counterparts. Therefore, Akhty and Shaki will be referred as the northern and the southern watersheds in the following parts of the research.



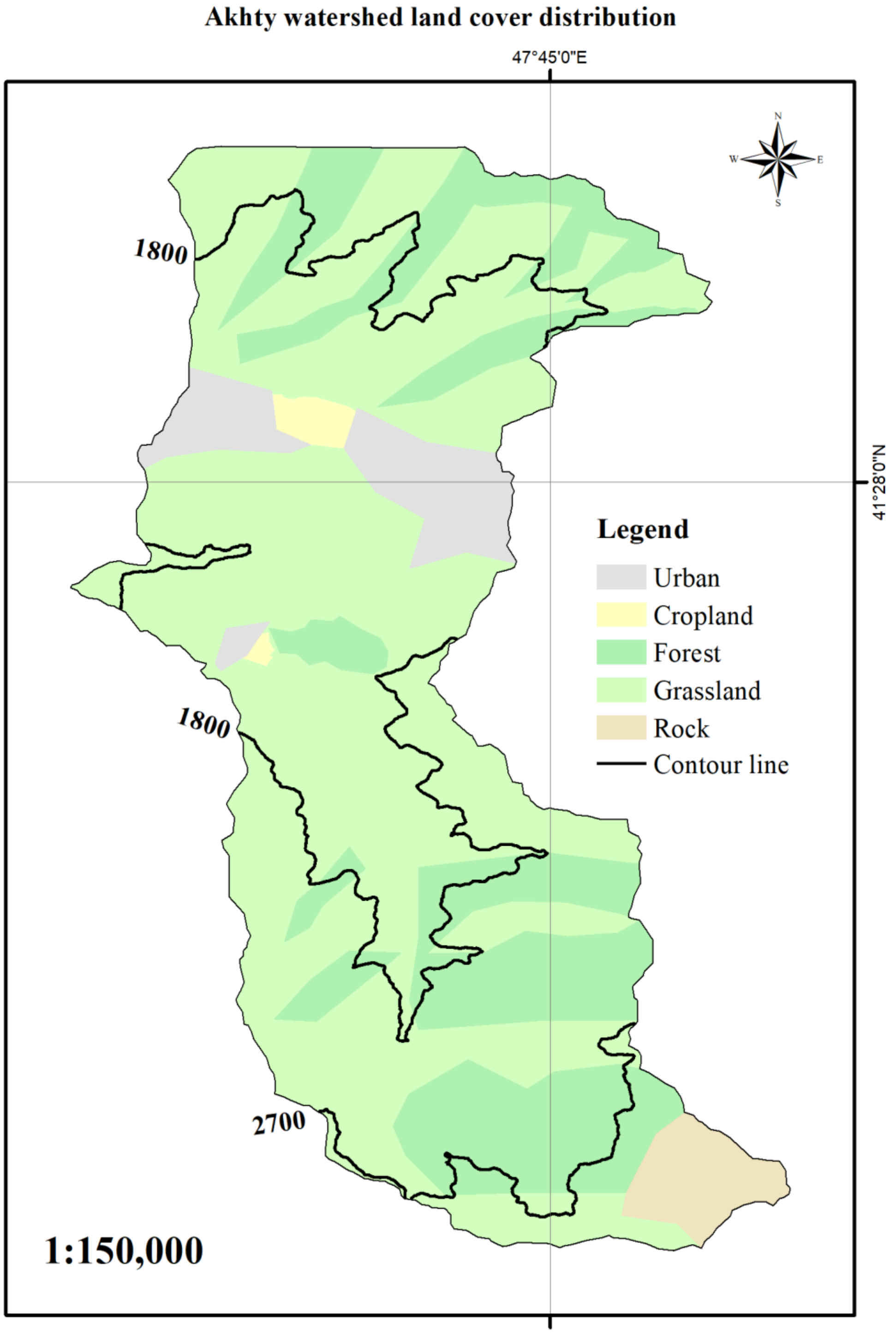
Map 1. *General map of the research area. Several sources have been utilized (USGS, 2018) (Global River Database, 2018).*

According to the altitude difference between the northern and the southern parts of the research area, the weight of the homogeneous landscapes is not in the same proportion for both sides of the watershed. So that, while Shaki is under semi-humid climate conditions with 700-1000 mm annual precipitation, Akhty encounters more than 1600 mm rainfall per annum within humid climate conditions (Beruchashvili, Shotadze, & Nikolaishvili, 2002) (Məmmədov, 2007).

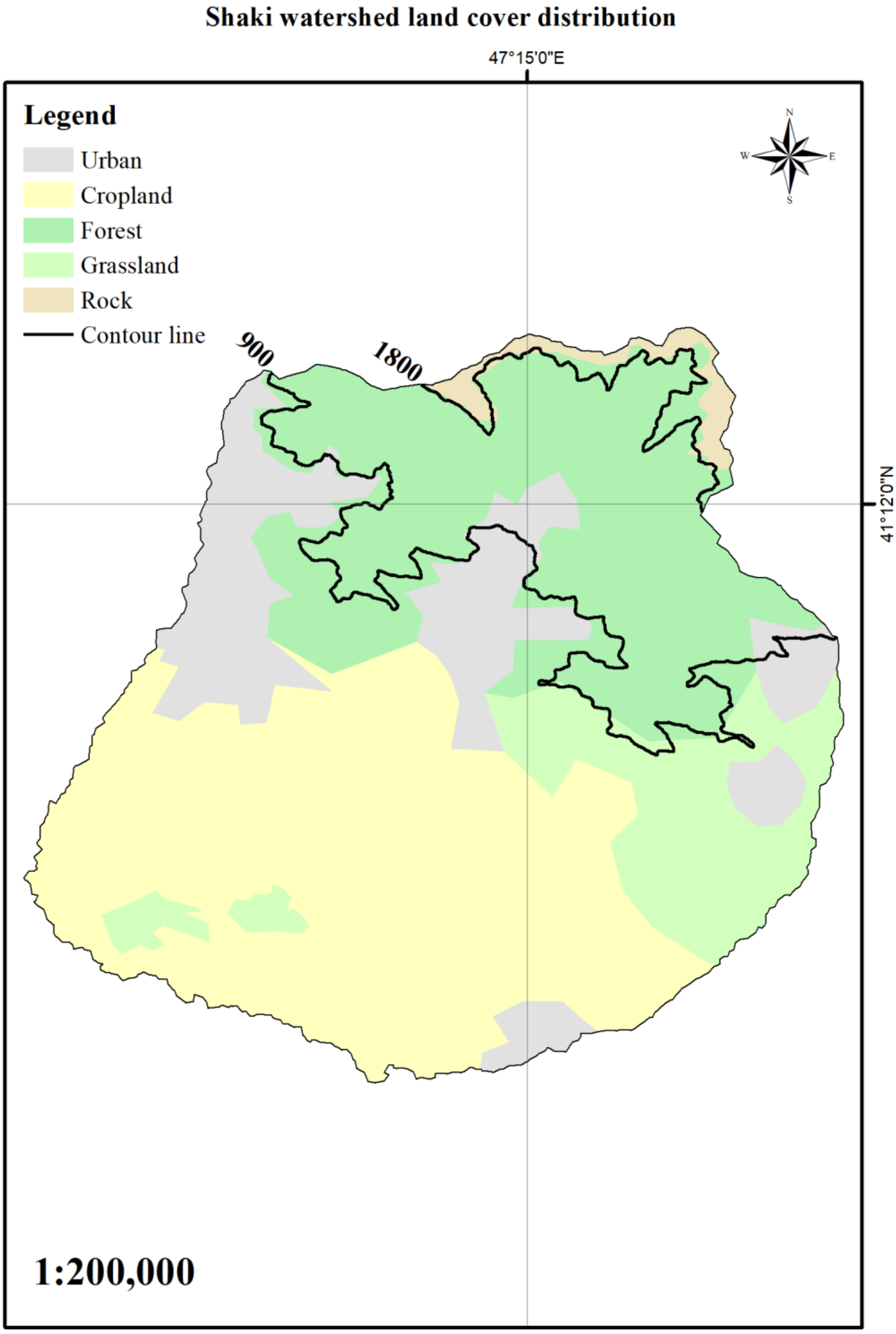
Five types of land cover areas were defined within both research fields, namely urban, cropland, forest, grassland and rock. Contour lines with the 900-meter interval have been generated for Akhty and Shaki watersheds from SRTM 1 Arc-Second Global digital elevation model (USGS, 2018). Although 900-meter interval contour lines do not follow cartographic rules as they seem unusual, the specific interval selection helped to visualize change results effectively.

The coherence of the land covers' distribution inside each contour line of the watersheds, have been carefully adjusted (*Map 2 - 3*). The land cover types were manually digitized by using QGIS 2.18.7 software's OpenStreetMap overlay (OpenStreetMap, 2018). As elevation difference is higher in Akhty compared to Shaki watershed, land cover distribution is slightly varying within the height contours. Although cropland, urban, a part of grassland and forest land types located in the lowest elevation in each watershed, the lowest elevation differs 900-meter as Akhty research field holds higher altitude itself. Therefore, the lowest elevation, 900 – 1800 m, in Akhty matches with the middle elevation interval, 900 – 1800 m, in its southern counterpart.

Middle elevation land cover consists of forest and a part of urban areas in Shaki, whereas it contains a huge part of grassland as well in Akhty region. While 1800 – 2700 m altitude range land covers are grassland and forest in northern watershed, southern watershed contains mainly rock areas in the same altitudes. Rock land cover located more than 2700 m elevations in Akhty watershed.



Map 2. *Akhty watershed land cover distribution. Several sources have been utilized (OpenStreetMap, 2018) (USGS, 2018).*



Map 3. *Shaki watershed land cover distribution. Several sources have been utilized (OpenStreetMap, 2018) (USGS, 2018).*

In the beginning, the research was in the aim of monitoring glaciers changes of Southern Caucasus mountains and its impact over the Akhty and Shaki watersheds. However, according to the research which has been completed in 2018 by a group of Georgian researchers, there is only 1 glacier has been recorded on the Agrichai and its branch, Shinchai, river basins, near to Shaki watershed. Meanwhile, 21 glaciers have been sensed on Samur river basin, near to Akhty watershed, by using Landsat 8 (2013 - 2016) and ASTER (2014) images. As reported by the research, mentioned glaciers revealed approximately 2 % shrinkage per year in the period of 1960 and 2014 (Tielidze & D.Wheate, 2018). Therefore, it was decided to observe snow cover change effects over the target research fields.

Both watersheds on different slopes of the Greater Caucasus range are impacted by global warming in the means of the excessive amount of glacier and snow melting whereat the river floods. In order to be aware of the snow cover area changes, remote sensing gives us wide range of opportunity to monitor the area of interest with optical and radar images. The results obtained from monitoring results help authorities to anticipate and prevent possible dangers for human-being, agriculture and so on.

