Snow Research activities report

Program Title:

Monitoring annual and inter-annual snow cover fluctuation in the summit areas of Kfardebian and their effects on water resources (Monitoring and analysis of Laban Spring discharge)

Presented to:

Organization Name: Saint-Joseph University (Centre Régional de l'Eau et l'Environnement CREEN).

Acronym: USJ CREEN ESIB.

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1 - Introduction

Global climate change induces transformations in rainfall and hydrological regimes in the Mediterranean regions. Lebanon is one of the richest countries in the Middle East for water resources thanks to its mountain ranges that trigger precipitation from the moist air masses coming from the Mediterranean Sea. Snowpack acts as natural water storage in winter and supplies fresh water during spring and summer. Yet, Lebanon is facing a serious water scarcity problem due to: i) the decreasing amount of snow precipitation and climate change; ii) the major growth of the original resident population and the large number of refugees that fled to the country during regional wars. Thus, continuous and systematic monitoring of the Lebanese water resources is becoming crucial.

For the last 21 years, only few studies have been conducted regarding the Lebanese snow cover. They were mainly focusing on estimating snow density and snow cover surface using remote sensing and terrestrial measurements on some zones. In 2020, USJ-CREEN started hydrological modeling. In 2010, Automatic Weather Station (AWS) was installed in the convention of (USJ, Institut de recherche pour le développement (IRD) - Centre d'Etudes Spatial de la Biosphère (CESBIO), and Centre National de la Recherche Scientifique (CNRS). In order to study the annual and interannual fluctuation of snow cover, low cost approaches have been tested in a pilot sinkhole (Jabal El dib, 2300m. a.s.l). The snow season in this pilot sinkhole has been observed i) using total station instrument during 2012, 2013 and 2015; and ii) using terrestrial steady cameras, drones and spatial from 2015 till present. Moreover, a research program under UNICEF impulse in 2017-2018 played an important role to validate some results obtained in the pilot sinkhole with another area that was called Bou Mechleh (ouyoun el siman, 2000m a.s.l.).

The use of the drone has, over the years, been shown to be very effective in assessing residual snow volumes during snow melt periods.

The current project aims to study the links between hydrogeology and the potential for groundwater recharge represented by snow. Water managers could thus predict the date of the low flow of the various sources dependent on the study area. To do this and for the snow team, two aspects are essential:

• Assessment of residual snowfield volumes of the current year in order to be able to assess the water equivalent they represent;

• the inter-annual fluctuations of these volumes in order to be able to discern if trends are emerging.

• understanding the role of terrain in snow retention and meltwater infiltration processes. Indeed, the summit areas of Lebanon present a very particular relief interesting from several points of view for a study of the snow cover.

2- The study area:

The study area occupies a large part of the summit areas of the heights of Ouyoun el Simane - Kfardebianne (Figure1). Level plateaus unfold in a Cenomanian karst formation (C4) and present over very large surfaces a multitude of sinkholes and undulations (closed depressions with a circular tendency for the former and elongated for the latter) (Figure 2). Their altitudes allow them to be covered by snow for up to 6 months a year, sometimes longer. However, in Lebanon, snow is an important component of groundwater recharge. It is therefore important to take an interest in the characteristics of the terrain in order to assess their role in the persistence of snowfields until the first months of summer; also to possibly evaluate the volumes of snow found there during the spring melt season knowing that the volume of snow is an essential parameter for evaluating the quantities of water that infiltrate throughout this time of the year.

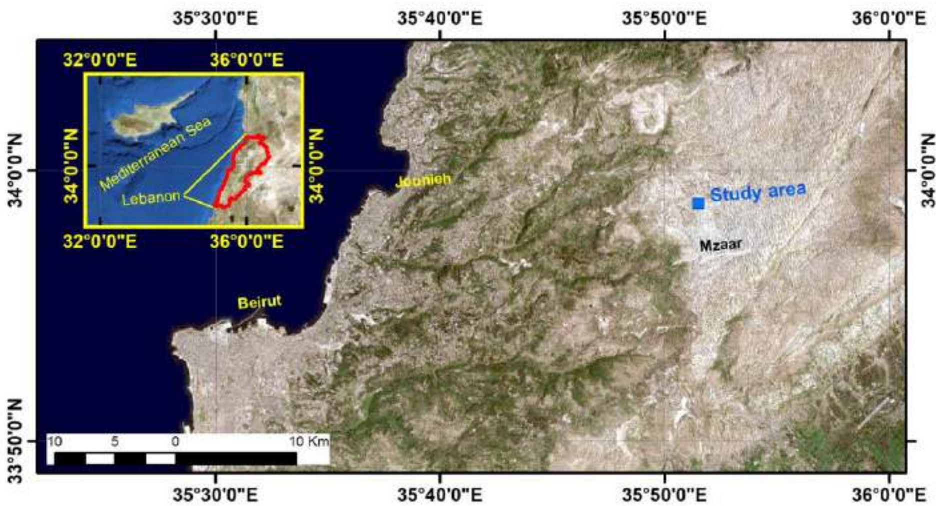


Figure 1: Localization map

Figure 2: Wavy land on the highest summits

This wavy land constitutes a water tank by retaining a lot of snow in the depressions and preserving accumulations from sun and winds.

There are different plateaus levels. Also, the period of peak water return from sources can extend over a period of three months due to the staging of the supply basins of the various sources dependent on the plateaus.

Digital altitude models established either by aerial overflights or by high-resolution stereoscopic satellite imagery shows these different levels but also large groups of sinkholes. Most of these are circular. Some have a flat bottom; others are more like sinkholes having a bottom similar to an inverted cone.

These depressions act as containers during the accumulation period. In addition, most of them are oriented perpendicular to the prevailing south-westerly wind (ie NW-SE) and therefore the snow accumulated on their crests is blown away by the wind and contributes to the filling of depressions. During the melting season, the neves of the sinkholes are protected from too rapid erosion either by melting or by wind erosion or sublimation. They are also partially protected from incident radiation by these hollow reliefs. Another advantage of these depressions is that they trap snow whose meltwater can only infiltrate (or be sublimated) because it cannot run off. Therefore they represent an enormous wealth because they promote the recharge of groundwater by acting as a veritable strainer.

This observation has been accomplished on three different scale areas: i) spatial observation; ii) aerial observation; and iii) pilot sinkhole (Figure 3)

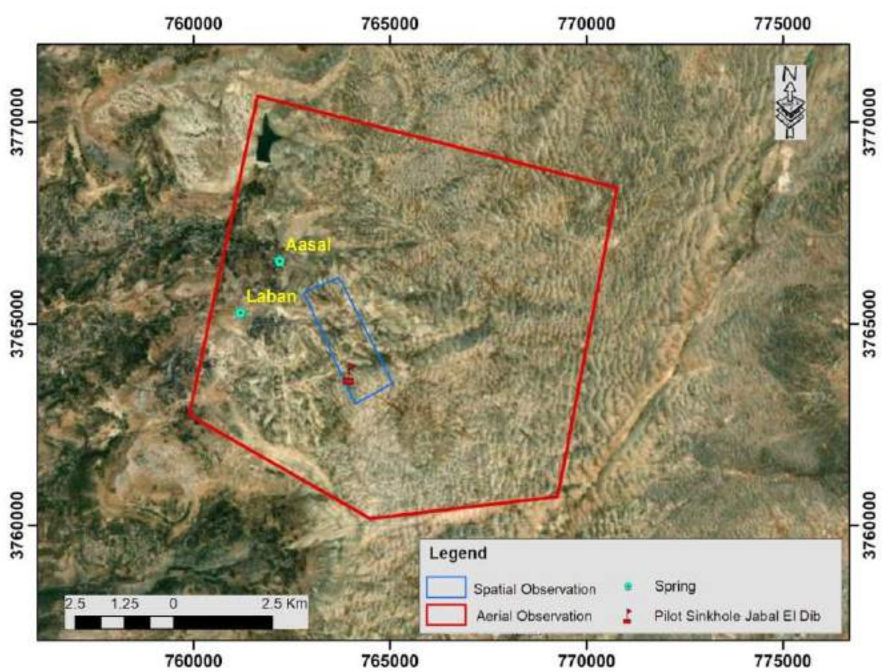


Figure 3: The zones of observations during the 2020 snow season

3- Objectives

The following tasks will be fundamental to provide the needed data-in regard to the snow cover:

- Geomorphological characterization: This characterization allows a good understanding of the geomorphology by classifying the terrain according to slope, aspect, altitude, roughness, basin, and sinkholes;

- evaluate snow volume in the pilot sinkhole of Jabal el dib. Why a pilot site? Because accurate continuous and sustainable snow cover observation is impossible on a very large territory, then a pilot sinkhole has been selected to conduct the precise snow measurement where an automatic weather station (AWS) is installed. The pilot sinkhole, situated on Ouyoun El Siman (Jabal El Dib), has been observed since 2012 using very accurate topographic instruments. It provides a highly important indicator for the internal-annual monitoring from 2012 until the present. Although Jabal el dib's pilot sinkhole only represents a very small area of 10000 sqm, it represents the plateau where it is located because the snow melts almost at the same time in all parts of the whole plateau that has approximately the same altitude. In addition, the snowmelt behavior observed in Jabal el Dib, has been validated in other areas. Thus, this sinkhole allows empirical prediction of the date of total snowmelt for this zone. These observations will be accomplished using Drone, total station, and GPS.

- evaluate snow area (surface) for larger territory: The snow volume that we talked about in the previous paragraph is only for a pilot sinkhole. It allows the SWE (snow water equivalent) calculation for the pilot sinkhole only. Obtaining the snow volume monitoring for a large territory requires a continuous series of 3D spatial data that will be too expensive and not always available. In regard, the Planet website provides a series of free 2D satellite images. Combining the 3D volume obtained by drone and 2D area obtained by satellite image may lead to estimate approximately the volume on a larger territory that will be important to estimate the SWE and link the snow measurement with the hydrological flow and spring discharge of the springs dependent on the highlands. Moreover, comparing the snowmelt trend of the pilot sinkhole and the larger territory could lead to snowmelt prediction in different areas.

4- Data Catalogue

4.1 Digital Elevation Model (DEM): Digital Elevation Model, this term is much known in geographic studies. In this project, DEM plays an important role in geomorphological characterization and snow volume. We distinguish three types of DEM that we will use in this study:

a) DEM provided by Directorate of Geographical Affaires (DGA):

In 2008, the Directorate of Geographical Affairs of the Lebanese army produced a national DEM through a Polish company specialized in aerial photogrammetry. They captured aerial stereoscopic images for Lebanese territory. This allows the obtaining of a DEM with 1.5m as spatial resolution. The DEM is the most used DEM in Lebanon for geographic studies since it is produced and approved officially by the Lebanese army. However, despite its accuracy, the aerial images were captured in a period where the high mountain summits were partially covered by snow (Figure 4).

For this reason, the obtained model will be called a digital surface model (DSM) because it not only represents the natural terrain or free snow area.

Figure 4: The obtained orthophoto shows the snowpack during the captured images that were used to construct the DSM

Consequently, the DSM can be useful for geomorphological characterization by determining the basins and the sinkholes. However, we cannot use it to identify the lowest altitude point for each doline or calculate snow volumes. But the DGA's DSM (Digital Surface Model) is important to validate the DEM obtained by Pleiades stereo images.

b) Digital Elevation Model obtained by Pleiades satellite:

Pleiades is a French constellation of very high-resolution satellites. It acquires both panchromatic as well as multispectral imagery in the Visible Near Infrared (VNIR) range. The added benefit of Pleiades is that it provides tri stereo-pair imagery at 0.5m spatial resolution, unlike its other contemporary systems like Quickbird and IKONOS. Tri stereo-pair is used for Digital Elevation Model (DEM) and Digital Surface Model (DSM) extraction because of its backward and forward look angles. We acquired images from this satellite thanks to the collaboration with IRD-CESBIO who communicated with CNES to get this product. The stereoscopic images allow obtaining the DEM for the bare land with a spatial resolution of 2 m. We consider the DEM obtained from Pleiades as a Base map for the elevation to characterize the Geomorphology of the study area (DAG zone).

c) **DEM obtained by Drone:**

The DEM obtained by drone is done by our team using a combination of data from Drone RTK, Total Station, and GPS. The concept is to create a flight mission that allows having a series of captured images with high side lap and overlap. This series of captured images allows obtaining orthophotos, accurate and precise DEM. The DEM could arrive at 10 cm or less as spatial resolution and be considered as bare land terrain to calculate the snow volume for each observed date.

The data drone will be as follow:

- Pilot sinkhole (study area):
- Aerial observation (study area):
- Data collection
- Data processing
- Snow Volume estimation or calculation

4.2 **Planet website:**

Planet is a website that has a big collection of satellite images that came from different satellites and sensors. The big advantage of this website is to provide high spatial and temporal resolution at the same time. In other words, we can have almost daily satellite images with a spatial resolution of 3 m that is great for snow cover application.

This website offers a very interesting temporal resolution for monitoring the Snow Cover Area (SCA). The advantage that we could get free is a 10 sqkm per month download due to the academic account.

This product will be important to:

- Calculate the annual and inter-annual snow surface fluctuations on a large territory;
- Compare to the snowmelt trend of the pilot sinkhole with the larger territory;

The data planet work by our team will be as follow:

- Data download;
- Preparing the mosaics to be processed;
- Data Processing;
- Snow Surface calculation.

4.3 Historical data:

The accurate snow cover monitoring for the pilot sinkhole started in 2012. This observation was accomplished using total station, GPS, drone, and steady cameras.

5- Data Processing and results

5.1 Geomorphological characterization:

The work executed for this part of the research was carried out using image processing software (PCI GEOMATICA) and GIS software (ArcGIS) (Figure 5).

High summits of Lebanon areas have few differences in their karstic characteristics:

- In Cedars, for example, snowmelt waters infiltrate through avens aligned along thalwegs (figure. 5)

Figure 5: Cedars region: Thalwegs punctuated by sinkholes

- In Jabal Jraid dolines are aligned and managed by a fracturation network (Figure 6)

Figure 6: Dolines aligned on the fracturation network

- In kfardebiane areas (figure 2) it can be observed undulations and trains of sinkholes trapped between 2 ridges with an asymmetry of the slopes: steeper on the North faces.

The general slope of the land is not obvious.