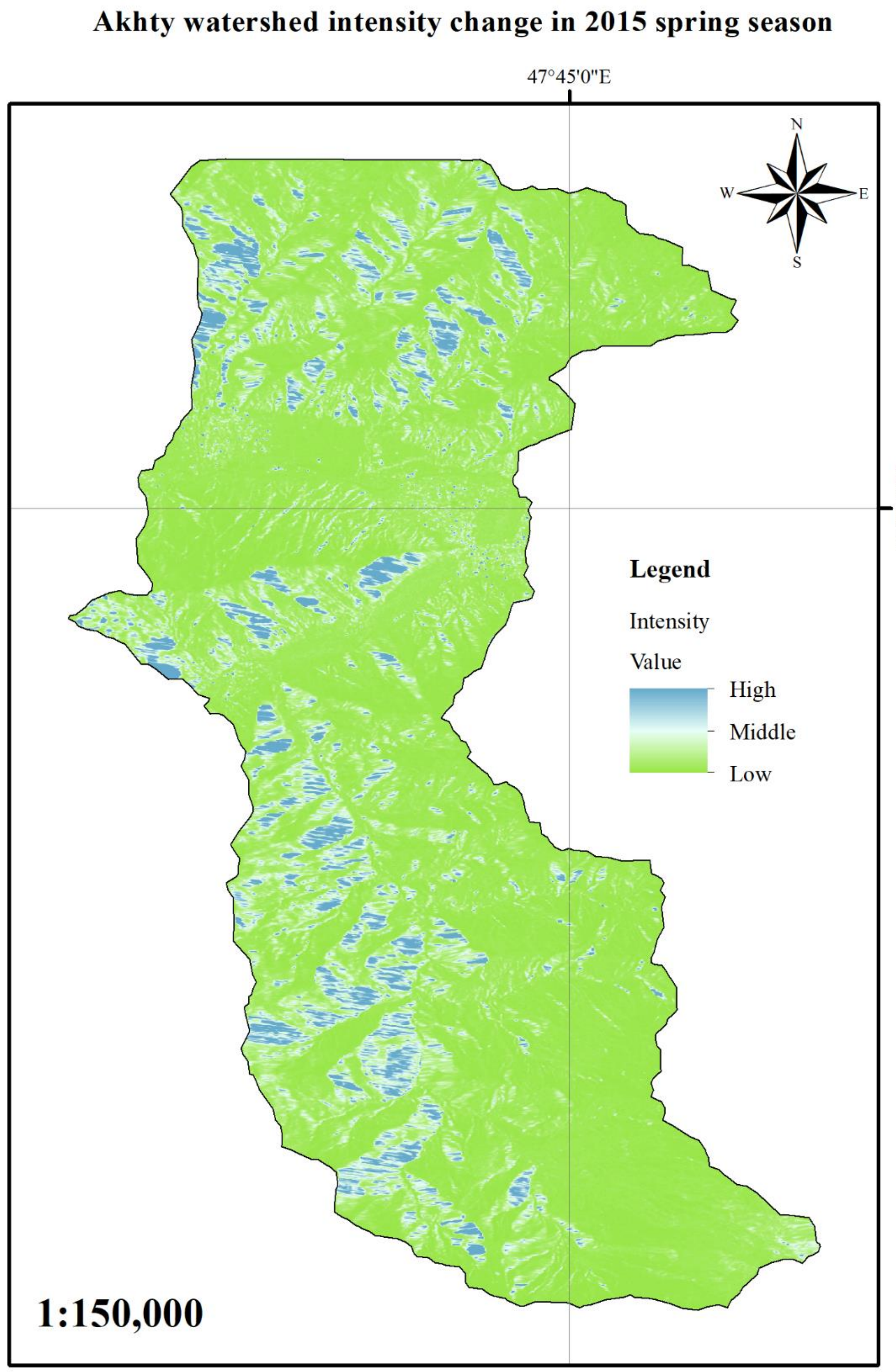
2.2 Pre-Classification Averages

Before going through the snowmelt classification with terrain corrected Sentinel 1 images, spring season image series from 2015, 2016 and 2017 have been processed in order to obtain rough average intensity change maps. The series of maps have been generated by using Band Math calculation in ENVI 5.3 Classic software. Within a season, only four days have been stacked together, as spring season of each year has four dates which are relatively overlapping in the three years' period to make effective comparisons.

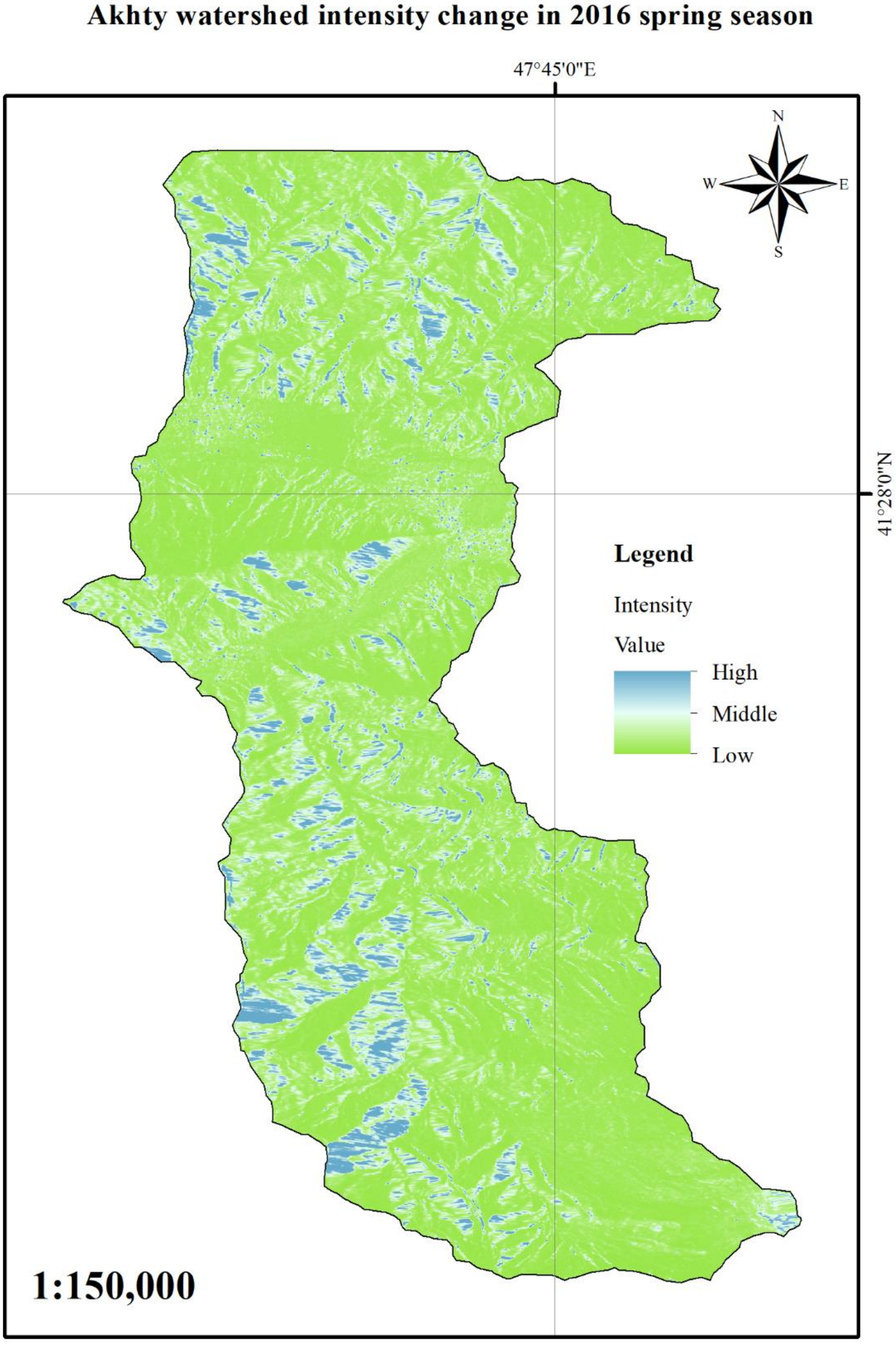
For better interpretation, the stretch color ramp has been applied to the change maps which defined automatically by calculating the standard deviation of intensity band sums of each spring season image series. As those maps have been obtained from unclassified radar images, there are no units for values to be represented on the legend. Therefore, intensity change maps illustrate a qualitative analysis of snow accumulation and melt intensity over the three years' period. Within the legend of map series, Low values, enlisted green, represents no intensity, whereas Middle and High criterions demonstrate snow density which represented in dark and light blue respectively.

According to the change maps of the Northern watershed, namely Akhty, logical correlation can be easily noticed on the snow cover differences in relation to the global warming (Räisänen & Dyn, 2012). As is illustrated on the earliest map, high snow intensity covers relatively large area in the Akhty watershed in 2015, however, a year later noticeable shrinkage on the same intensity can be seen by the bare eye. Due to continuous global warming impact over the region, middle intensity snow cover increased its frequency in 2016 in comparison with 2015 map.

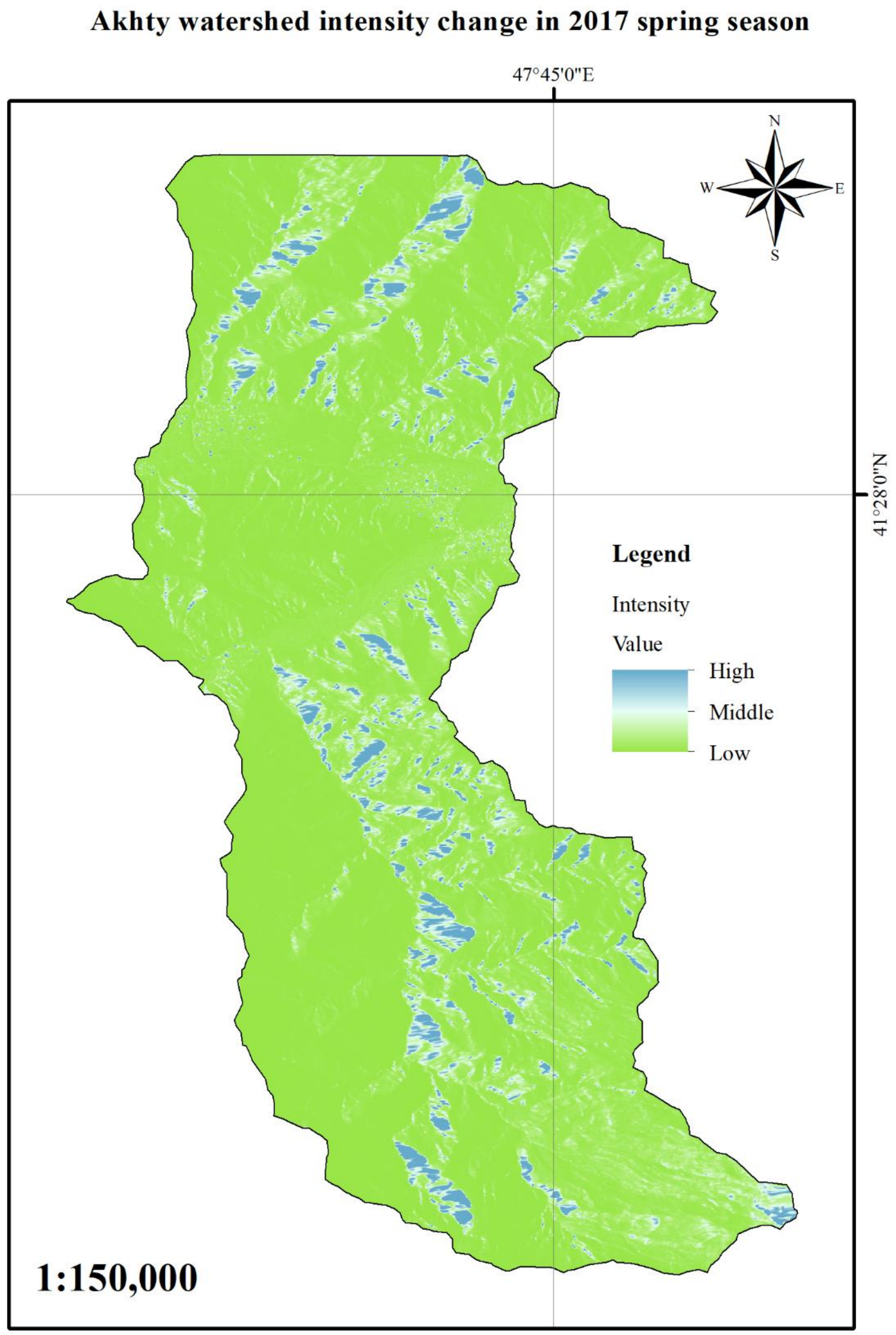
While 2015 and 2016 intensity change maps of Akhty illustrated compatible overview, the last map of the series for the northern watershed demonstrated completely different outline. Similar to the first map, high intensity of the snow cover during the spring season of the third year stood out in the relief. In spite of 2015 map, snow intensity has not been distributed evenly, hence eastern slopes of the watershed received larger amount of solid precipitation in 2017. When it comes to the middle intensity change on snow cover, the last year of the series revealed the lowest density comparing with the first two years.



Map 4. *Akhty watershed average snow intensity in 2015 (Copernicus Open Access Hub, 2018).*



Map 5. *Akhty watershed average snow intensity in 2016 (Copernicus Open Access Hub, 2018).*



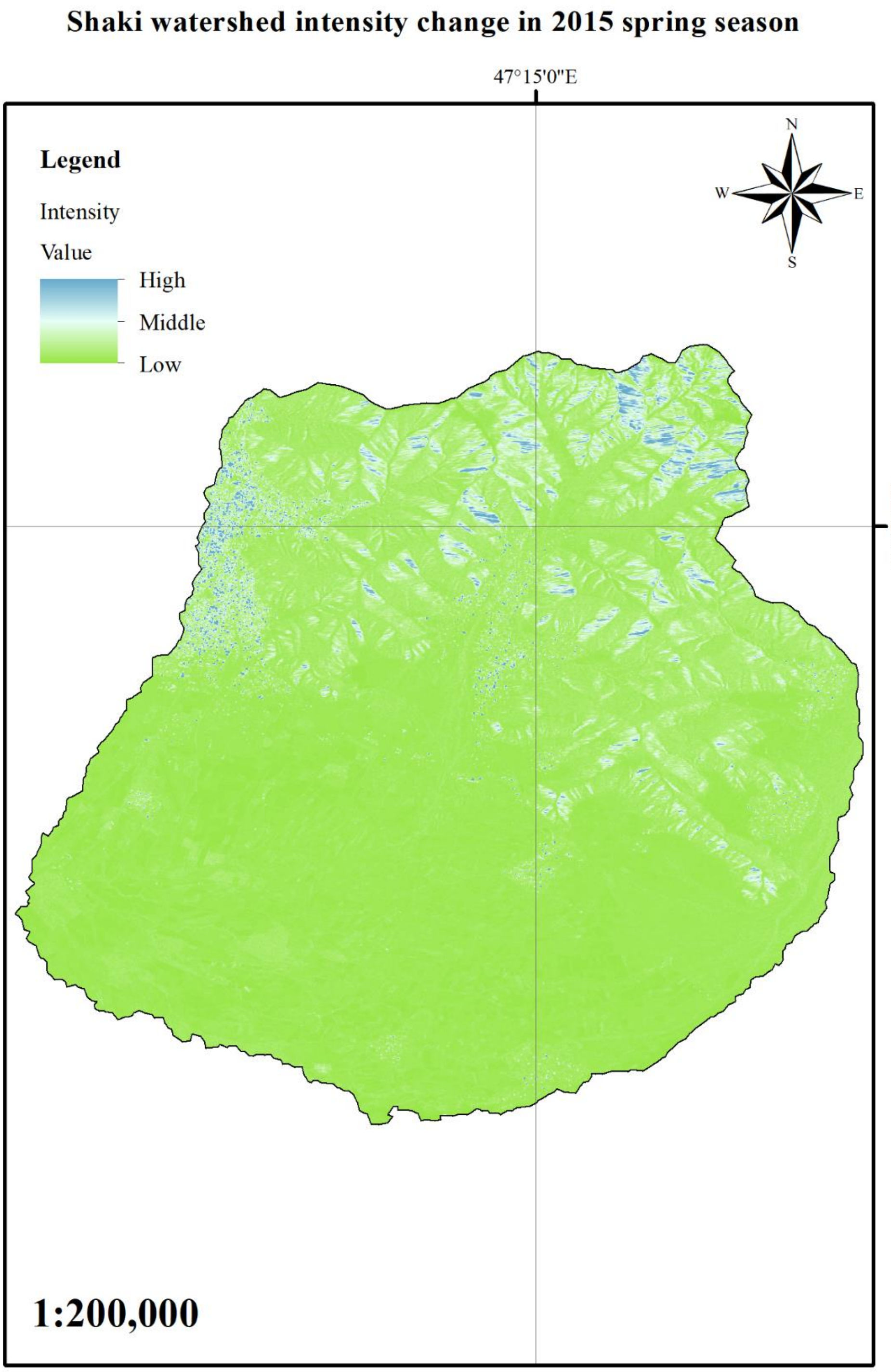
Map 6. *Akhty watershed average snow intensity in 2017 (Copernicus Open Access Hub, 2018).*

In contrast with the Akhty watershed, sharp changes on the average intensity of the snow cover can hardly be seen on the southern watershed, namely Shaki. As Shaki watershed located at 900 m lower altitude than its northern counterpart, smoother intensity changes over the region observed in three years' period.

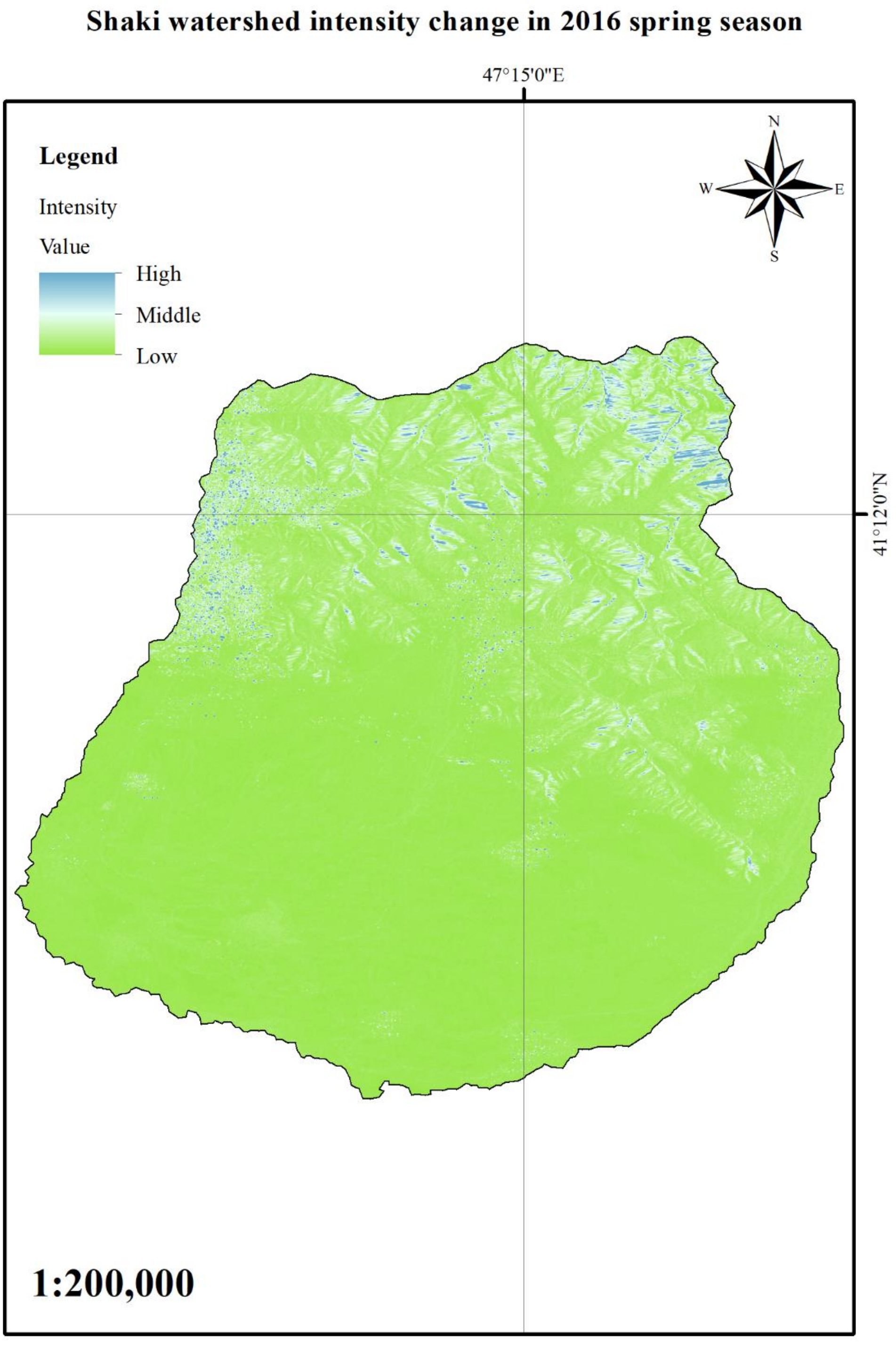
To have a detailed view of the southern watershed map series, 2015 and 2016 average intensity maps are slightly differentiated from each other. According to the first year spring season averages, solid snow precipitation was larger in quality on the northern part of the Shaki watershed, however, the same part of the region received slightly lower snowfall in high density in 2016.

As a result of the global warming effect, the average temperature of the spring season increased approximately 1 ºC between 2015 and 2016 (*Table 1, page 42*). The temperature rise caused less solid snow precipitation in middle criterion especially on the southern part of the Shaki region in 2016 compared with the earlier year.

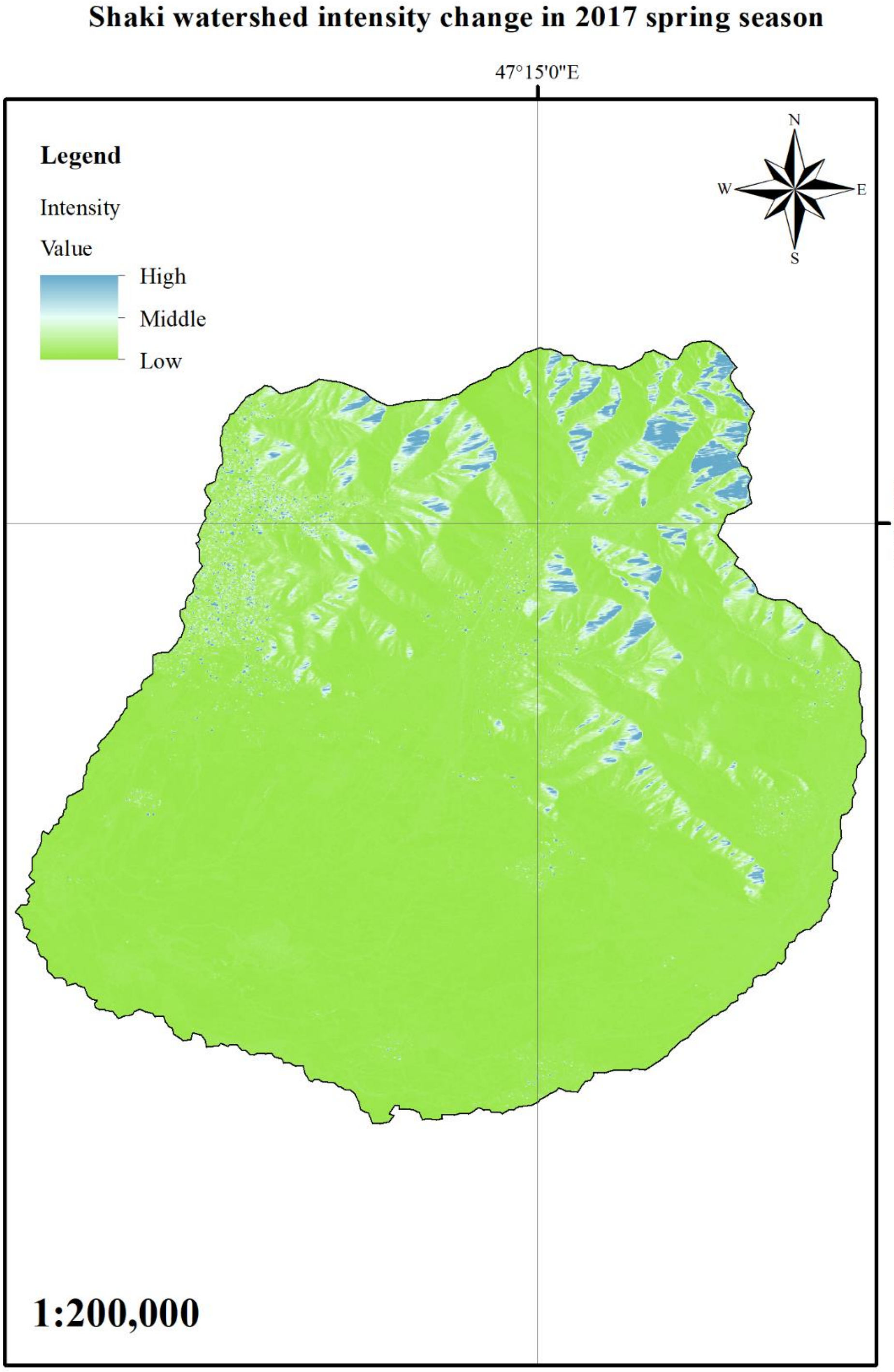
Qualitative analysis of the average snow intensity changes in 2017 illustrated significant diversity in contrast with 2016 and 2015 in southern watershed similarly with the northern one. Considerable quality of the solid snow precipitation observed mainly in high density over the northern part of the Shaki watershed within the last year map of the series. While high density of snow precipitation came to the foreground in 2017, middle density faced with the largest quality loss of the snow intensity in comparison with the earlier two years in Shaki watershed.