No tabular rock in place as shown in the following diagram which would allow us to understand the reason for the undulations and sinkholes (Figure 7)

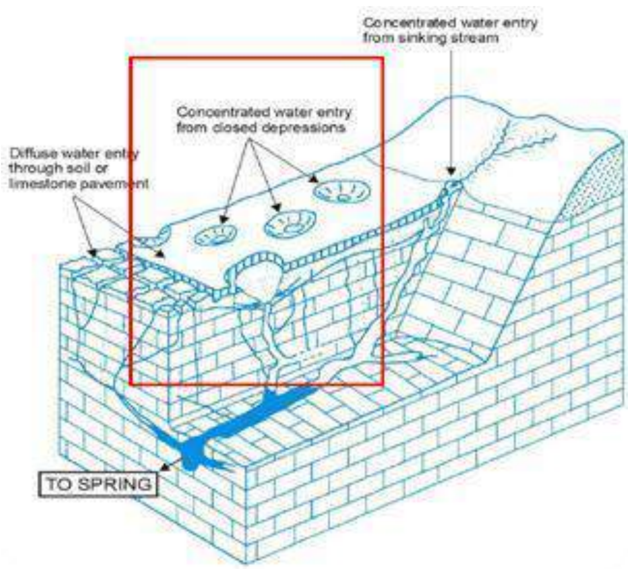


Figure 7: sinkholes formation

On Ouyoun al Simane terrain is riddled by sinkholes. The strainer effect of the area (figure 8) is highlighted by the calculation of the portion of the sky seen by each of the pixels

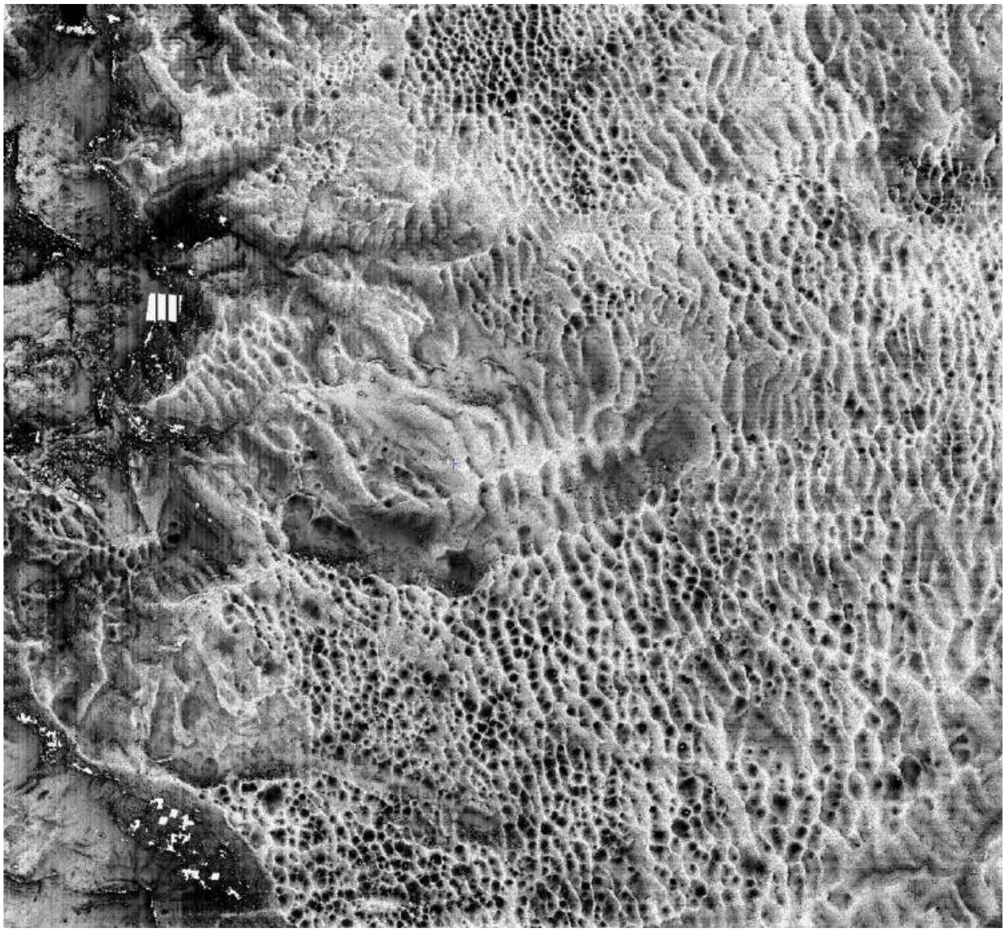


Figure 8: Colander effect of the ground (Skyview)

In fact, to understand the characteristics of the terrain, we set out to map the sinkholes and identify their lowest point(s) as an indicator of the infiltration zone. Only, in that case, the mapping was carried out using the DEM Pleiades set at 10 m resolution to minimize shapes artefacts (Figure 9).

The process involves

• a raster layer flow direction extracted from the DEM Pleiades that have 10 m of spatial resolution (Figure 10),
• a layer of polygons surrounding each sinkhole and delineating each basin[1] (Figure 11),

[1] The drainage basins are delineated within the analysis window by identifying ridge lines between basins. The input flow direction raster is analyzed to find all sets of connected cells that belong to the same drainage basin.

• a layer of points (sinks)[2], with their altitude, indicators of the most infiltrating part of each sinkhole (Figure 12).

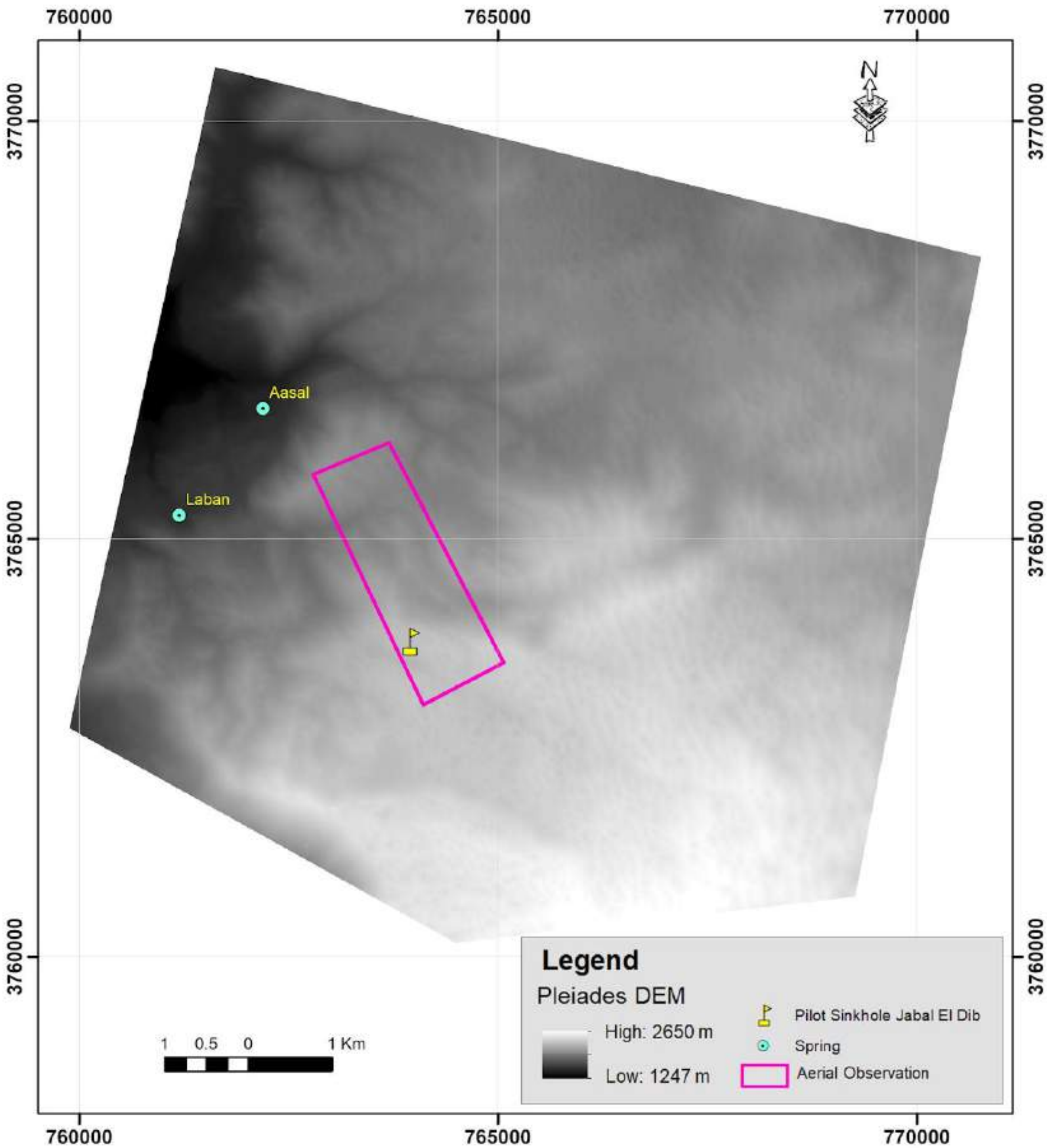


Figure 9: Digital Elevation model extracted from Pleiades stereo images

[2] A sink is a cell or set of spatially connected cells whose flow direction cannot be assigned one of the eight valid values in a flow direction raster. This can occur when all neighboring cells are higher than the processing cell or when two cells flow into each other, creating a two-cell loop.The output of the Sink tool is an integer raster with each sink being assigned a unique value. Sinks are numbered between one and the number of sinks. A sink is a cell or set of spatially connected cells whose flow direction cannot be assigned one of the eight valid values in a flow direction raster. This can occur when all neighboring cells are higher than the processing cell or when two cells flow into each other, creating a two-cell loop.The output of the Sink tool is an integer raster with each sink being assigned a unique value. Sinks are numbered between one and the number of sinks.