Map 7. *Shaki watershed average snow intensity in 2015 (Copernicus Open Access Hub, 2018).*



Map 8. *Shaki watershed average snow intensity in 2016 (Copernicus Open Access Hub, 2018).*



Map 9. *Shaki watershed average snow intensity in 2017 (Copernicus Open Access Hub, 2018).*

3. Methods

3.1 SAR Geometry

Synthetic Aperture Radar (SAR) technology is used either ground or space-based according to the coverage and the purpose of the interest area. In contemporary life, SAR data is applied to agriculture, flood mapping, soil moisture, forestry, terrain analysis, oceanography, snow and glacier mapping, geology etc. In order to observe ecosystem, land and ice displacement of Earth in high resolution, SAR is an unexampled technology. European Space Agency (ESA) launched its first European Remote Sensing satellite (ERS-1) which provides SAR in 1991, since then, SAR became one of the observation tools of Earth.

Nowadays, performing SAR orbits uses C (5.3 GHz), L (1.2 GHz) and X (10 GHz) bands of the microwave which is in the capable of going through the clouds. As SAR transmits its own electromagnetic emanation to the point and emits backscattered energy, any weather condition and time of a day is suitable for microwave imaging.

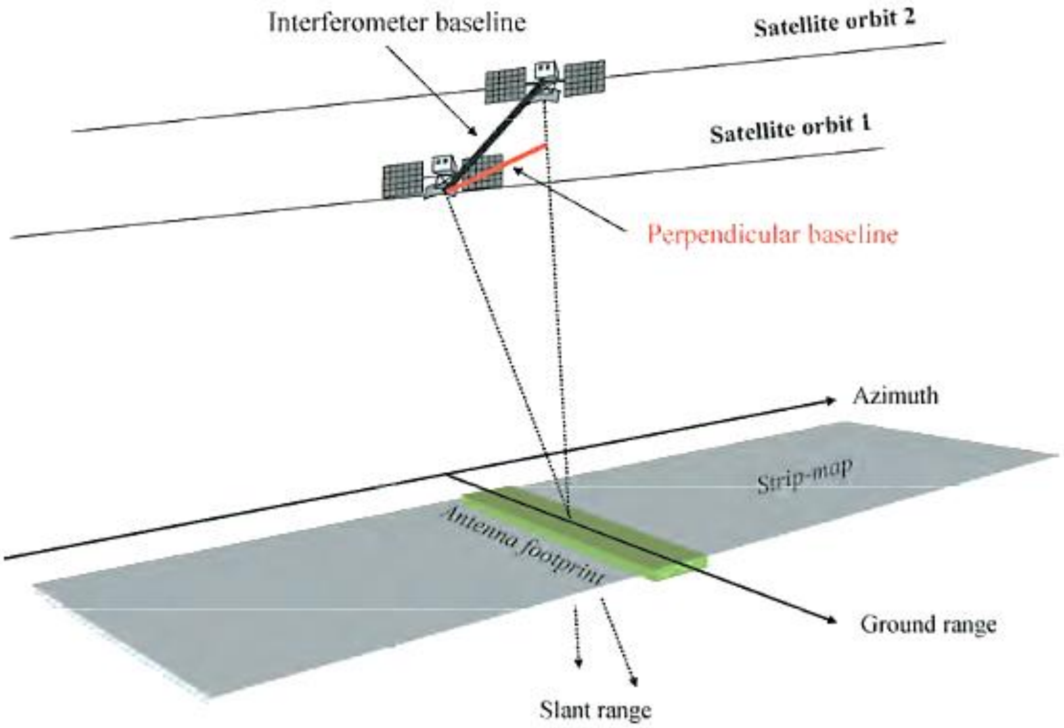


Figure 1. *Geometry of a satellite Interferometric SAR system (Alessandro Ferretti, 2007).*

Currently, the technology is used for snow cover and glacier motion analysis is called Interferometric Synthetic Aperture Radar (InSAR). InSAR supplies two or more look of the same area from diverse angles. The method can be done by two concurrent radars which are in the target area or by utilizing the same satellite signals with the slight time difference. In the former method, the interval of the two orbits is defined as interferometric baseline. The projection of the interferometric baseline is perpendicular to the slant range which is called perpendicular baseline (*Figure 1*).

InSAR images are prepared pixel by pixel by the cross-multiplying method. In this occasion, the amplitude of the final product is generated by multiplication of the first image to the second one, however, the interferometric phase differs per image. Backscattered SAR signal consists of amplitude and phase data where the amplitude represents radar response durability and phase is a property of the wavelength (Alessandro Ferretti, 2007).

3.2 Data Source, Image Processing and Classification

For analyzing and classification of the snow cover of the research area, Sentinel 1A platform radar images have been used which was launched in 2014, April by ESA (Alessandro Ferretti, 2007). Sensing period of the Sentinel 1 images is varying between 12 to 19 days for the Southern Caucasus area during 2015, 2016 and 2017. Altogether, 21 Sentinel 1 Ground Range Detected (GRD) radar images with IW, Interferometric Wide about 250 km swath, and VV polarization have been used during the research. The series of the images have been accessed through the ESA Scientific Hub website online (Copernicus Open Access Hub, 2018).

Intensity band of the series of the radar images have been accounted to calculate and classify the snow cover changes of Akhty and Shaki watersheds which locate on the northern and southern slopes of the Greater Caucasus ranges respectively. Classification and analyses based on the intensity values of the Sentinel 1 images are a rough approximation of snow accumulation and melting during the spring season of 2015, 2016 and 2017 years.

Using Shuttle Radar Topography Mission (SRTM) digital elevation model which has been obtained from Earth Explorer website (USGS, 2018), watershed analysis has been generated in ArcGIS 10.4.1 software. 42°0′0″ N, 47°0′0″ E, 48°0′0″ N, 41°0′0″ E bounded digital elevation model analyzed automatically for defining watershed areas according to the northern and southern slopes of the Caucasus ridge. In consequence of watershed analysis, Akhty and Shaki sub-watersheds were selected as the primary research area.

Within the SNAP 6.0 software, downloaded series of radar images masked with the shapefiles of Akhty and Shaki watersheds by using Land-Sea Mask method. In the following step, terrain correction method, namely Range-Doppler Terrain Correction, applied to the intensity band of raw GRD radar images with only VV polarization. Afterwards, geographically corrected image data series exported to ENVI 5.3 Classic software in order to be classified.

All intensity bands inside a season were stacked to a layer in ENVI. To get the snow intensity difference results, Band Math have been operated between every two bands in reverse order, so the earlier date image subtracted from the later one. The operation has been done for every couple of images within a season of a year. According to the count of the images per year, 7, 5 and 4 Band Math difference results gained for 2015, 2016 and 2017 respectively.

Subsequently, K-means unsupervised classification with the parameters of 10 classes and maximum 1 mean and standard deviation accomplished for every intensity difference images of a season. The results of the classifications have been visualized on linked displays constantly in order to define the classes without values. Due to empty classes of K-means classification which is also referred as Cluster Analysis, first four classes combined under the name of unclassified features, while the rest of the class, from 5th to 10th, defined as one class during Post Classification operations for the result of every intensity difference classification.

Post Classification followed the computation of statistics separately for all land cover shapefiles distributed within elevation contours of the watersheds. Mean and standard deviation was calculated for classified images in the means of statistics. The results exported to text files for both, Akhty and Shaki watersheds for the three years' period.

In the following step, statistics results examined in Microsoft Excel software in order to generate snow intensity change and average temperature correlation graphs. At the same time, the output of the statistics has been visualized within some couples of maps for a series of images of a season.

4. Results

4.1 Snow Cover Loss and Temperature Correlation

To have a general review of the cluster analysis of snow cover intensity change statistics for Northern and Southern watersheds in 2015 *(Figure 2 "a", Figure 3 "a")*, similarities can be observed on intensity change meanwhile the average temperature which was calculated according to the image sensed days' period, is slightly higher in Shaki rather than in Akhty counterpart. During the first half of the spring season in 2015, average temperature increased about 7 ºC for both watersheds which contributed to the snowmelt indicator rise, approximately 14 %. During the second half of the season, research areas confronted about 3 ºC decrease on temperature average of both slopes of the range, despite this the indicator reached to approximately 20 ºC till the end of the season. Accordingly, snow intensity percentage adapted to the temperature rise and revealed about 40 %. To sum up, snow cover changes of 2015 spring, created similar overview within the northern and southern watersheds.

When it comes to the snowmelt and temperature correlation in Akhty and Shaki watersheds, the first half of the season seem harmonious for both areas, however, snowmelt percentages create sudden changes in Shaki during the second half in 2016 (*Figure 2 "b", Figure 3 "b"*). To describe in detail, the temperature increased to 15 ºC in the northern and the southern research area while snow cover loss percentages hit the highest value, about 65 % in Shaki, the same indicators for Akhty faced slight snow loss with 25 % starting from the second part of the season. Contrary to the statistic results of 2015, research areas revealed significant difference on snowmelt results as the temperature of the southern watershed was higher than northern one in 2016.

The graphs which demonstrate snowmelt percentages in Akhty and Shaki creates almost no difference in 2017 spring (*Figure 2 "c", Figure 3 "c"*). Temperature averages of 12 days which matches with the sensing interval of the Sentinel 1 images, altered around 13 ºC for Akhty while Shaki counterpart reached to 19 ºC towards the end of the season. Tough the temperature averages were higher in Shaki, Akhty confronted the highest snowmelt loss during 2017, spring.

Taking everything into account, 2015 and 2016 revealed relatively the same amount of snowmelt intensity loss, however, statistic results for 2017, maintained almost the same level of changes for both parts of the research area.

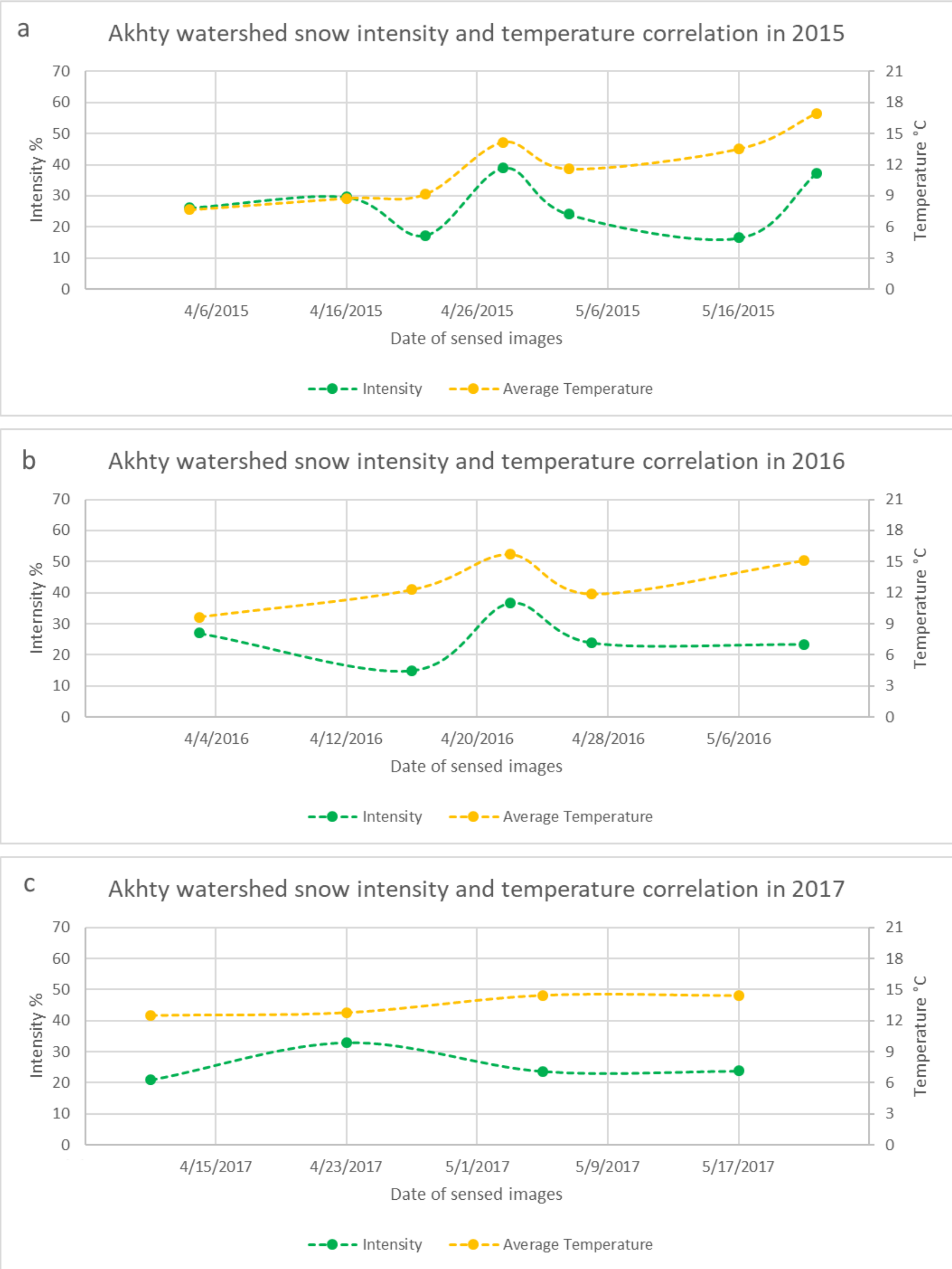


Figure 2. *Akhty watershed snow intensity and temperature correlation in three years' period. Various sources have been used (Copernicus Open Access Hub, 2018) (Weather for 243 countries of the world, 2018) (Climate Data Online, 2018).*