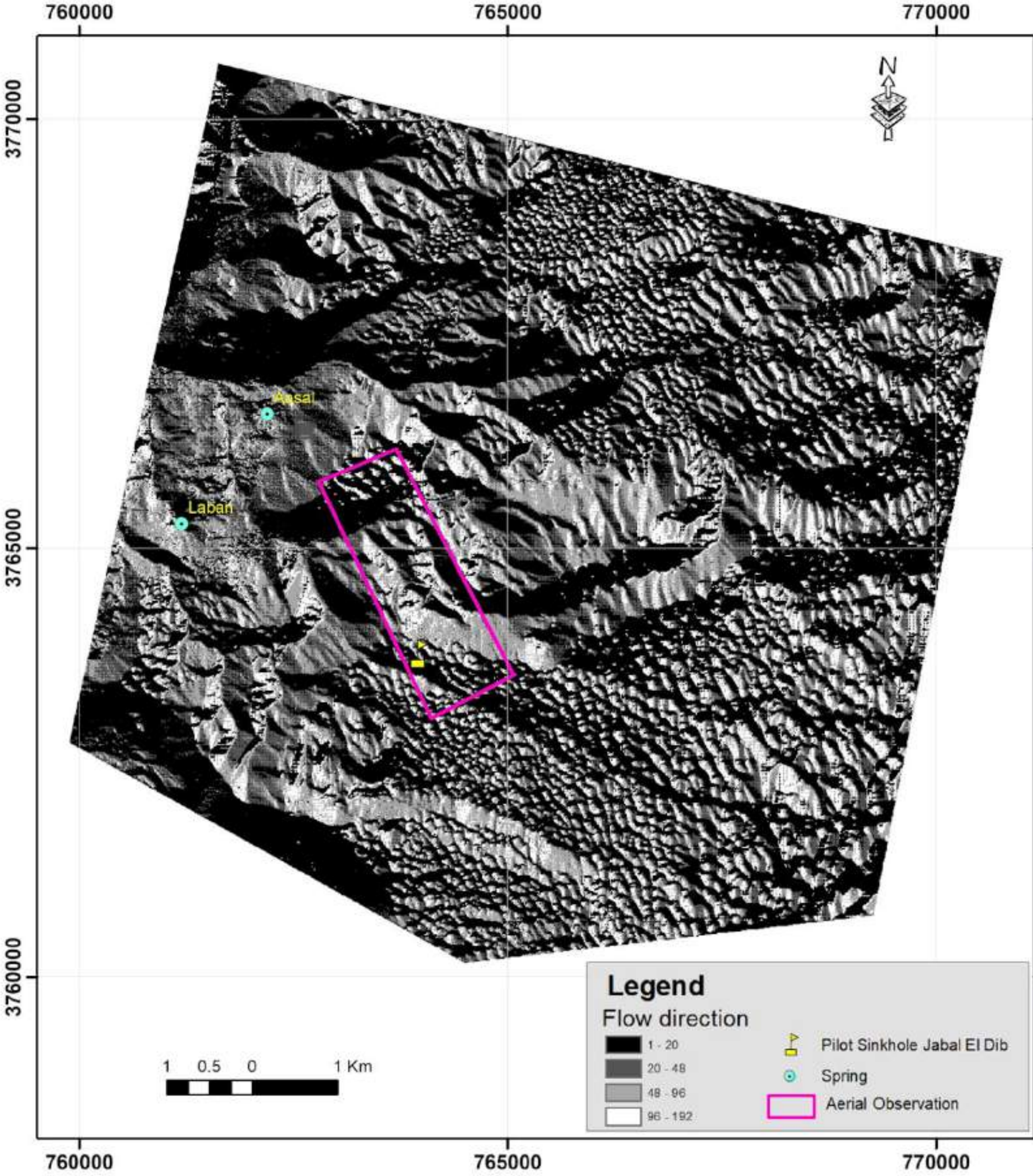


Figure 10: Flow direction

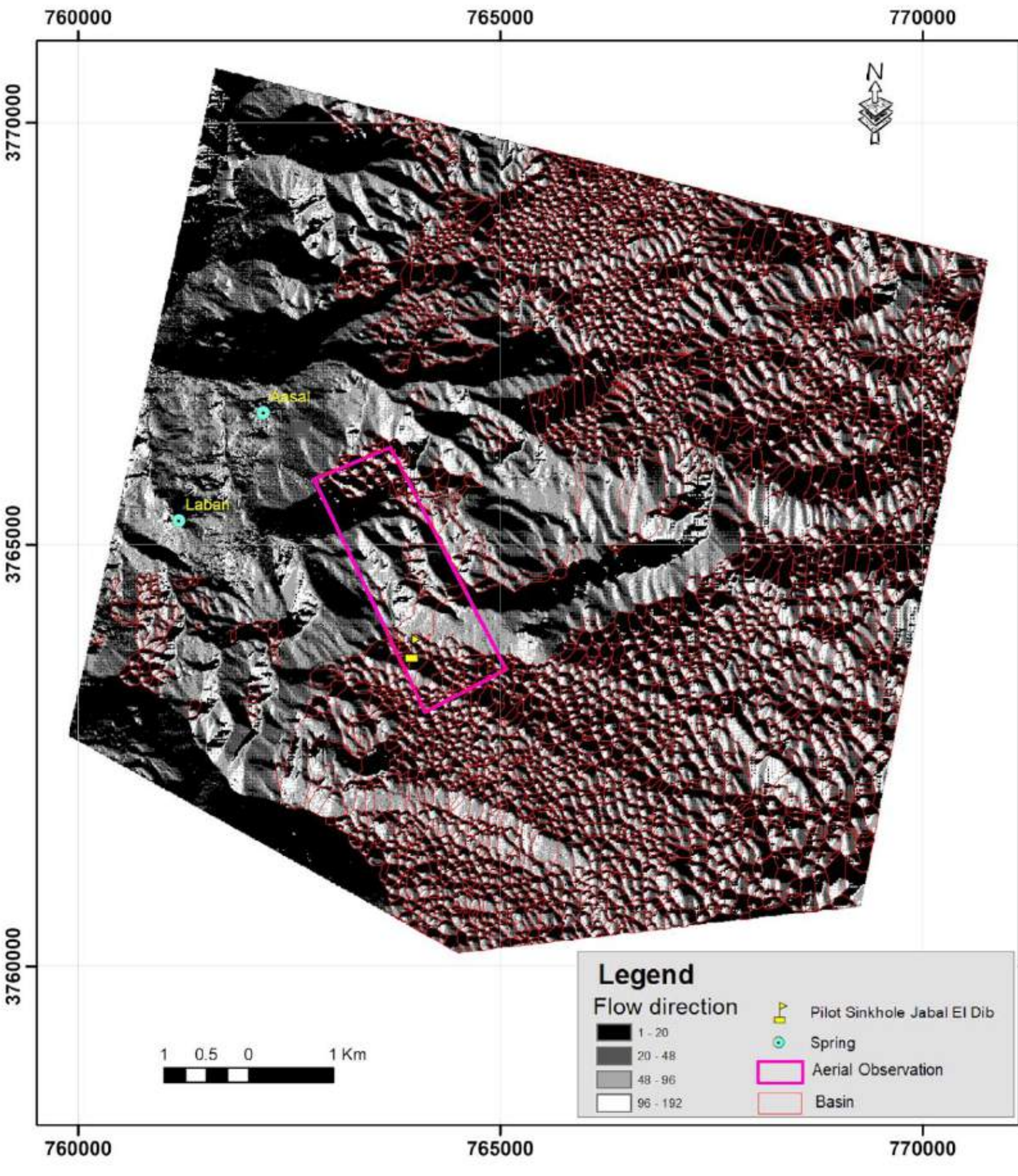


Figure 11: Flow direction and sinkholes perimeter

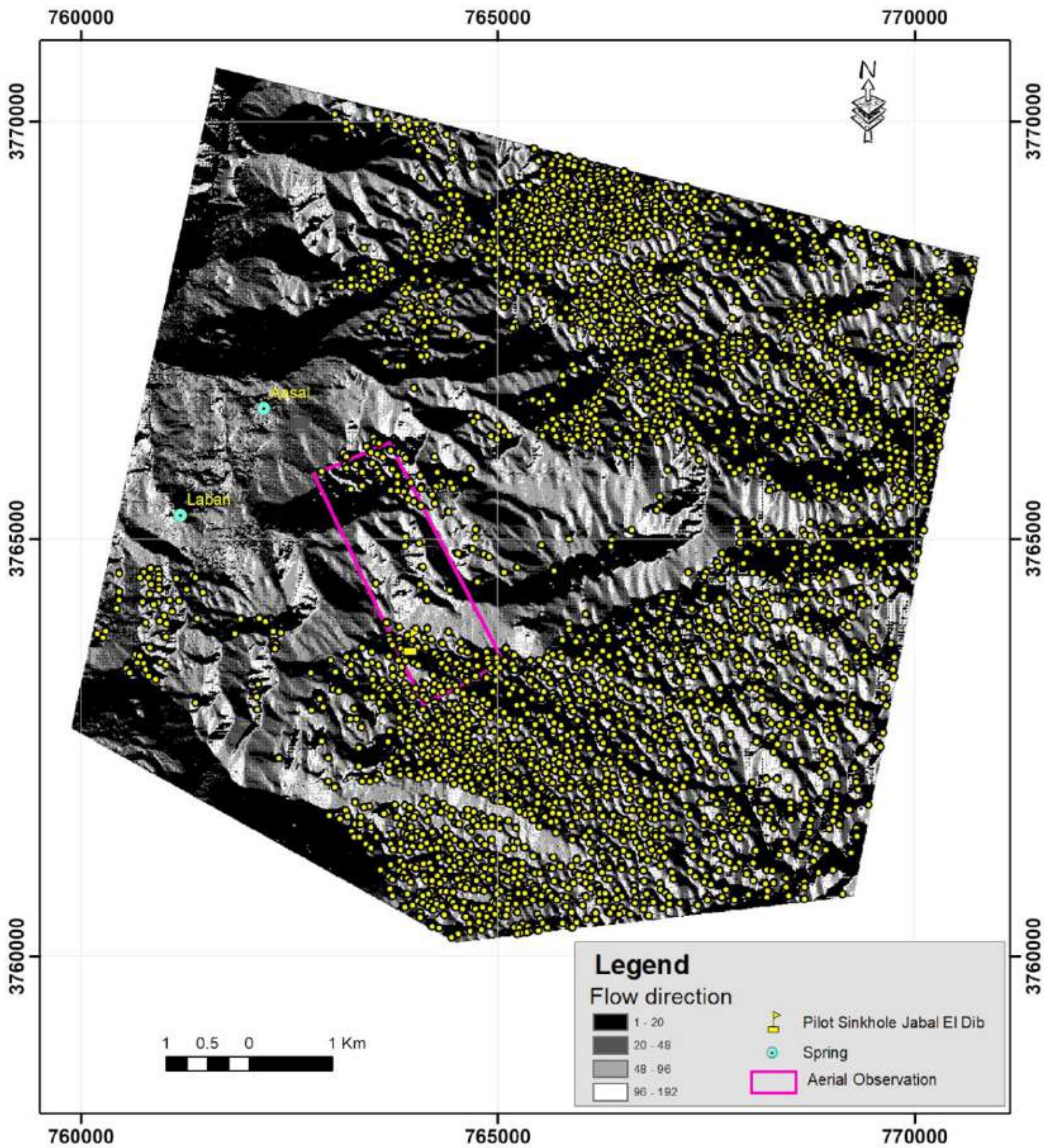


Figure 12: Flow direction and sinks

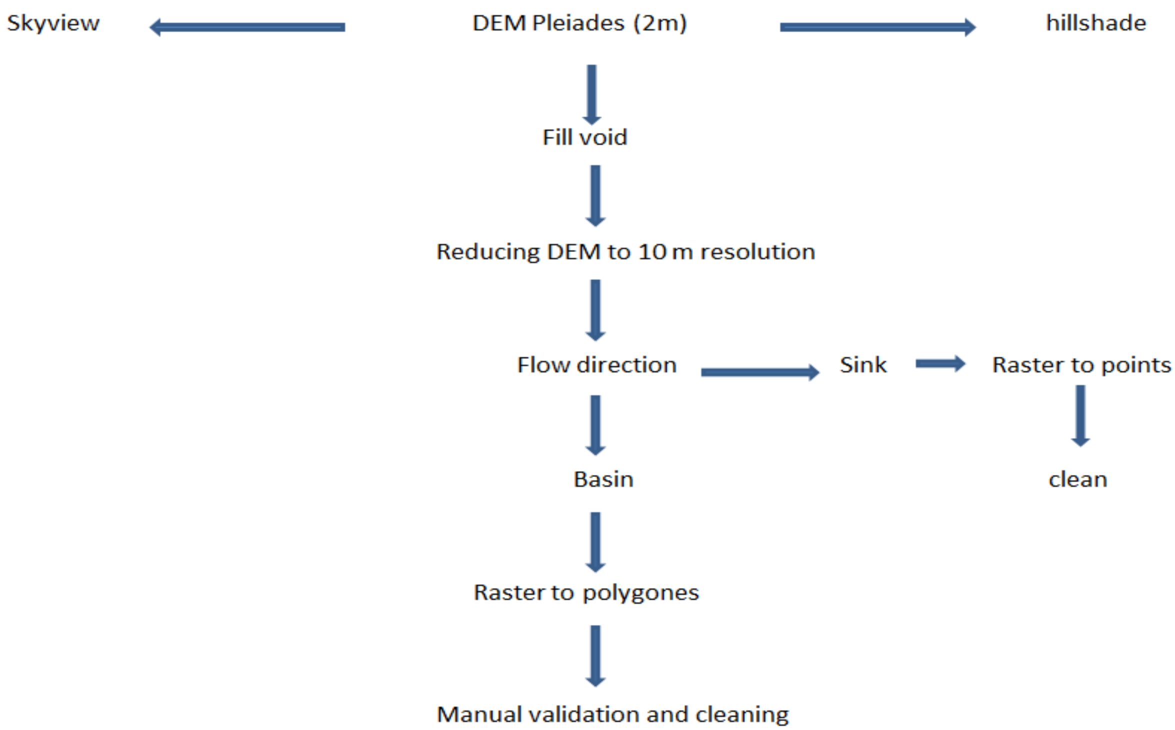
• To ensure the correct positioning of the points, two images enhancing the relief were realized:

- a) "Skyview" (PCI Geomatica), is produced from the percentage of sky seen by each pixel;

- b) the other: “hillshade” is a shaded relief (ArcGIS).

The procedure can be resumed in the following flowchart (1).

(Flowchart 1) Procedure for delimiting the sinkholes and the infiltration zone



Flow chart (1) of geomorphological characterization

Fill void: corrects the numerical errors of the model by re-interpolation.

If supernumerary polygons occur there will be easy to clean by starting the basin routine again after decimating the DEM to 10m resolution to smooth terrain artefacts.

Same procedure if there are too many points (sink) outside the sinkholes.

Visualizing the DEM in Hillshade helps to verify the correct positioning of the lowest points of the sinkholes, these being considered as infiltrating points (Figure 12).

To a better view of the doline alignment, the skyview image can be threshold to enhance ridges values and color them with a graphic plan (Figure 13).

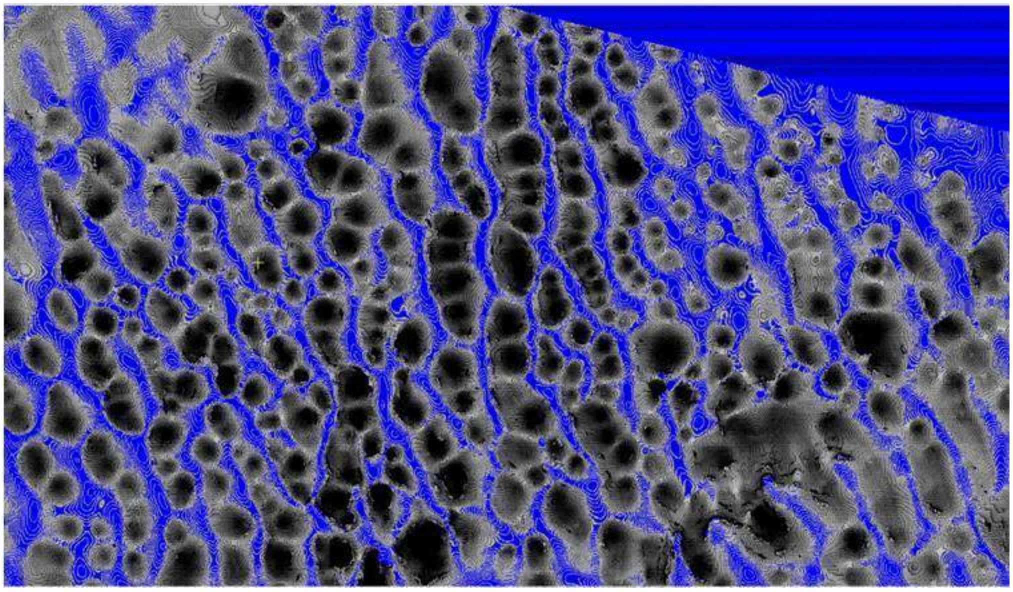


Figure 13: Extracted from a threshold of the skyview image to highlight the major ridges of the relief. The sinkholes seem aligned in the direction of the ridges, trapped by them

If we try to connect the dolines which seems aligned what would indicate the network (Figure 14)

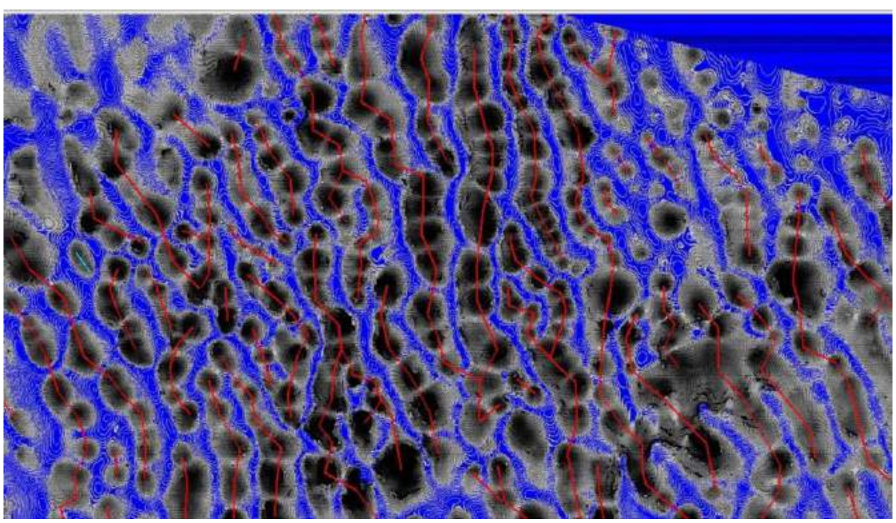


Figure 14: dolines network

The alignment of the sinkholes seems to be in the general direction of the flow rather than an arrangement of faults or fractures (Figure 15).

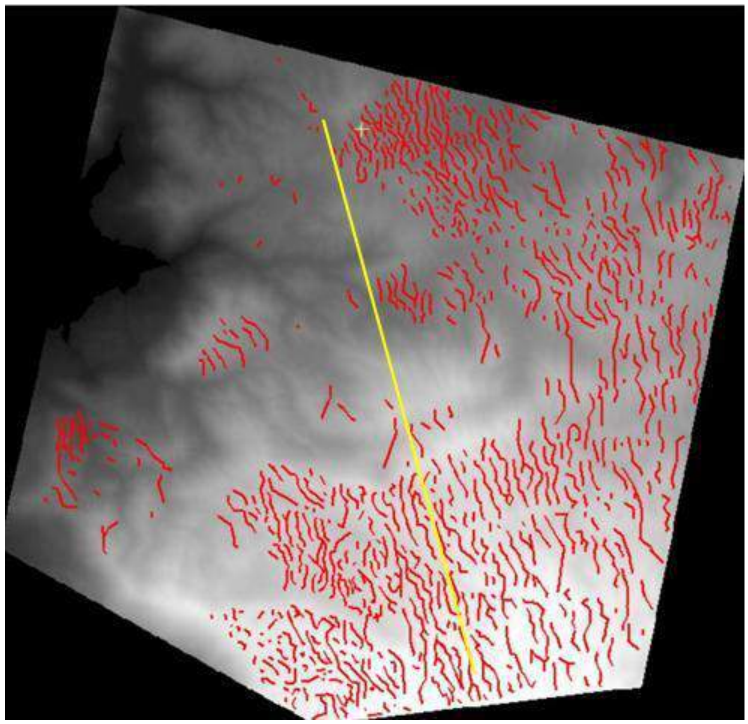


Figure 15: Major orientation of vectors: SSE-NNO.

The alignment of the sinkholes seems to be in the general sense of the flow rather than an arrangement of faults or fractures.

We can then extract the slope profile (Figure 16).

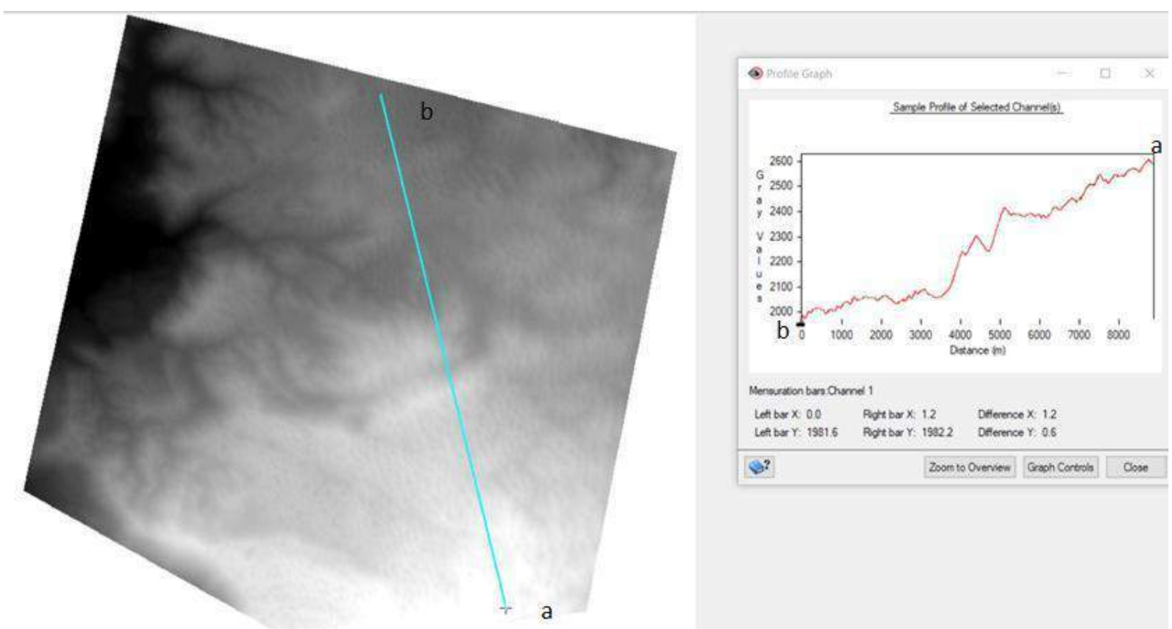


Figure 16: The a – b segment gives the general slope of the field (NNW-SSE)

5.2 Snow surfaces decreasing

This part of the project aims to calculate the surface percentage of occupancy by snow at different times.

The interest of this calculation is that we can, in a possible subsequent research extract information about:

- Snowmelt steps and speed;
- Try to find a correlation between this information with the results concerning the volumes of snow patches;
- observe the inter-annual fluctuations in snow cover and extract trends in climatic changes;

This part of the work requires the following steps:

<u>Data processing of Planet images:</u>

- Download images corresponding to sampling dates on the field by the team;

- Mosaicking images data which covers our working zones: Zone DAG (Figure 3); Zone Drone (Figure 3 and Figure 6);

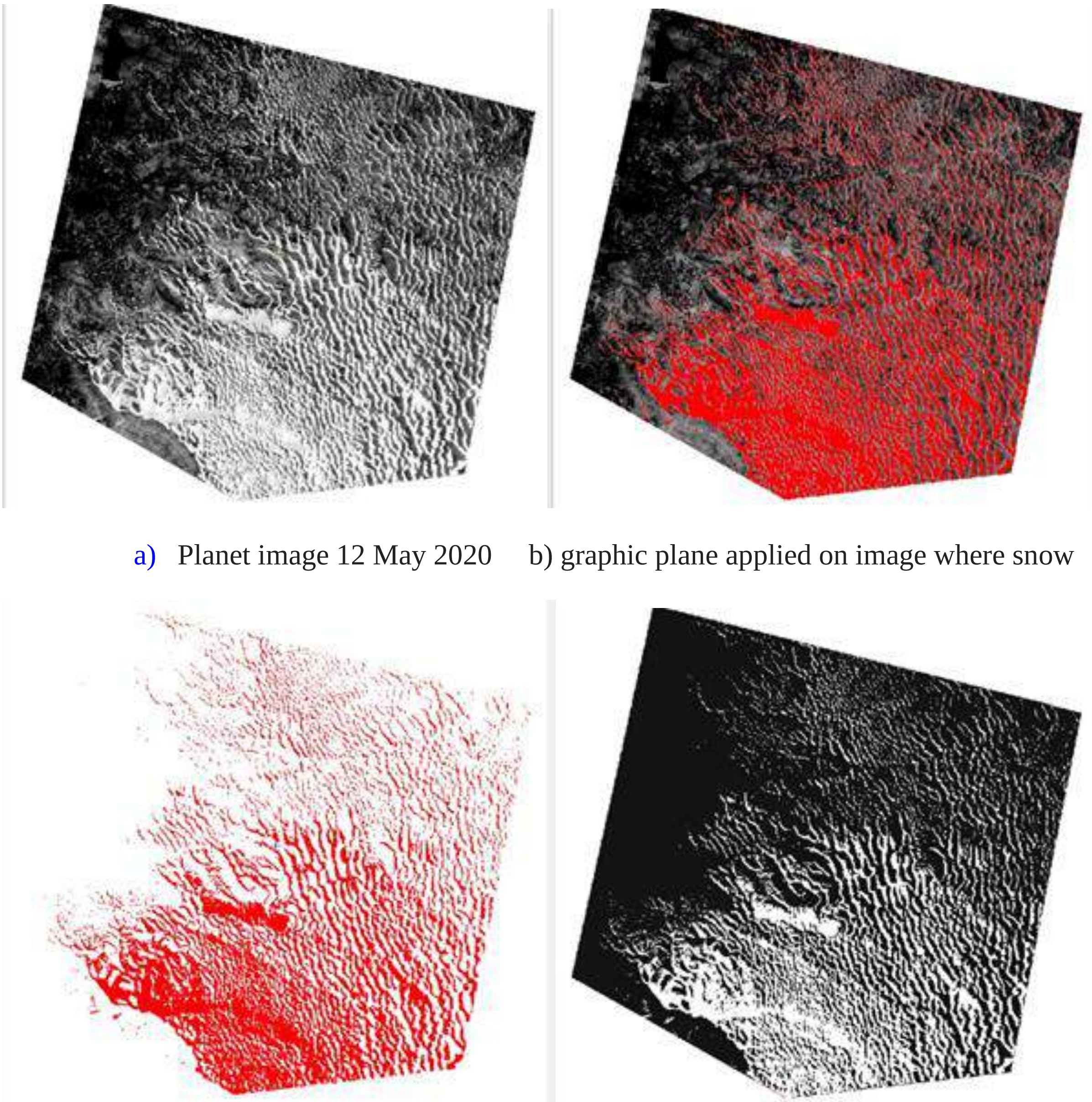
- Creating a graphic cover of the snowfields for each studied image (Figure 17, b) c)). The way through from the image to the graphic plane is done by thresholding the radiometric values of the image. It is quite easy because the snow has a high radiometric value;

- Nevertheless, it is necessary to clean the graphic plane because sometimes the snow radiometry merges with the radiometry of the surrounding limestone terrain;

- Translate the graphic plane into a binary image plane (snow; no snow), (Figure 17, d);

- Automatic creation of this last image attribute table and obtaining the percentage of occupancy of the area by snow; analysis of those data with excel table and graphs (table 1; Figure 18)

- Correlate them with snow volume data to extract trends.



a) Planet image 12 May 2020 b) graphic plane applied on image where snow

c) Graphic plane of the snowfields d) binary image of the snowfields

Figure 17: Processing steps to extract snow field's image

Preliminary results and discussion

Concerning the geomorphological characterization:

On a total area of 83 km2 (Q2) there are 3,036 dolines that occupy 60% of the total surface (Figure 8). The minimum surface of these sinkholes is 860 m2, maximum 488,977 m2. The sum of the surfaces is 49,953,719 m2, or about fifty km^2.

We can consider that this zone has essentially two types of areas:

- One that can be named as: infiltrating zone, which is the dolines area;
- One that could be named as runoff or flowing area (zone ruisselante) because its slopes drive water downslope with less infiltration than the infiltrating zones.

The map with sink points may show only one point in a doline or more. One point could indicate an aven shape and two or more points may indicate a doline with a quasi flat bottom.

Those data (dolines polygons and sink points) may allow extracting dolines density maps. The polygons should help to evaluate if needed, the dolines area capacity of snow retention.

Results for surface occupancy by snow (Table 1; Figure 18)

Dates	% occupation(Z DAG)	% occupation(Z drone)
12-mai	25,52	36,38
21-mai	15,45	16,43
01-juin	11,25	9,56
15-juin	6,6	3,86
27-juin	2,66	1,07
05-juil	1,15	0,29

Table 1. 2020: Percentage of occupation by snow

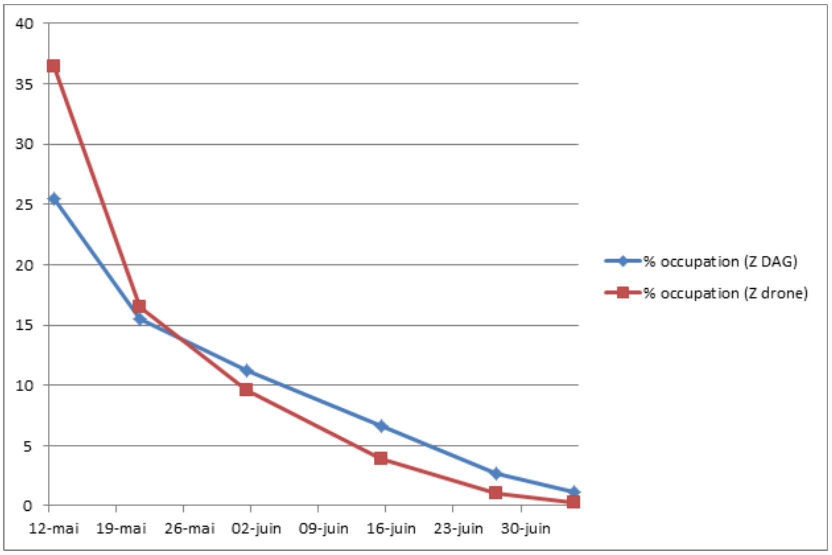
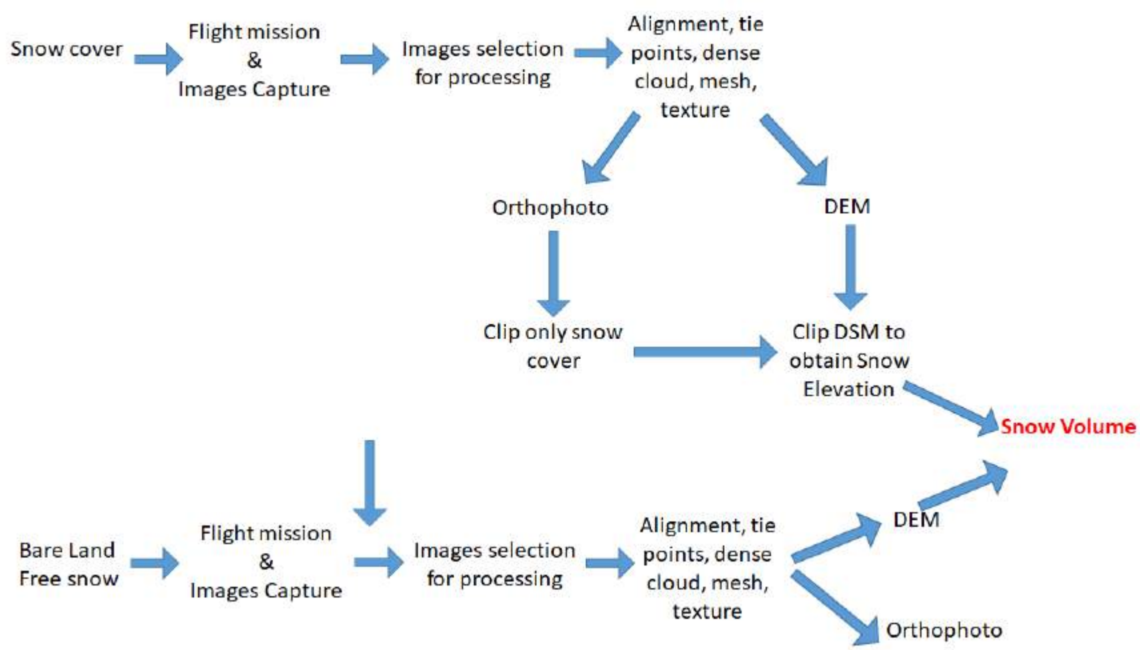


Figure 18. 2020: decreasing percentage of occupation by snow

5.3 Processing for snow volume calculation

a) Processing for volumes in the pilot sinkhole of Jabal Al Dib

The below flowchart (2) shows the general workflow of the snow cover volume estimation for the pilot sinkhole.



Flowchart (2) of the snow cover volume calculation using drone, Pix4D, and ArcMap

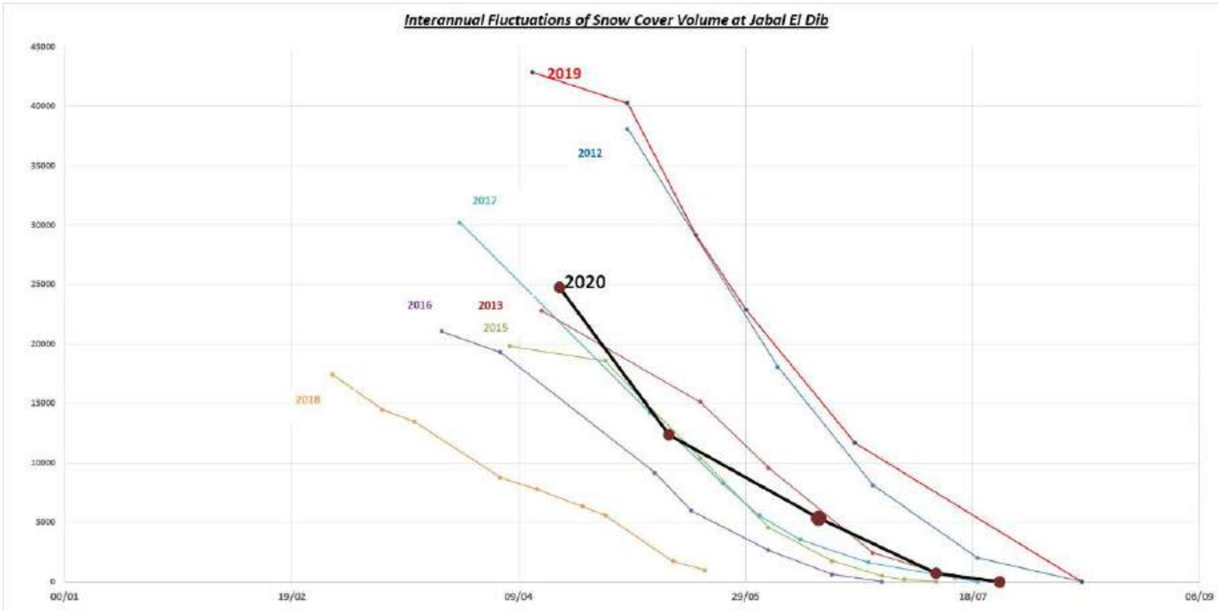


Figure 19: Interannual fluctuations for the pilot sinkhole

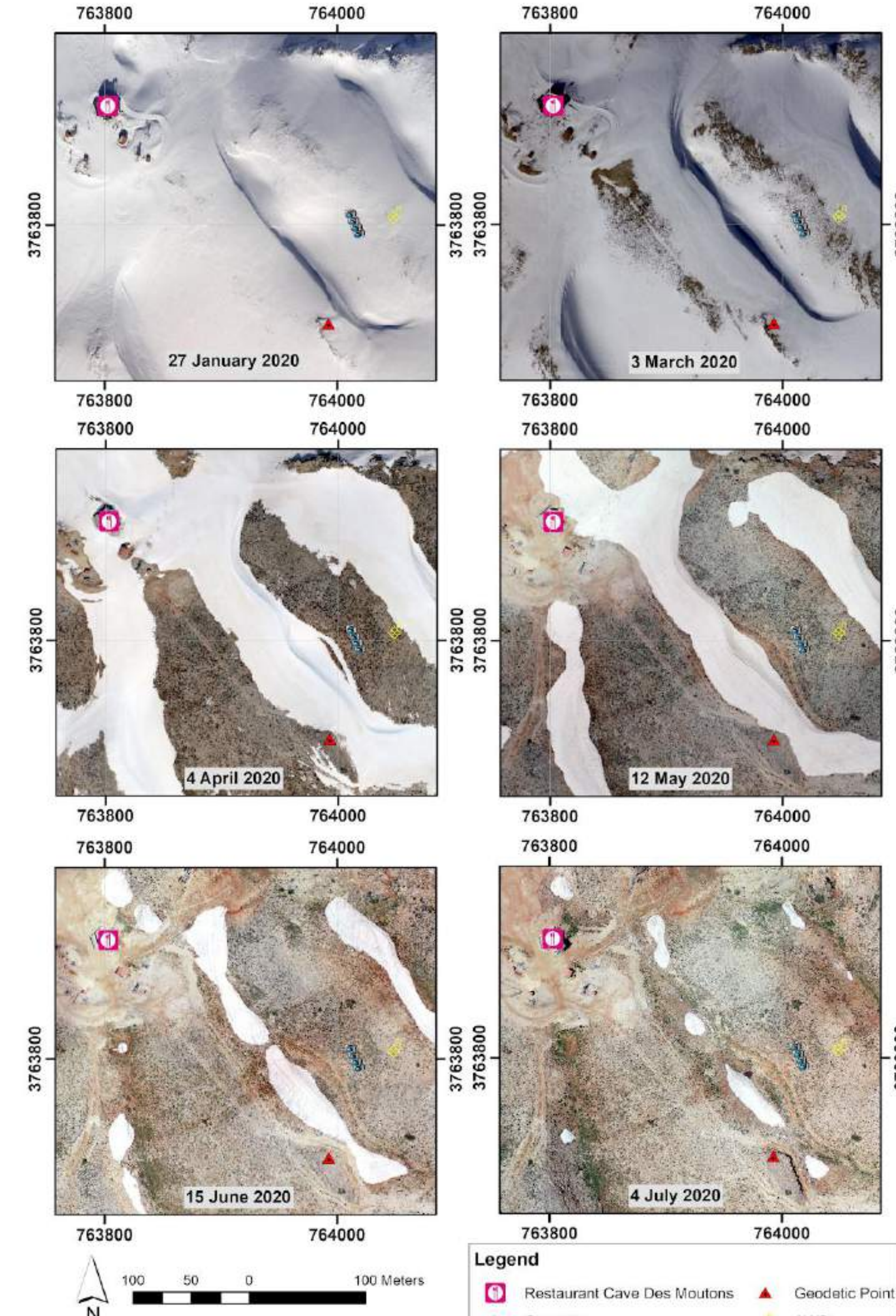


Figure 20: Snow cover monitoring for the pilot sinkhole during 2020 snow season

b) Processing for volumes in for Mzaar area (zone drone):