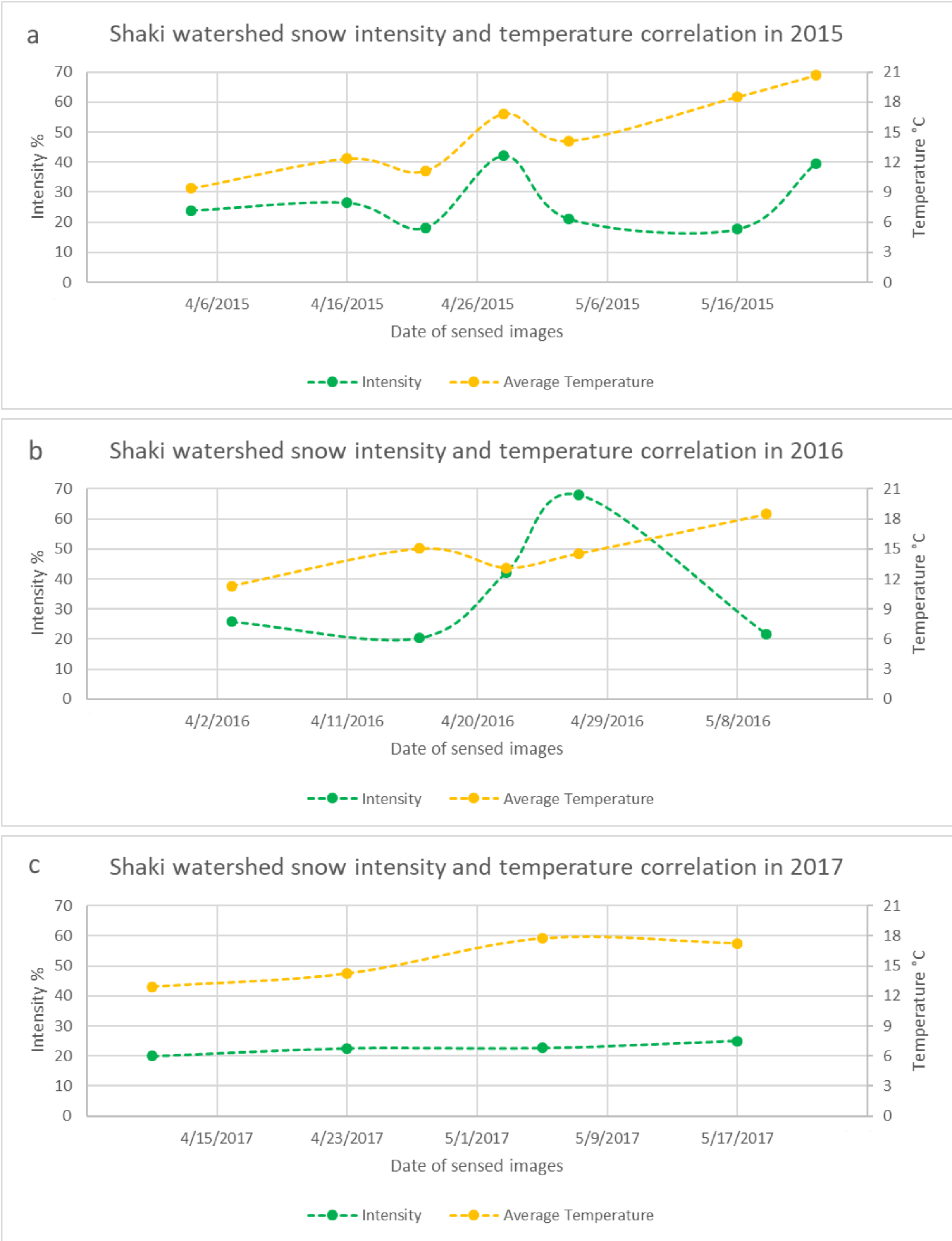


Figure 3. *Shaki watershed snow intensity and temperature correlation in three years' period. Various sources have been used (Copernicus Open Access Hub, 2018) (Climate Data Online, 2018) (World Weather Online, n.d.) (Ministry of Ecology and Natural Resources of Azerbaijan Republic, n.d.).*

4.2 Elevation Impact Over the Snow Cover Change

Other couples of graphs have been created from statistic results of a series of Sentinel 1 images due to a better interpretation of snow cover changes depending on elevation contours of interest areas. Altitude ranges changes between 900 and 2700 meters for both, Akhty and Shaki watersheds.

First pairs of graphs illustrate similar overview for the northern and southern slopes of Caucasus mountains from temperature aspect which is slightly higher, about 3 ºC, in Shaki compared to the Akhty one in 2015, spring (*Figure 3 "a", Figure 4 "a"*). As the temperature has a direct relation with snowmelt percentage changes of the target areas, the highest rates within both elevation contours can be observed in the middle and at the end of the season by around 40 % snow cover loss in 2015. While snowmelt indicators revealed more or less 20 % between 1800 and 2700 m altitude ranges in Akhty, the same sign maintained on the same level, around 15 %, in Shaki between the first and the second half of the season. Lower altitude snow cover loss indicators changed between 20 and 30 % on the northern and the southern watersheds in 2015. To sum up, snow coverage loss in 2015 for Akhty and Shaki created alike results.

When it comes to the second pairs of the graphs, noticeable differences can be seen between northern and southern part of the research fields as temperature varied in the middle of the season in 2016 (*Figure 3 "b", Figure 4 "b")*. During the first half of the season, snowmelt percentages fluctuated around 20 % within both altitude ranges and watersheds and reached about 30 % in Akhty while it was 40 % in Shaki. The greatest difference between the snowmelt indicators of two watersheds happened right after 10 ºC temperature inequality on 21st April 2016. During the next 6 days, the temperature in Akhty declined more than 10 degrees which caused around 20 % snow cover loss on lowland and highland areas, while Shaki snow coverage loss changed 5 % between two elevation ranges and reached about 65 % on highland areas. Snowmelt indicators of 900 – 1800 m and 1800 – 2700 m elevations in both watersheds, completed the season with 10 % difference where the lower altitude snowmelt percentage reached around 30 % in Akhty, while it was 20 % in Shaki counterpart.

Overall, snowmelt rates in 2016 within the northern and southern watersheds showed dissimilarities after the second part of the season according to the temperature changes.

Figure 4. *Akhty watershed terperature and snow intensity change graph in relation with elevation contours in the three years' period (Copernicus Open Access Hub, 2018) (Climate Data Online, 2018) (Weather for 243 countries of the world, 2018).*

Figure 5. *Shaki watershed terperature and snow intensity change graph in relation with elevation contours in the three years' period (Copernicus Open Access Hub, 2018) (Climate Data Online, 2018) (World Weather Online, n.d.) (Ministry of Ecology and Natural Resources of Azerbaijan Republic, n.d.).*

The third pair of the change graphs illustrates a coherent image of the temperature and snowmelt indicators for Akhty and Shaki areas in 2017 (*Figure 3 "c", Figure 4 "c"*). Contrary to the earlier years, temperature average represents relatively equally-distributed outlook which effects over snowmelt rates similarly for both research areas in 2017. While the snow cover loss rates in Shaki revealed approximately 20 % inside lowlands, highland snowmelt indicators changed between 15 and 20 % all over the season. Snow cover loss percentages maintained around 20 % in Akhty lowlands and highlands that slightly differed from each other, up to 5 %, during the season.

In conclusion, snow cover loss indicators per elevation contours slightly differentiated between lowlands and highlands within each watershed, however, changes demonstrated fluctuations in snow cover loss values according to the temperature changes in Akhty and Shaki watersheds.

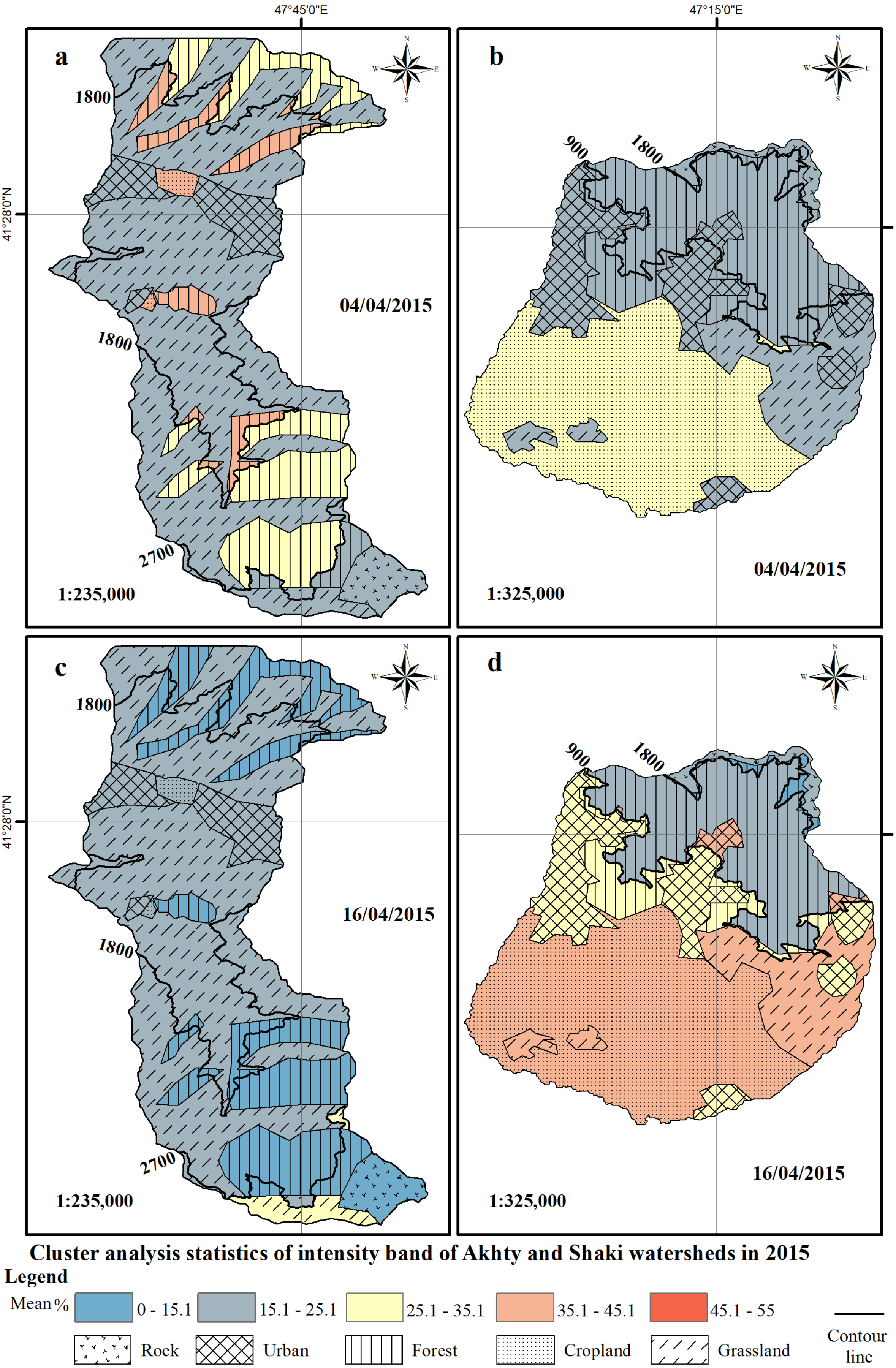
4.3 Visual Comparison of the Cluster Analysis Results

After statistic calculations, the results of each intensity change difference map of Northern research area compared with its Southern counterpart. Considering the maximum and minimum snowmelt quantity in percent per land cover of each elevation (900 - 1800 m; 1800 - 2700 m; 2700 m and higher in Akhty; 0 - 900 m; 900 - 1800 m, 1800 - 2700 m in Shaki), intervals were defined in five classes for three years' map series separately. Within a season of a year, four dates have been selected to be compared which more or less match with the other selected dates from each year.