Figure 21: Snow cover monitoring for the study area using UAV on 27 January 2020

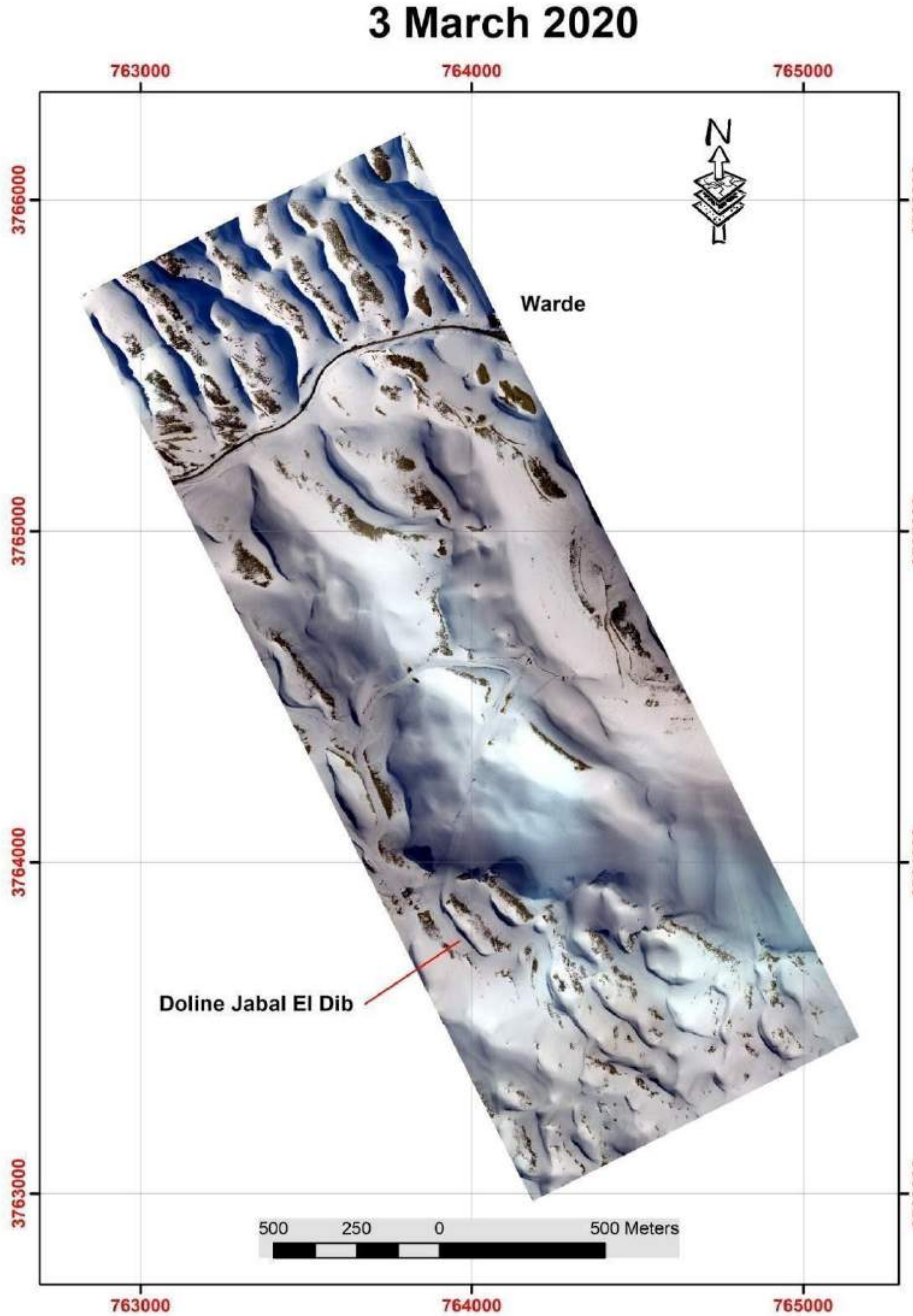


Figure 22: Snow cover monitoring for the study area using UAV on 3 March 2020

Figure 23: Snow cover monitoring for the study area using UAV on 11 March 2020

Figure 24: Snow cover monitoring for the study area using UAV on 4 April 2020

Figure 25: Snow cover monitoring for the study area using UAV on 18 April 2020

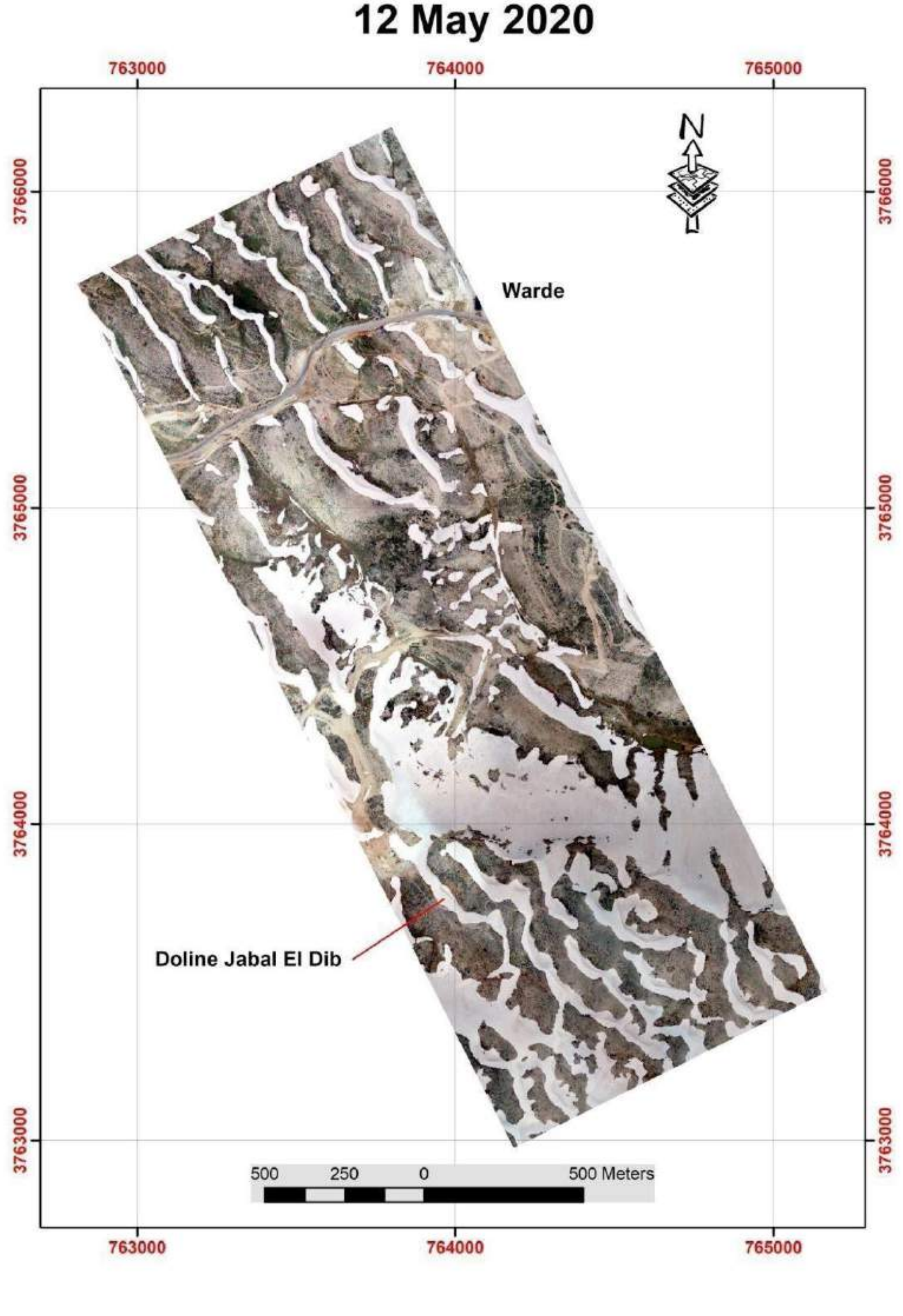


Figure 26: Snow cover monitoring for the study area using UAV on 12 May 2020

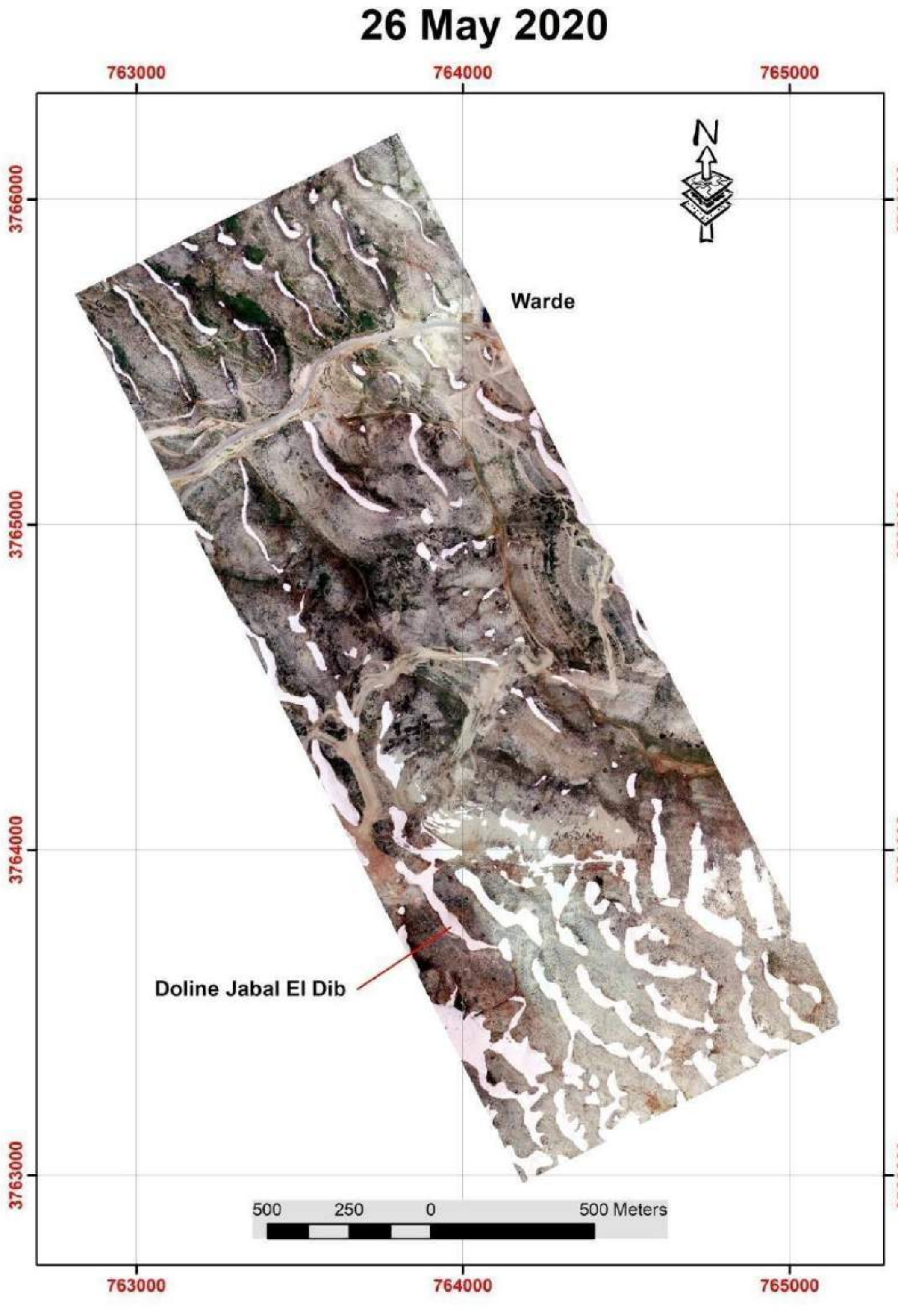


Figure 27: Snow cover monitoring for the study area using UAV on 26 May 2020

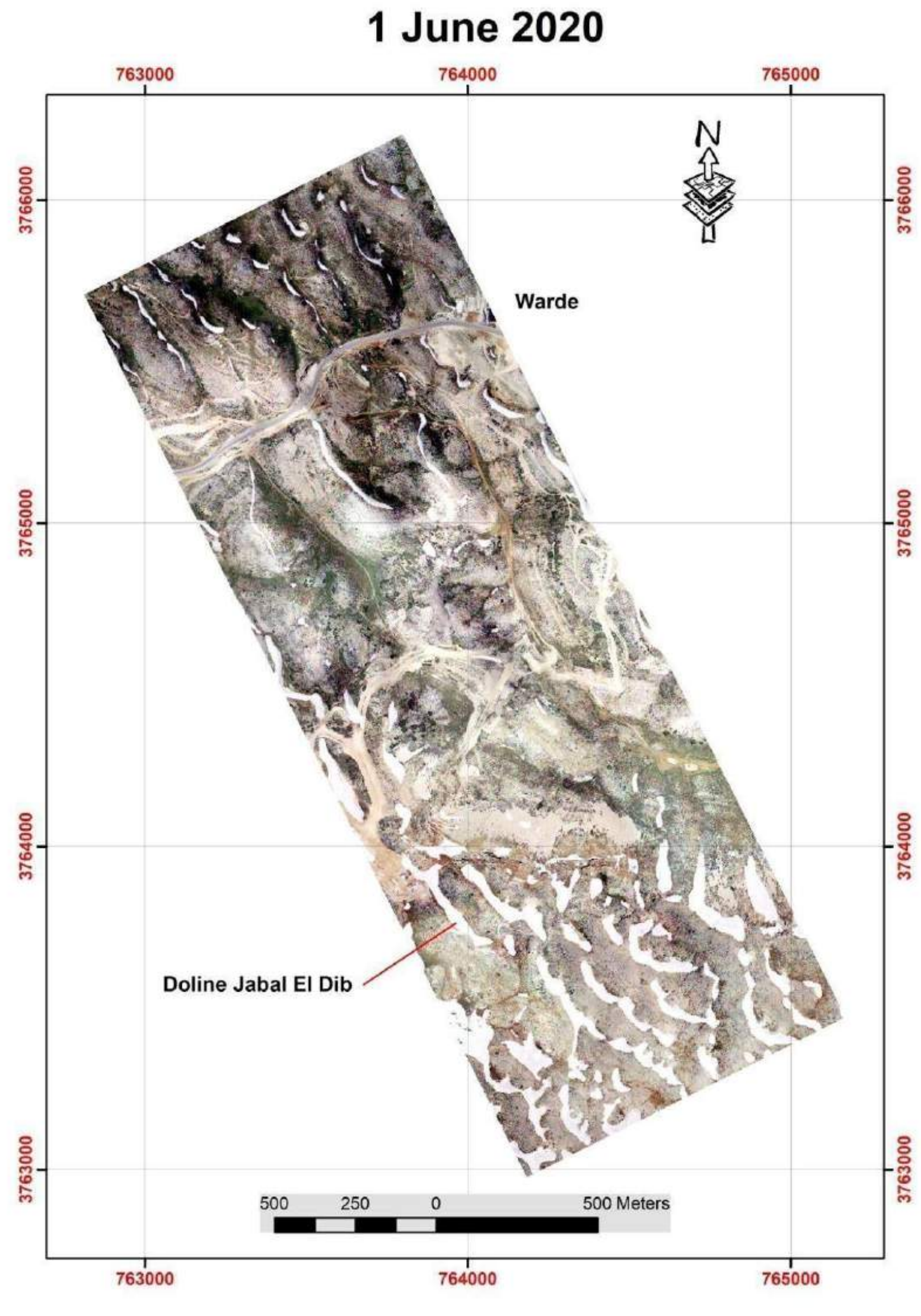


Figure 28: Snow cover monitoring for the study area using UAV on 1 June 2020

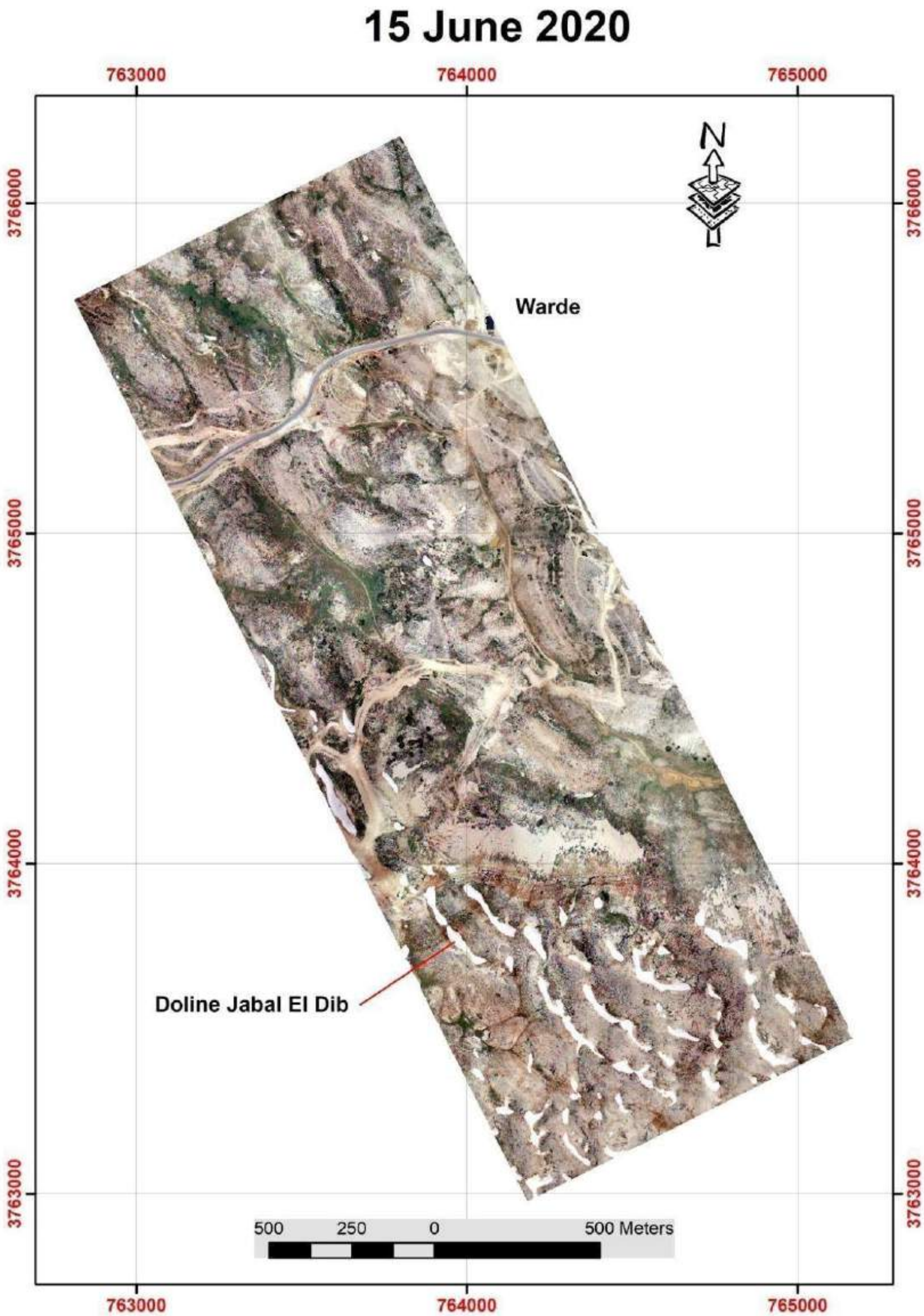


Figure 29: Snow cover monitoring for the study area using UAV on 15 June 2020

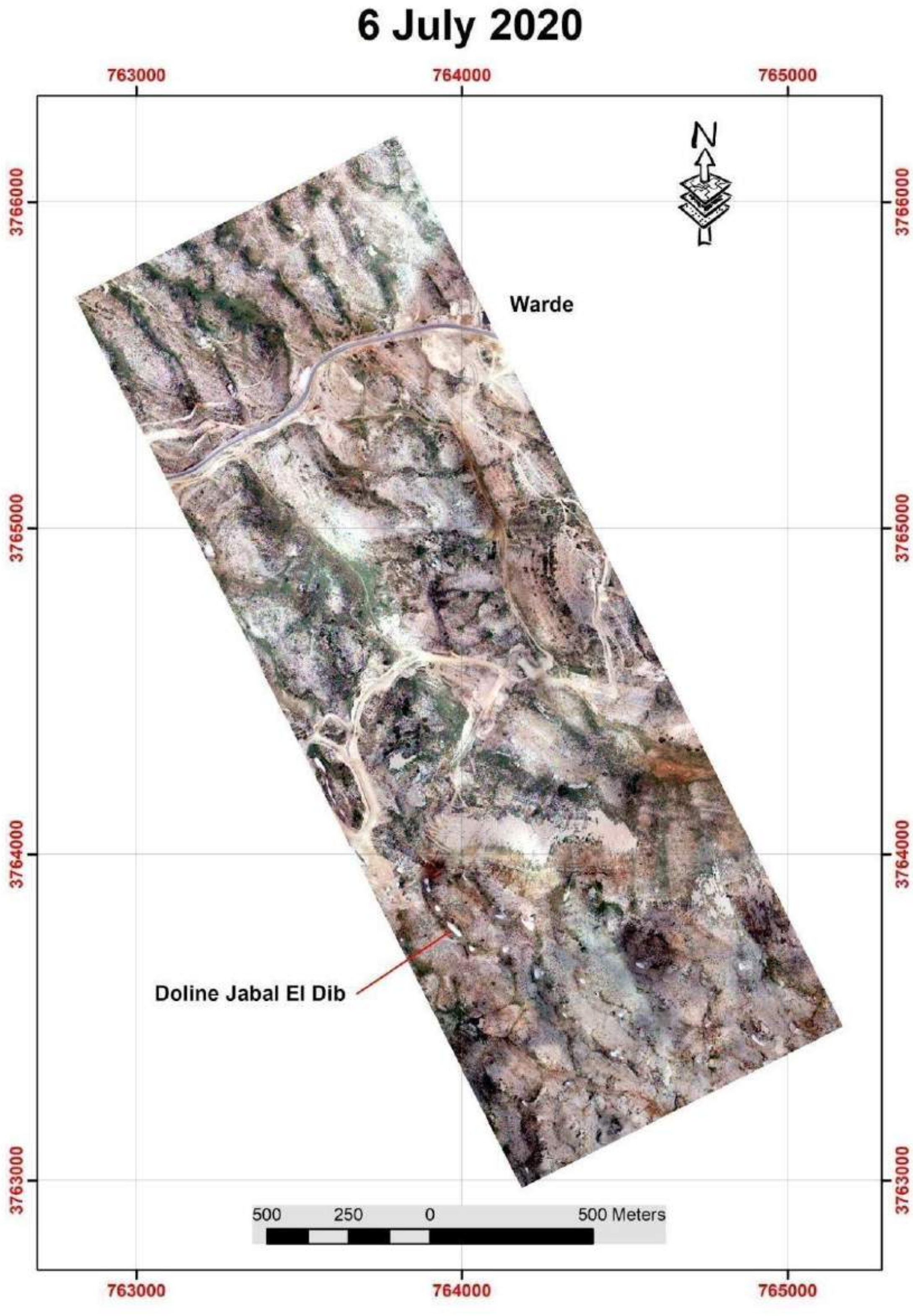


Figure 30: Snow cover monitoring for the study area using UAV on 6 July 2020

Using supervised classification and Iterative closest points (ICP) algorithm, we corigester the snow DSM and then extract the snow thickness map for the following date.

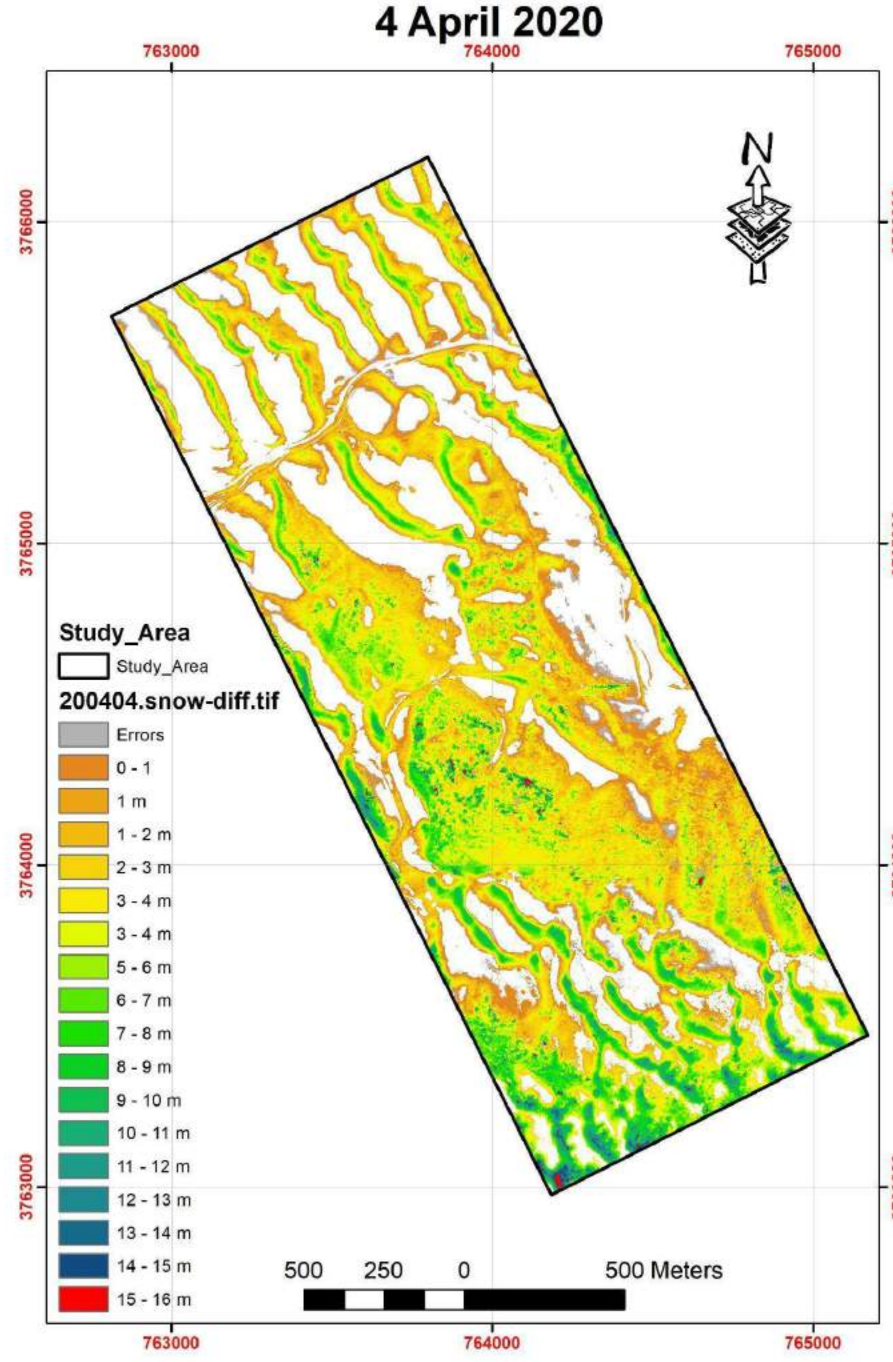


Figure 31: Snow cover thickness for the study area on 4 April 2020

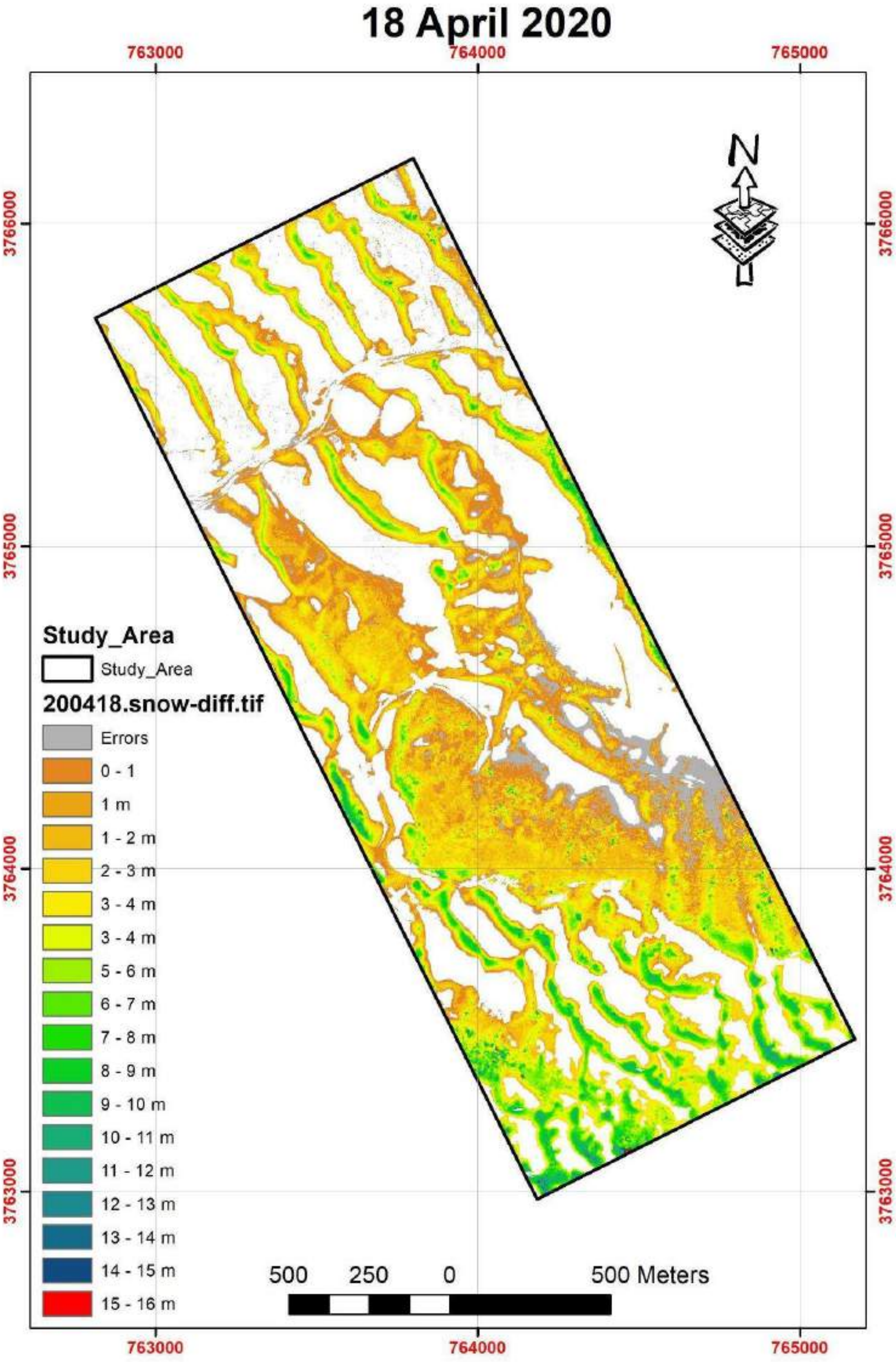


Figure 32: Snow cover thickness for the study area on 18 April 2020

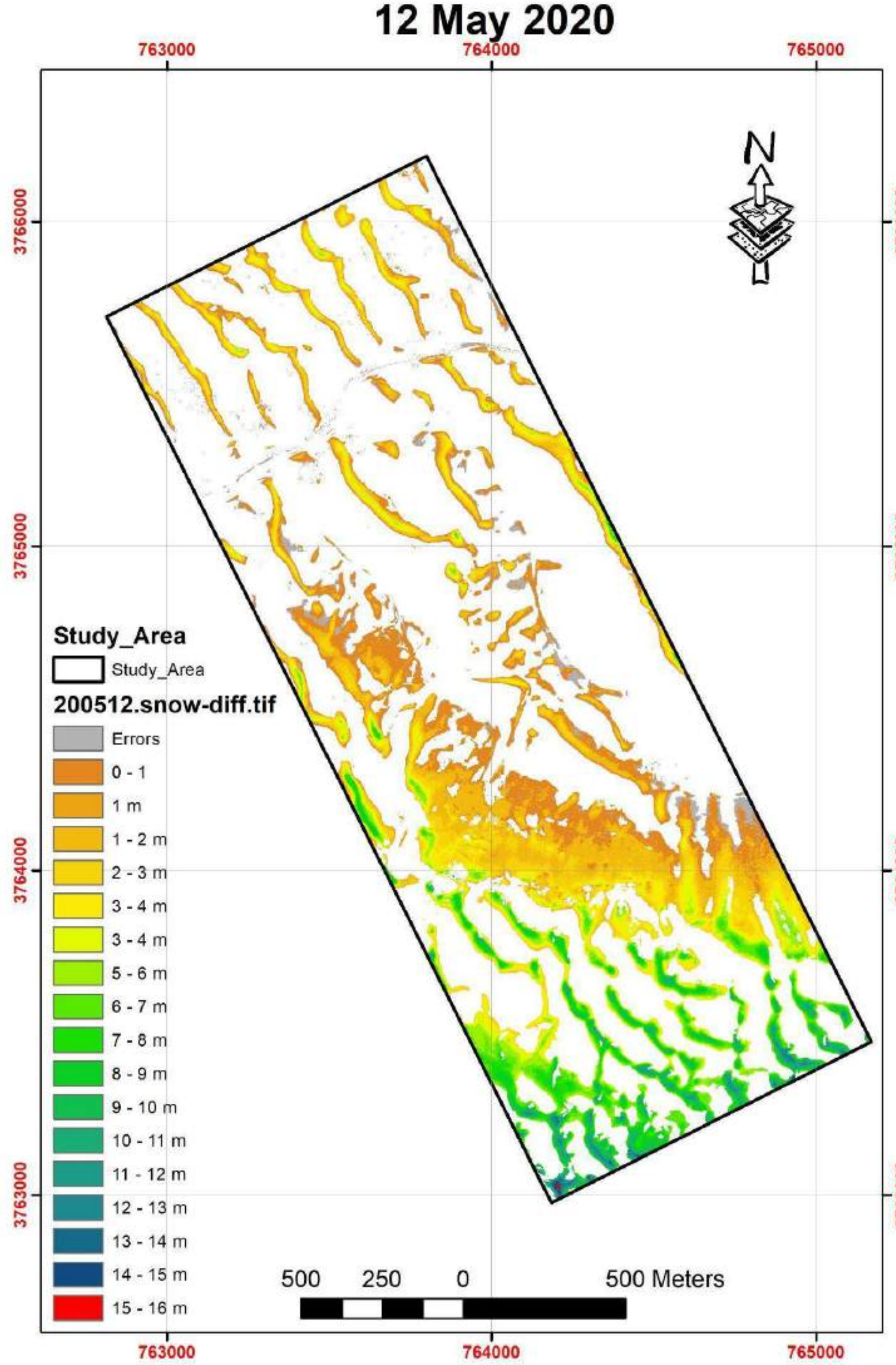


Figure 33: Snow cover thickness for the study area on 12 May 2020

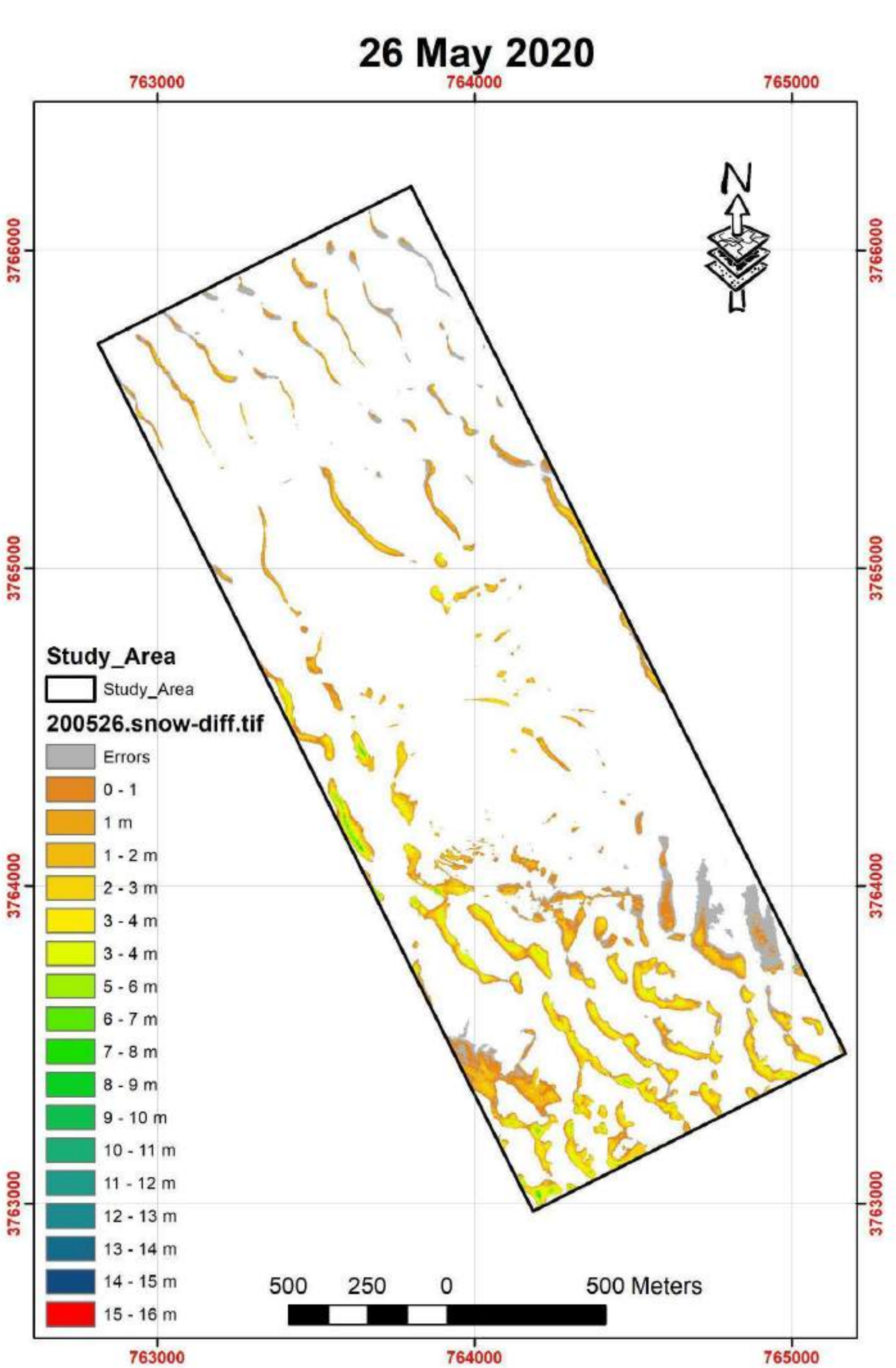


Figure 34: Snow cover thickness for the study area on 26 May 2020

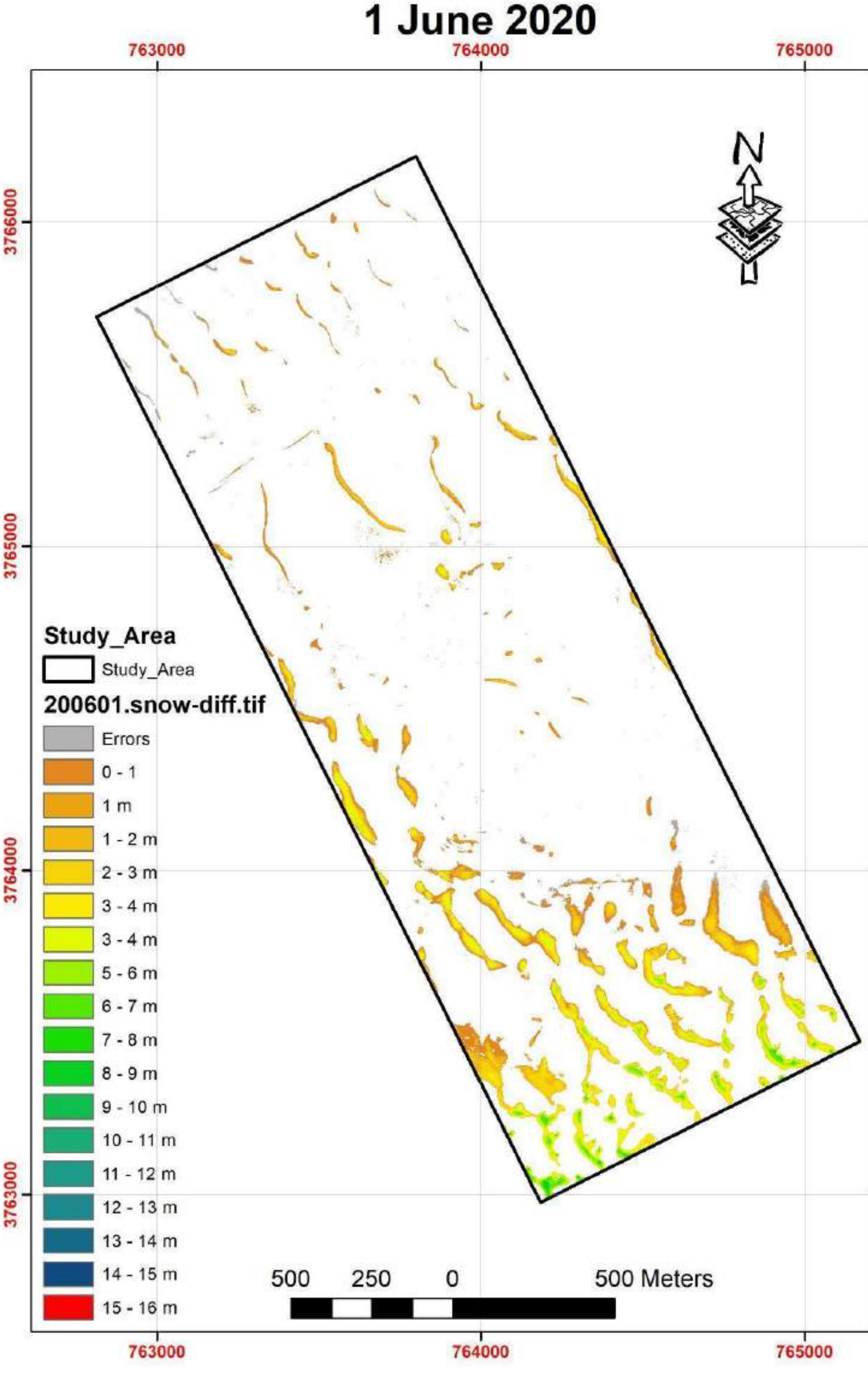