To have a glimpse to the first couple of maps in 2015 (*Map 10 "a", "b"*), cropland and a part of forest areas have lost noticeable quantity, between 35 to 45 %, snow cover intensity inside 900 – 1800 m elevation on 4th of April in Akhty watershed. Northern and southern watersheds demonstrated same amount snow cover loss, approximately 30 %, within higher elevation forest land cover in Akhty and cropland areas in Shaki counterpart. The rest of the land types (grassland, urban, rock) in both watersheds revealed more or less 20 % snow cover intensity reduction regardless to the elevation on early April, 2015.

The second pair of maps in 2015 (*Map 10 "c", "d"*) illustrates relatively different overview of snow intensity reduction values within the northern and southern watersheds. Shaki watershed differs with approximately 30 and 40 % snow cover loss over the urban, a part of forest, cropland and grassland areas within 0 - 900 m altitude, similarly, grassland areas in Akhty demonstrated around 30 % snow intensity decrease in the highest elevation, more than 2700 m.

As oppose to the map "a" (**Map 10**), higher snow intensity loss on forest land cover replaced with the lowest quantity, approximately 15 %, twelve days later in the map "c" (**Map 10**) on the northern watershed, meanwhile forest land covers' snow intensity reduction revealed about 20 % on the southern counterpart. Rock land type in Akhty preserved approximately 85 % of its snow cover, however, the same land cover has lost around 20 % of snow intensity.



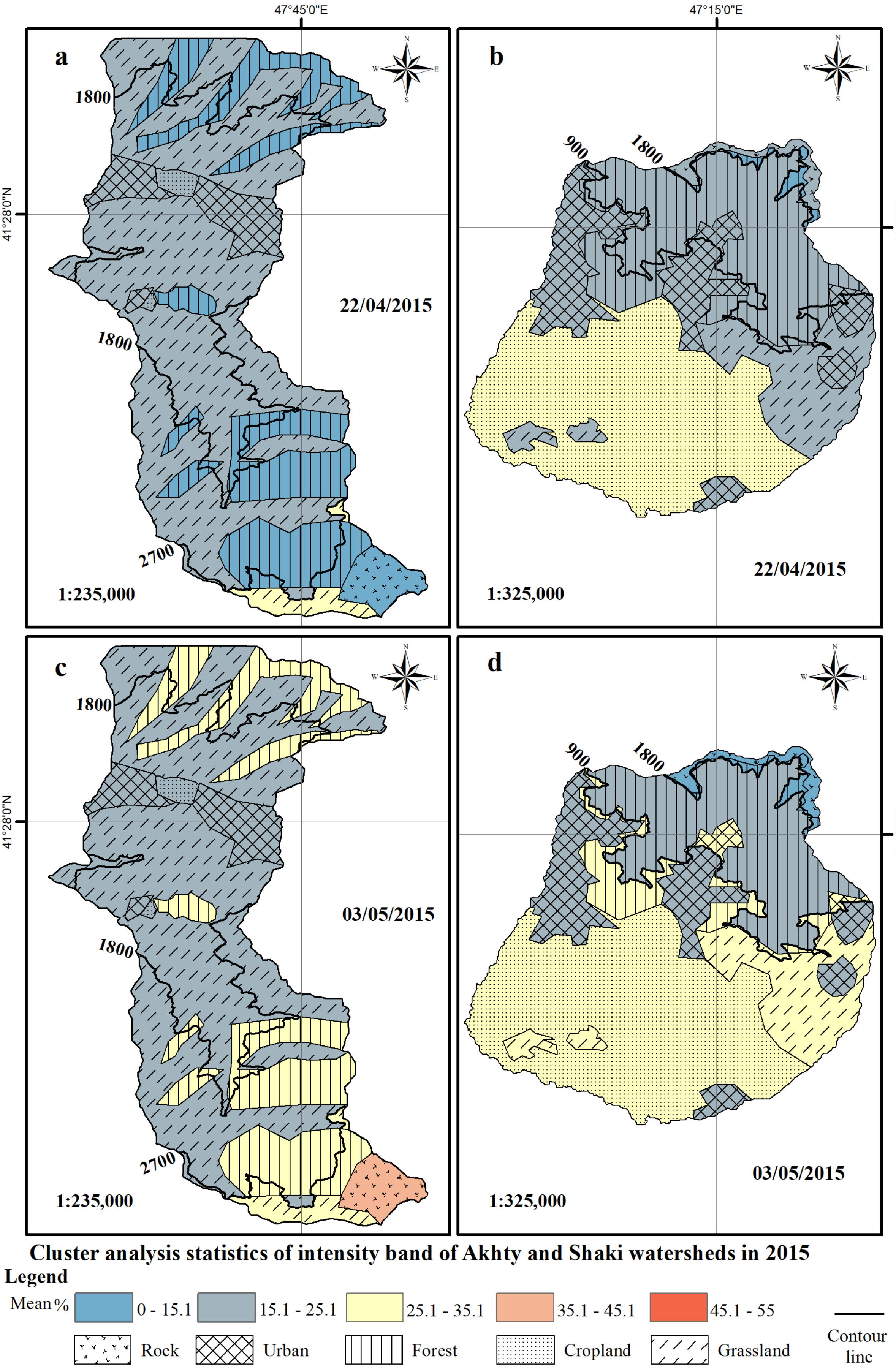
Map 10. *Classification results in 2015 (Copernicus Open Access Hub, 2018).*

The third couple of the maps (**Map 11** “a”, “b”) do not illustrate steep differences on snow cover reduction percentages from the first sight. Cropland area of Shaki watershed revealed around 30 % of its snow cover, meanwhile similar quantity of reduction on snow intensity happened on grassland areas in Akhty counterpart.

While forest land cover within 900 – 1800 m and 1800 – 2700 m elevations have lost the smallest amount of snow cover, about 15 % in the northern watershed, the same land cover in the southern counterpart demonstrated 15 to 25 % loss on middle elevations and preserved almost 85 % of its snow cover on the highest altitude.

The last pair of maps in 2015 (*Map 11 “c”, “d”*) creates relatively reverse order of the snow cover melt indicators with the land covers of Akhty and Shaki watersheds. Meantime the northern region intensity losses reached to 40 % within the highest elevation which covers rock area, southern region’s rock land cover confronted the lowest quantity of snowmelt by 15 %.

Grassland and cropland areas showed more or less 20 % snow intensity decrease in Akhty, whereas the same land covers revealed about 10 % higher snow cover loss in Shaki. While forest area’s snowmelt indicators reached to 20 % in Shaki, it demonstrated approximately 30 % in Akhty counterpart.



Map 11. *Classification results in 2015 (Copernicus Open Access Hub, 2018).*

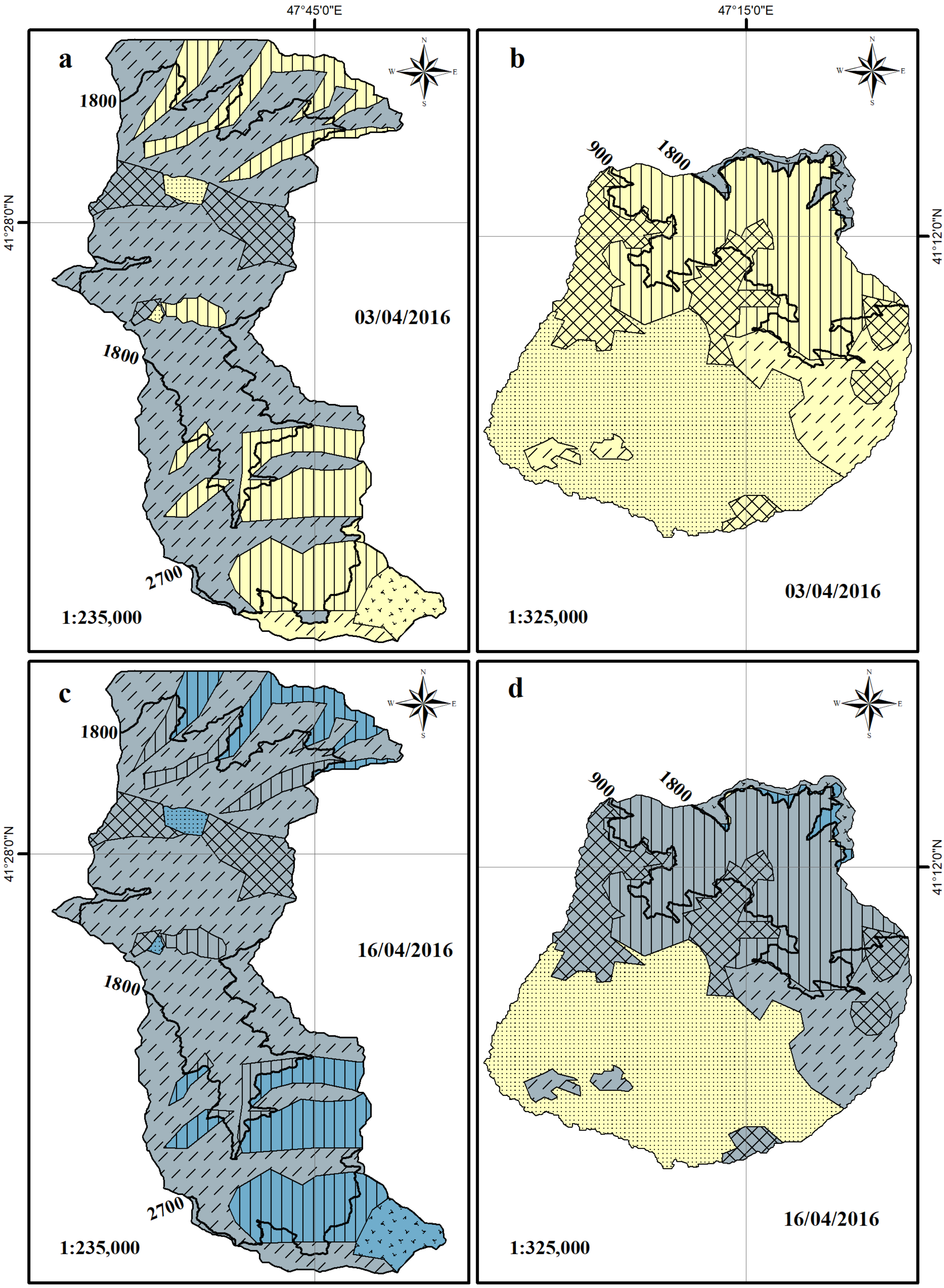
According to the first pair of maps in 2016 (**Map 12** “a” , “b”), northern and southern watersheds’ snow cover loss quantities did not exceed 35 % regardless to the land cover types. Except for rock and a part of forest land cover types in Shaki watershed, snow cover intensity reduction demonstrated more or less 30 % until 1800 m elevation contour.

While cropland and forest areas have lost the same quantity of snow intensity, between 25 to 35 % within both watersheds, rock land type showed about 10 % less snow cover shrinkage indicator in the northern part in comparison with the southern watershed. When it comes to the grassland and urban land cover types’ snow intensity change, Shaki watershed has lost around 30 % intensity value, whereas Akhty counterpart preserved more than 70 % snow cover itself.