Figure 35: Snow cover thickness for the study area on 1 June 2020

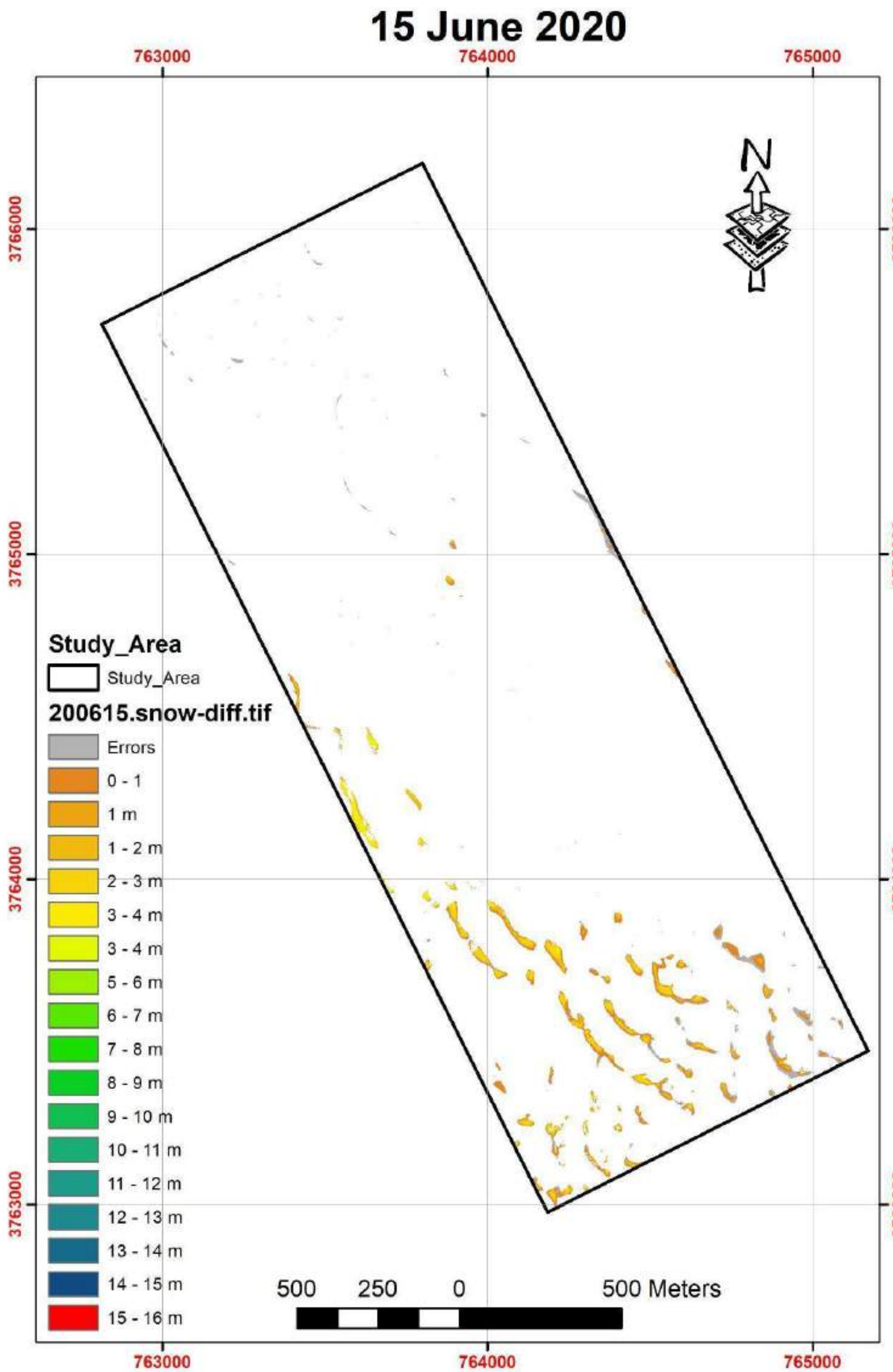


Figure 36: Snow cover thickness for the study area on 15 June 2020

Based on the thickness, we calculated the annual snow volume for the 2020 snowy season

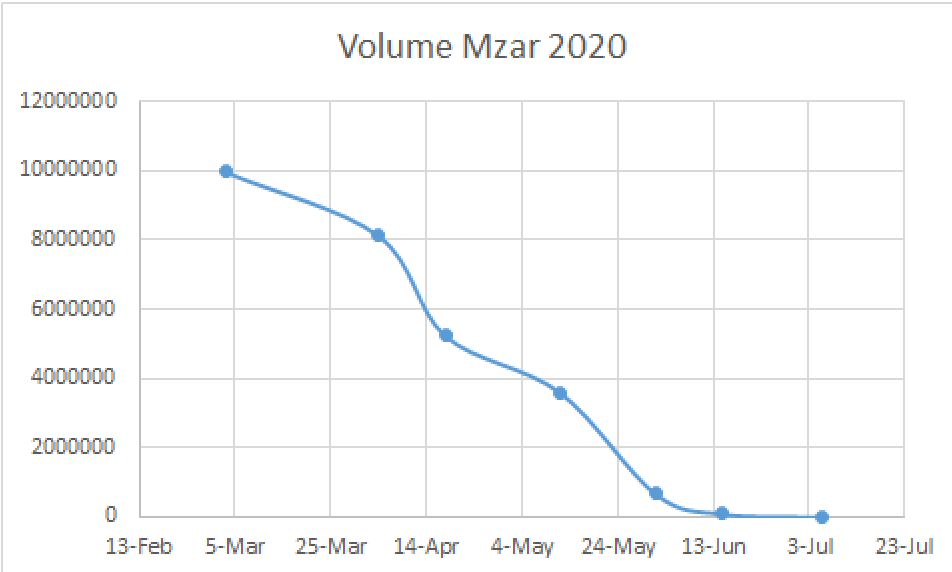


Figure 37: Snow volume during 2020 snow season for zone drone

5.4) Volume for SWE:

We have divided the study area to 3 zones based on their approximate altitudes and snow spatial distribution.