The second couple of maps (*Map 12 “c”, “d”*) in 2016 illustrated similar amount of snow intensity loss between 900 – 1800 m altitude inside both, northern and southern watersheds. So that, urban, forest and grassland areas’ snow intensity loss demonstrated no more than 25 % in Akhty and Shaki regions.

While the northern watershed preserved almost 85 % snow cover itself, southern one confronted approximately 30 % snow shrinkage. Akhty watershed land covers’ snowmelt indicators changed between 0 and 15 % where the rock, cropland and forest areas hit the lowest snowmelt quantity, however, Shaki showed the same amount of snow intensity loss within a part of forest area between 1800 – 2700 m altitudes.

In comparison with 1st half of spring season, 2015 series maps (*Map 10*), the same period maps in 2016 (*Map 12*) differentiated by less quantity of snow intensity reduction.



Cluster analysis statistics of intensity band of Akhty and Shaki watersheds in 2016

Legend

Mean% 0 - 15.1 | 15.1 - 25.1 | 25.1 - 35.1 | 35.1 - 45.1 | 45.1 - 55

Rock | Urban | Forest | Cropland | Grassland | Contour line

Map 12. *Classification results in 2016 (Copernicus Open Access Hub, 2018).*

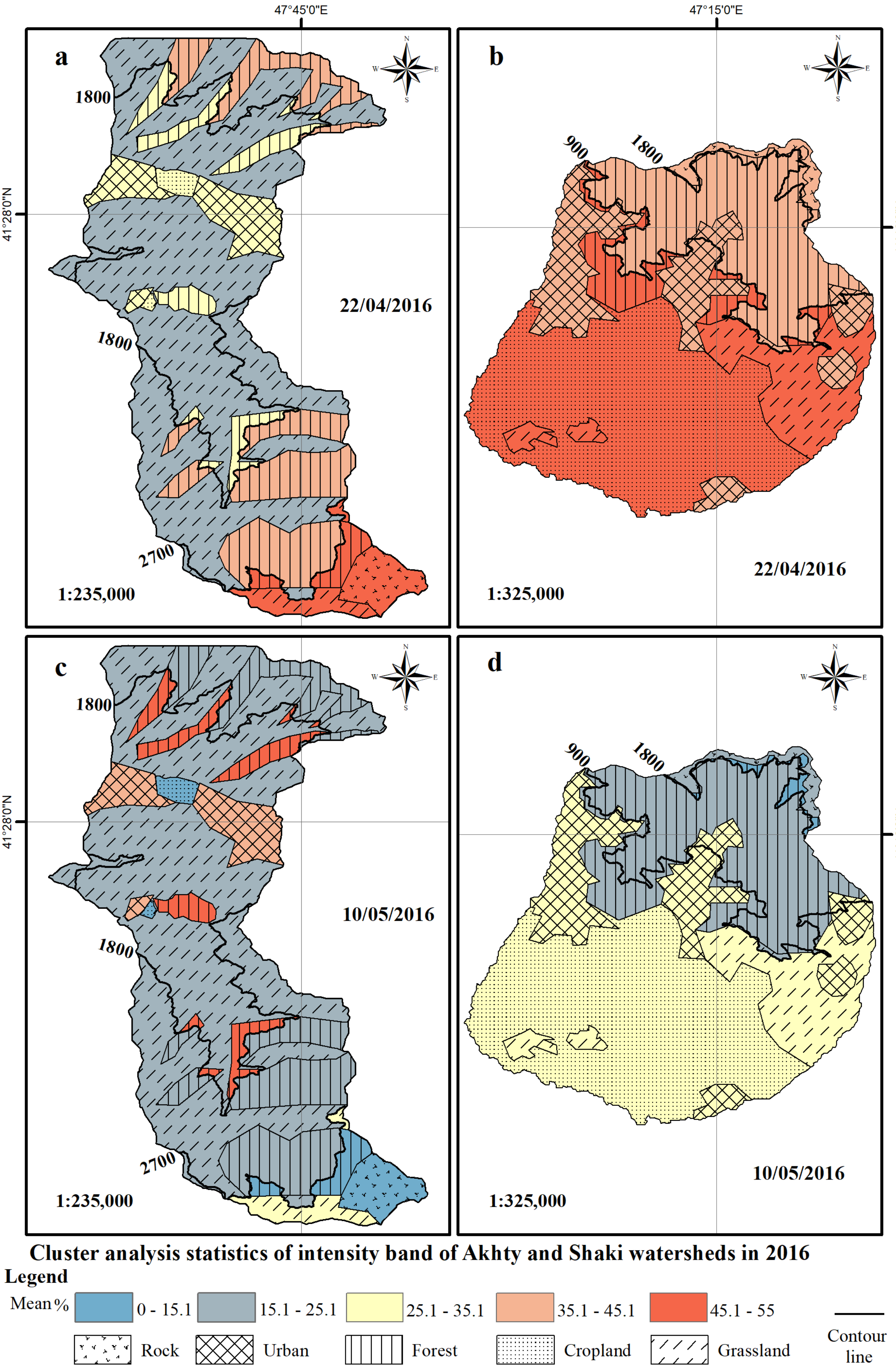
The third pair of maps (*Map 13 "a". "b"*) demonstrated relatively high values of snow shrinkage quantities compared with the first half of the spring season in 2016. Only grassland area revealed lower snow cover reduction, around 20 %, in Akhty, whereas the same land type demonstrated the highest quantity of snow reduction, by 50 %, in Shaki counterpart.

Within 900 – 1800 m altitude, forest and a part of urban areas have lost approximately 40 % snow intensity in the southern watershed, meanwhile, the same land cover types revealed about 10 % less reduction in the northern region. Rock, a part of forest and grassland areas on more than 2700 m altitudes in Akhty watershed hit the highest value of the snow intensity reduction.

Negligible correlation between the Northern and the Southern watersheds can be noticed on 4th pair of snow intensity reduction maps (*Map 13 "c", "d"*) in 2016. Cropland, rock and a part of forest areas within Akhty watershed faced the lowest snow cover loss quantity, by 10 %, meanwhile, the same figures except for cropland in Shaki watershed revealed no more than 25 % snowmelt.

While forest land cover reached to the highest snowmelt level, approximately 50 %, in the northern watershed, the same land cover in Southern watershed revealed about 30 % less snow cover loss between 900 – 1800 m altitudes. Urban land cover's snow cover reduction quantity demonstrated about 30 % in Shaki, however, the same figure showed 40 % snow shrinkage in Akhty watershed.

In comparison with 2nd half of spring season, 2015 series maps (*Map 11*), the same period maps in 2016 (*Map 13*) illustrated the higher amount of snow cover intensity loss.

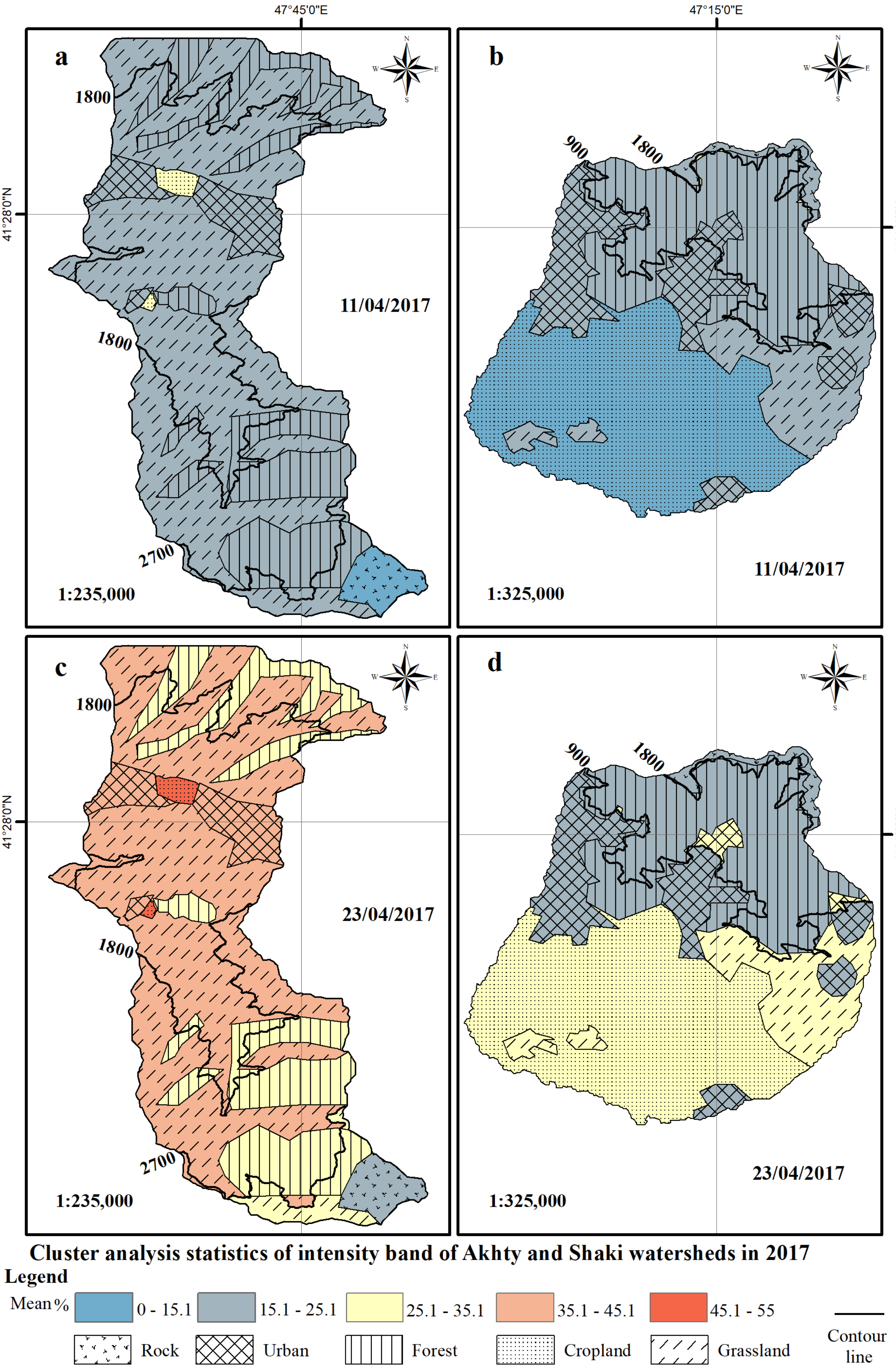


Map 13. *Classification results in 2016 (Copernicus Open Access Hub, 2018).*

The first couple of maps (*Map 14 "a", "b"*) described harmony over the snow cover loss rates within the forest, urban and grassland areas in both, northern and southern watersheds. However, cropland area has lost approximately 30 % snow intensity in Akhty while it showed the lowest snow reduction amount, more or less 10 %, in Shaki counterpart. Furthermore, rock land cover's snow intensity decreased around 20 % in the southern watershed, whereas it demonstrated about 10 % less snow shrinkage in Northern region in comparison.

To have a glimpse to the second pair of the snow cover intensity change maps (*Map 14 "a", "b"*) within different land covers in 2017, almost no correlation can be seen between Akhty and Shaki research areas. Northern watershed illustrated very high quantity of snow cover loss percentages, mainly around 30 and 50 %, whereas southern part did not exceed 35 % intensity loss.

Forest area of the northern watershed demonstrated no more than 35 % snow intensity loss, however, the same figure revealed almost 10 % less intensity loss in the southern one. Only rock land cover type showed the same amount of snow cover intensity decrease, approximately 20 %, within both watersheds. While grassland area confronted about 30 % snow shrinkage in Shaki, the same figure revealed approximately 10 % higher intensity reduction in Akhty counterpart.



Map 14. *Classification results in 2017 (Copernicus Open Access Hub, 2018).*

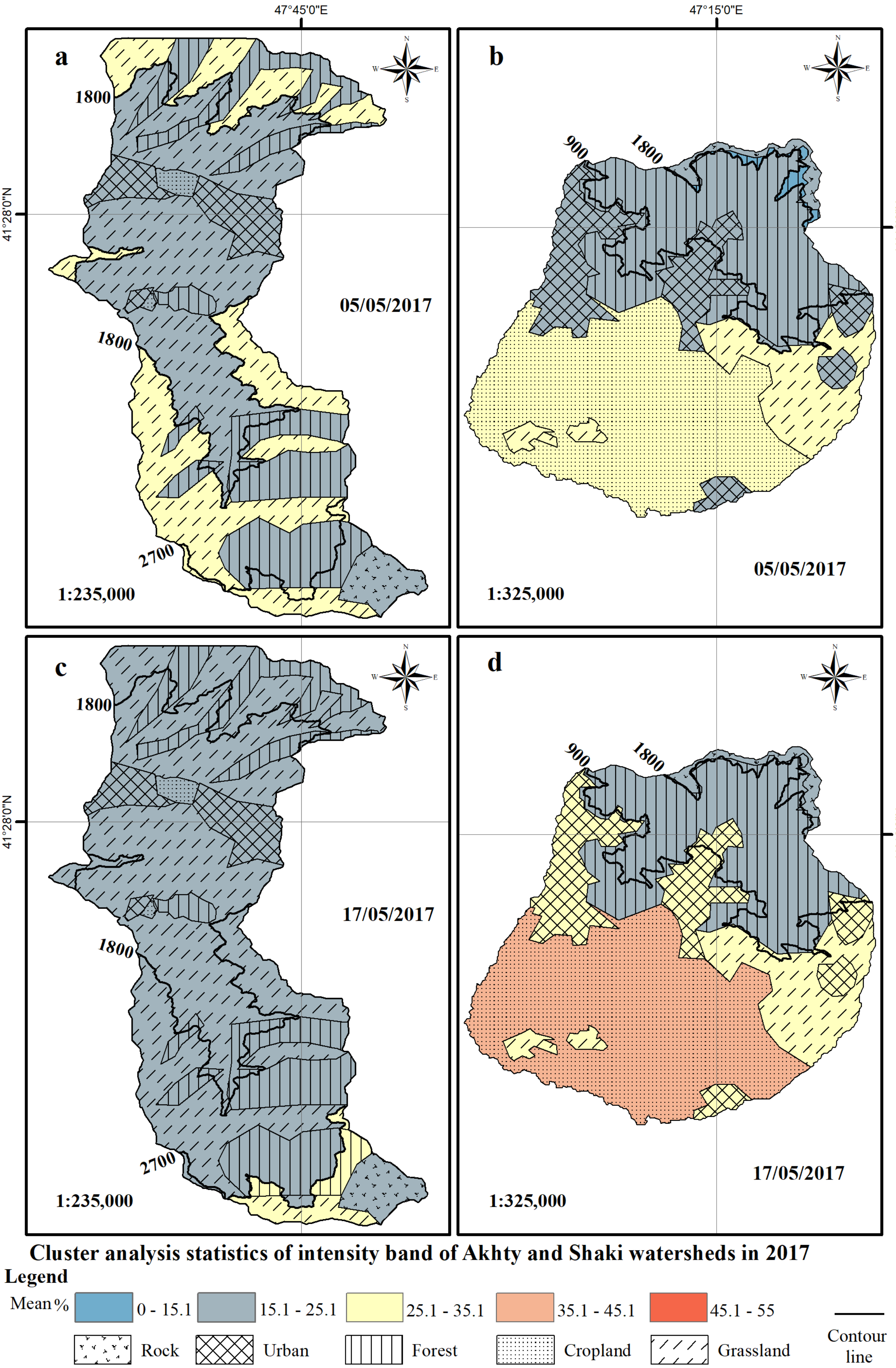
The third couple of maps (*Map 15 "a". "b"*) described more or less comparable images of both watersheds' snowmelt percentages in 2017, spring. Urban, rock and forest land types demonstrated pretty the same quantity of snow intensity decrease inside the northern and southern watersheds.

Within 900 – 1800 m elevation contours, grassland area's snow intensity reduction quantities were more or less 20 % in Akhty, while the same figure revealed approximately 30 % snow intensity loss in Shaki which matches with the higher elevation grassland areas' snow reduction rates. Cropland areas' snowmelt indicators revealed no more than 15 % loss within Akhty watershed, whereas Shaki demonstrated 20 % higher snow cover loss on the same land cover type.

The last pair of the change maps (*Map 15 "c", "d"*) in 2017 illustrated completely different results between the northern and the southern watersheds. While Akhty region's snow cover intensity loss values changed between 15 to 25 %, it matched with rock and forest land covers' snow shrinkage quantities in Shaki counterpart.

The highest snow cover decrease happened within the cropland area of Shaki, up to 45 %, whereas the same area lost maximum 25 % of its snow cover in Akhty counterpart. Urban and grassland areas in Shaki illustrated about 30 % snow cover loss, meantime Akhty confronted almost a half percent less snow intensity loss in comparison.

In comparison with 2nd half of spring season, 2016 series maps (*Map 13*), the same period maps in 2017 (*Map 15*) illustrated less amount of snow cover intensity loss.



Map 15. *Classification results in 2017 (Copernicus Open Access Hub, 2018).*

4.4 Discussion of the Results

Considering average temperature indicators within the spring season, the southern watershed was always warmer than the northern one about 2 ºC for each year. Moreover, the average temperature of the spring season for each watershed was increasing 1 ºC comparing with the earlier year indicator. Hence, besides snowmelt, increasing temperature rates during three years' period impacted on snow accumulation as well (*Map 4 - 9*). From this point of view, complex correlation with the temperature rise and snowmelt percentage changes noticed on result maps.

Table 1. *Average temperature and snow intensity changes in Akhty and Shaki watersheds in three years' period.*

	2015		2016		2017	
	Intensity %	**Temperature ºC**	**Intensity %**	**Temperature ºC**	**Intensity %**	**Temperature ºC**
Akhty	27.11	11.01	25.18	12.4	25.32	13.5
Shaki	27.02	13.8	35.5	14.4	22.8	15.4

Snow intensity reduction map series in 2015 (*Map 10 - 11*) revealed balanced overview between the northern and the southern watersheds. While Shaki watershed has lost a remarkable amount of snow intensity on cropland areas, cropland, rock and a part of forest land types differentiated in Akhty for higher snow intensity reduction in the spring season in 2015.

Noticeable snow cover intensity loss in 2016 (*Map 12 - 13*) could be seen around 50 % in both watersheds, however, Shaki counterpart illustrated relatively high values of snow cover reduction as a result of 2 ºC higher average temperature in the southern watershed. While cropland and grassland areas illustrated the main part of snow intensity loss in Shaki, forest and rock land cover types showed noticeable snow cover decrease similarly to the previous year in Akhty watershed.

Due to global warming, temperature averages reached their highest value around 15 and 13 ºC in southern and northern watersheds respectively in 2017 (*Table 1*). Therefore, significantly lower snow accumulation has been noticed in both, Akhty and Shaki watersheds as it can be seen from pre-classification maps (*Map 4 - 9*). According to the classification result maps in 2017 (*Map 14 - 15*), Shaki watershed snow cover intensity loss increased steadily on lower altitudes until the end of the season, whereas Akhty revealed remarkable intensity change within the middle elevations, 900 – 1800 m.

5. Summary

Under the name of the research, snow cover intensity of two sub-watersheds of the Caucasus Mountains, namely Akhty and Shaki, have been monitored by using remotely sensed data, Sentinel-1 radar images in 2015, 2016 and 2017. The main deficiency of the method was its generalization of intensity unit which is defined as snow reduction by selecting convenient season of image sensing according to the purpose.

Following outcomes have been obtained from the main study:

Snow accumulation was expected to reduce its quality towards 2017 due to higher overall temperature than the previous years caused by global warming, however, qualitative analysis of high snow intensity revealed an increase, while middle one has lost its frequency on both watersheds (*Map 4 – 9)*.

Snow cover changes map series derived by using radar images' intensity band illustrated that land covers above 1800 m elevation demonstrated approximately 25.5 % snow reduction in Akhty watershed, while the same altitude's land types revealed 23.9 % snowmelt in Shaki counterpart during the three years' period. Considering the rivers' origin altitudes within the region, more than 2900 m.a.s.l. (National Encyclopedia of Azerbaijan, 2007), three years' snowmelt average for the northern and the southern watersheds did not contribute to the flash floods. However, the ever-increasing trend of the temperature indicator due to global warming is anticipated to increase water level of the region rivers.

The method has been used in the research, can be completed with the advanced statistics of snowmelt and region rivers' level rise calculations in the means of preventing flash-floods by related institutions.

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7. References

Alessandro Ferretti, A. M.-G. (2007). *InSAR Principles: Guidelines for SAR Interferometry.* Noordwijk: ESA Publications.

Beruchashvili, N. L., Shotadze, M., & Nikolaishvili, D. A. (2002). *Caucasus Environment Outlook (CEO).* Tbilisi: New Media Tbilisi.

Borisov, A., Halstead, C. A., & Ledward, R. (1965). *Climates of the U.S.S.R.* Edinburgh: Oliver & Boyd.

Climate Data Online. (2018). Retrieved from https://www.ncdc.noaa.gov/cdo-web/

Global River Database. (2018). Retrieved from http://gaia.geosci.unc.edu/rivers/

Lydolph, P. (1977). *Climates of the Soviet Union.* Amsterdam - London - New York: Elsevier Publishing Company.

Marsh, P., & Woo, M.-K. (1985). Meltwater Movement in Natural Heterogeneous Snow Covers. *Water Resour.*, 1710–1716.

Məmmədov, Q. (2007). *TORPAQŞÜNASLIQ VƏ TORPAQ COĞRAFİYASININ ƏSASLARI* . Baku: Elm.

Ministry of Ecology and Natural Resources of Azerbaijan Republic. (n.d.). Retrieved from http://eco.gov.az/en/hava/

National Encyclopedia of Azerbaijan. (2007). Mənbə: *National Encyclopedia of Azerbaijan* (ss. 871–872). Baku: "National Encyclopedia of Azerbaijan" Scientific Center.

Pivot, F. C. (2012). C-Band SAR Imagery for Snow-Cover Monitoring at Treeline, Churchill, Manitoba, Canada. *Remote Sensing*, 2133-2155.

Räisänen, J. &., & Dyn, J. C. (2012). 21st Century changes in snow climate in Northern Europe: a high-resolution view from ENSEMBLES regional climate models. *Climate Dynamics*, 2575–2591.

Ranco, P. D., De, M. C., M., M., & P., M. (2016). Comparing COSMO-CLM simulations and MODIS data of snow cover extent and distribution over Italian Alps. *Climate Dynamics*.

Shahgedanova, M., Hagg, W., Hassell, D., Stokes, C. R., & Popovnin, V. (2009). Climate Change, Glacier Retreat, and Water Availability in the Caucasus Region. *NATO Security through Science Series C: Environmental Security*, 1-8.

Solomina, O., Bushueva, I., Dolgova, E., Jomelli, V., Alexandrin, M., Mikhalenko, V., & Matskovsky, V. (2016). Glacier variations in the Northern Caucasus compared to climatic reconstructions over the past millennium. *Global and Planetary Change*, 140, 28-58.

Tampellini, L., Brivio, P. A., Ober, G., & Pepe, M. (2012). Monitoring Snow Cover in Alpine Regions through the Integration of MERIS and AATSR Envisat Satellite Observations.

Tielidze, L. G., & D.Wheate, R. (2018). The Greater Caucasus Glacier Inventory. *The Cryosphere*, 81-94.

USGS. (2018). Retrieved from https://earthexplorer.usgs.gov/

Wang, Y., Huang, X., Liang, H., Sun, Y., Feng, Q., & Liang, T. (2018). Tracking Snow Variations in the Northern Hemisphere Using Multi-Source Remote Sensing Data (2000–2015). *Remote Sensing*, 136, 0-22.

Weather for 243 countries of the world. (2018). Retrieved from https://rp5.ru/Weather_in_the_world

World Weather Online. (n.d.). Retrieved from https://www.worldweatheronline.com/

Гаджиев, В. (1967). *История Дагестана, Volume 1.* Москва: Главная Редакция Восточной Литературы.

(2018). Retrieved from OpenStreetMap: https://www.openstreetmap.org/

(2018). Retrieved from Copernicus Open Access Hub: https://scihub.copernicus.eu/dhus/#/home

DECLARATION

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Budapest, *15 May 2018*

(signature of the student)