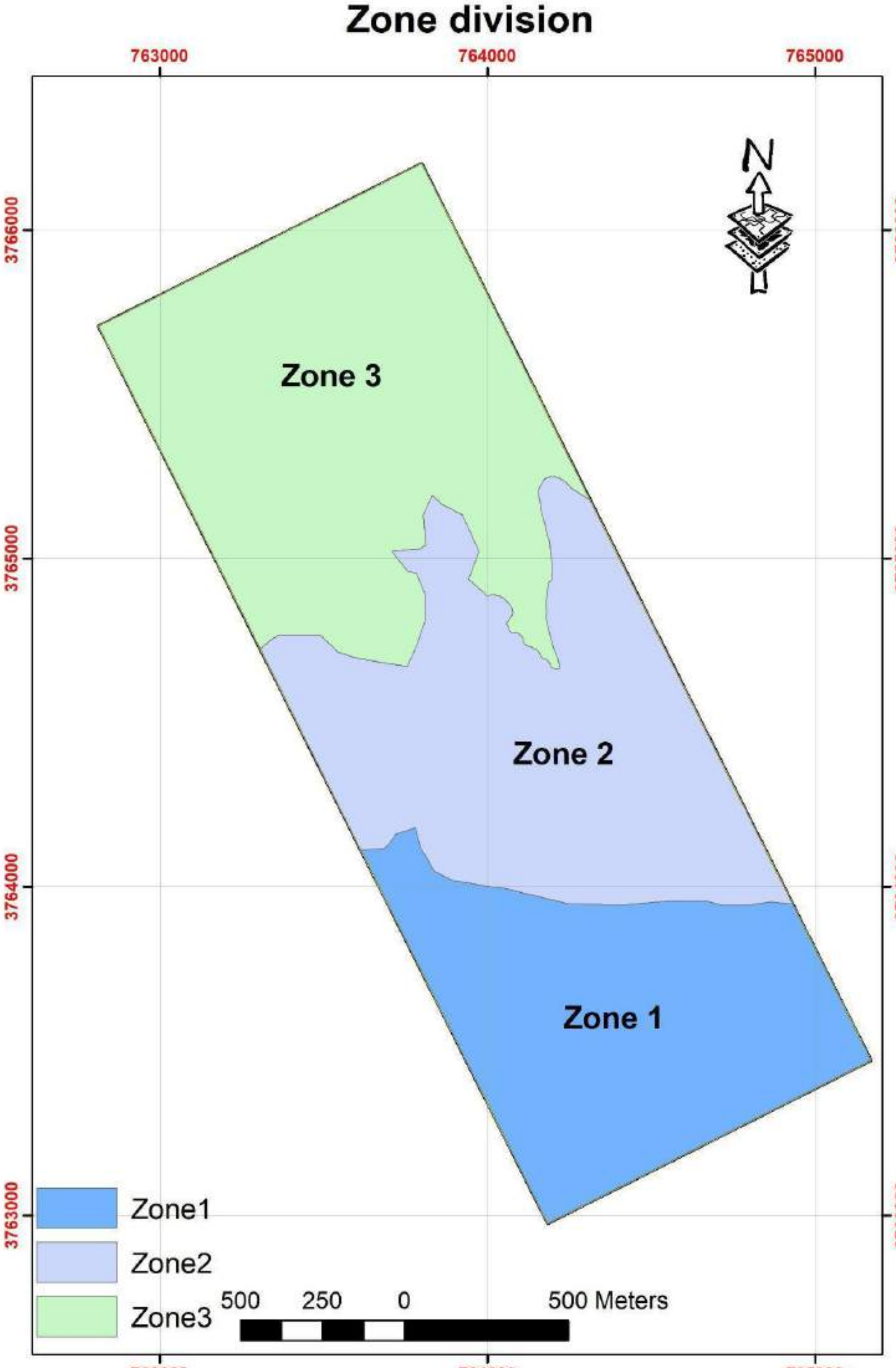


Figure 38: Zones division for the study area

Zone	Date and	Date	Area_2D	Area total	Area_3D	Volume zone	Volume total	% Area
Zone1	200404_z1	4-Apr	689381.8583	2165514.133	821595.6974	3368819.766	8089541.564	72.1838
Zone2	200404_z2		799735.7438		1000965.641	2793334.707		
Zone3	200404_z3		676396.5304		758640.4465	1927387.091		
Zone1	200418_z1	18-Apr	589842.2196	1752201.16	692037.3781	2606750.745	5204547.555	58.40671
Zone2	200418_z2		629571.1678		778784.3833	1409135.306		
Zone3	200418_z3		532787.7731		597793.252	1188661.505		
Zone1	200512_z1	12-May	408086.2837	1071523.535	438521.7225	2445240.239	3539077.717	35.71745
Zone2	200512_z2		435243.3054		459856.1122	728882.1727		
Zone3	200512_z3		228193.9455		242248.6882	364955.3051		
Zone1	200526_z1	26-May	219273.8059	336274.5463	241989.8787	423814.7915	596793.7433	11.20915
Zone2	200526_z2		75166.60141		84674.30882	133904.9925		
Zone3	200526_z3		41834.13903		45572.83848	39073.95933		
Zone1	200615_z1	15-Jun	56873.60814	66381.50394	59518.83494	69994.77844	88858.96379	2.212717
Zone2	200615_z2		9492.146715		9920.348762	18851.50022		
Zone3	200615_z3		15.74908577		19.91329769	12.68513837		

Figure 39: Snow volume based on the zones division

6. Estimation of the water equivalent of snow over the drone zone.

During the period of winter 2001, a global campaign on snow contribution in water resources of mount Lebanon lead to many master theses and PHDs at CREEN (Tarek Touma, Chadi Bitar, Selim Khalil and Angèle Aouad) with the support of IRD (Jean Olivier Job). The data cover all parameters for snow depth, snow cover and water equivalent during all the season.

In his Master “Equivalent en eau de la couverture neigeuse sur le Mont-Liban”, Mr Chadi Bitar measured the water equivalent (D_A) based on the elevation and the date:

a- For altitude less than 2000 m:
D_A double for width between 25 and 60 cm: from 0.22 to 0.41

b- For altitudes between 2000m and 2400m. the D_A values are :

hauteur	145-150	100-105	45-50	20-30	0-10
28-01-01	0.30	0.31	0.30	0.26	0.26
13-05-01	0.55	0.57	0.65	0.63	0.70
Diam. (mm)	Agrégats	3	4	6	zone capillaire

Based on the snow volume over the Drone area between April 4 and June 15, 2020, we can recommend the value of water equivalent for different altitudes:

		4-Apr	18-Apr	12-May	26-May	15-Jun
2150-2300 m	Zone 1	0.50	0.55	0.60	0.60	0.65
2000-2150 m	Zone 2	0.50	0.55	0.60	0.60	0.65
1600-2000 m	Zone 3	0.35	0.35	0.40	0.40	0.40

We obtain the water volume over the drone aria during the year 2019-2020:

Altitude (m)	Surf (km2)
	Zone Dag
2300-2546	13.56
2150-2300	14.05
2000-2150	14.44
1600-2000	35.12
1231-1600	5.90

Altitude (m)	Surf (km2)			4-Apr	18-Apr	12-May	26-May	15-Jun
	Zone drone							
2150-2300	**0.947**	**Snow volume**	Zone 1	3,368,820	2,606,751	2,445,240	423,815	69,995
2000-2150	**1.109**	**(m2)**	Zone 2	2,793,335	1,409,135	728,882	133,905	18,852
1600-2000	**1.311**		Zone 3	1,927,387	1,188,662	364,955	39,074	13
Total	**3.367**							
		Water equivalent	Zone 1	0.50	0.55	0.60	0.60	0.65
			Zone 2	0.50	0.55	0.60	0.60	0.65
			Zone 3	0.35	0.35	0.40	0.40	0.40
		Water volume	Zone 1	1,684,410	1,433,713	1,467,144	254,289	45,497
		(m2)	Zone 2	1,396,667	775,024	437,329	80,343	12,253
			Zone 3	674,585	416,032	145,982	15,630	5
				3,755,663	2,624,769	2,050,456	350,261	57,755
		Equivalent height of water (m)		**1.115**	**0.780**	**0.609**	**0.104**	**0.017**
			% remaining		**69.9%**	**54.6%**	**9.3%**	**1.5%**
		Equivalent height of precipitation (m)		**1.185**				

The precipitation at Laklouk station for 2019-2020 is 1185 mm on the 4th of April. The equivalent height of water still on the surface is about 1115 mm. 84% of the snow is preserved on the drone area until this date to feed all the mountain springs.

Monitoring of the flow water of Laban spring and correlative analysis

7- Monitoring of the Laban Spring Flow

The monitoring of the Laban Spring has been going on since April 2020 with regular visits on sight and measurement of the water height and discharge of the spring. Some of the pictures of the visits are shown below in Figures 40, 41 and 42.

Figure 40 - Canal of Laban Spring (2020)

Figure 41- Measurement of the water height (May 2020)

Figure 42- Snow on Laban (March 2021)

The calibration of the hydrometric station of Laban has been done using the different measurements done on sight to define the relationship between the water levels and the discharges H = f(Q) to make the transformation of the water level curve (hydrograph) into discharge curve (hydrogram).

After the definition of the rating curve for Laban, we draw the Hydrogram below for the period of the project (Figure 43).

Figure 43- Hydrogram for Laban in 2020

The maximum discharge of 6,5 m3/s was obtained on May 18, 2020 and we have a very steep recession curve.

8. Correlative analysis of Assal and Laban springs

Time series analysis comprises various methods for extraction of meaningful statistics and other characteristics of time series. Among these methods, correlation and spectral analysis have had an important role in studies of karst hydrological systems. The correlation analysis most often has been based on determination of correlation coefficients, autocorrelation functions and cross-correlation functions. These functions have found various applications in karst hydrology. They have been used for determination of basic characteristics of karst underground including investigations of groundwater hydrodynamics, processes on karst surface, transport properties, interactions between surface and underground flows, etc. Cross-correlation function is a measure of the strength of the linear relationship between two time series depending on a time lag between them. Autocorrelation function measures the strength of the linear relationship between successive values of a time series depending on a time lag between them

Generally, the autocorrelation functions (ACF) of discharge quantifies the linear dependency of successive values over a time and outlines a system memory. In karst hydrology, ACF of spring discharge provides the information about the storage capacity of the karst system. The storage capacity depends on the degree of karstification, but also on the surface ponds, soil cover and epikarst properties. To compare functions of various aquifers, the so-called memory effect is defined as the time lag where ACF becomes less than 0.2 [Mangin].

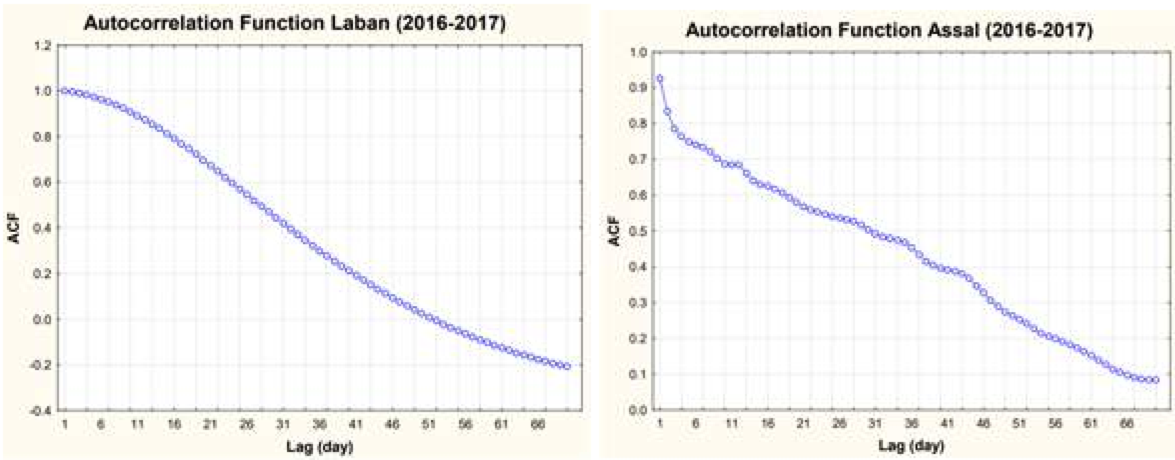


Figure 44 - ACF for Laban and Assal Springs

An undeveloped karst system, with a large storage, has a high memory effect where ACF shows a slightly decreasing slope. On the contrary, a developed karst network, without important storage, corresponds to a low memory effect where ACF has a much steeper slope. In Figure 44, it can be noted that ACF for the Laban and Assal springs have very similar forms, steep slopes and a high memory effect of approximately 40 and 55 days.

The cross-correlation functions between rainfall and temperature and discharge are presented in Figure 44 and 45. CCF is an indicator of linear dependency between two time series as a function of time lag k. If CCF shows statistically significant values and it is not symmetrical, a causal relationship between two series exists. This is the case for the CCF in Figure 45 between the discharge and temperature for Laban and Assal. The duration of the system response represents the range of lags from the origin where CCF has statistically significant values. The time delay of 75 days for both springs (time to peak or response time) gives an estimate of the pressure pulse transfer times through the karst system. This is a very particular property for snow fed springs where the snow melting and transfer are extremely dependent on the temperature.

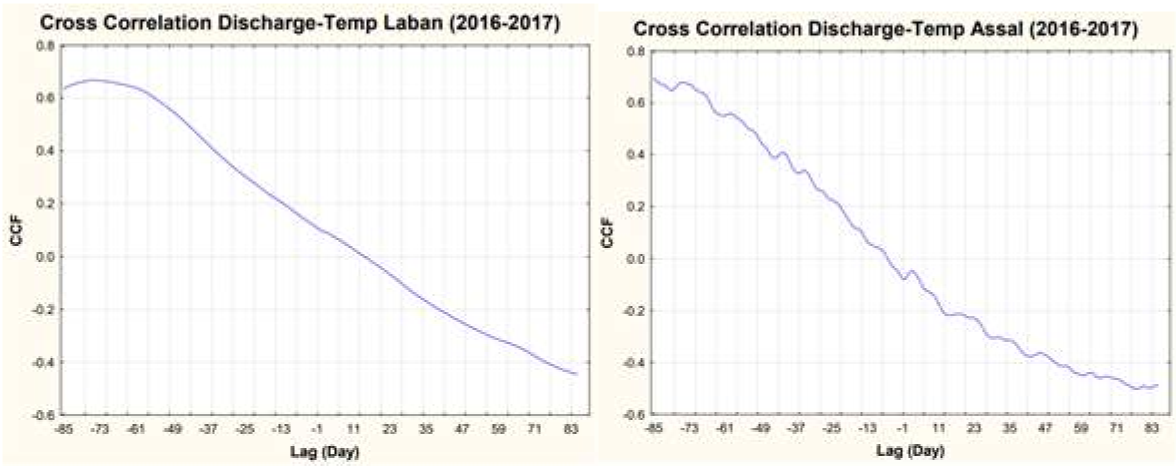


Figure 45- CCF for Discharge and Temperature at Laban Spring (2016-2017)

Considering a karst hydrological system, CCF between the input time series of rainfall and the output time series of discharge provides the information about the system response including significance, duration, and time delay. It also indicates the degree of karstification.

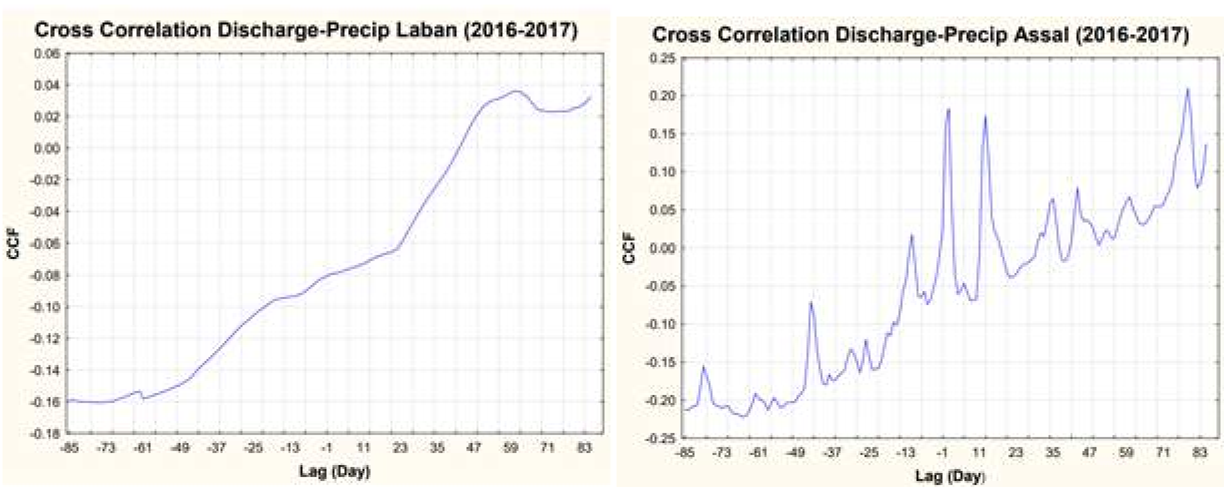


Figure 46- CCF for Discharge and precipitation at Laban Spring (2016-2017)

In Figure 46, CCF shows statistically non-significant values and no evidence of a causal relationship between precipitation and discharge for Laban spring corresponding to rare values of surface runoff this year. As for Assal spring, the CCF has a complete different behavior than Laban, it shows two maximas, one corresponding to lag = 1 and the other to lag = 13. The lag 1 is due to very rapid surface runoff in response to high precipitation. The lag 13 corresponds to high discharge in response to delayed subsurface runoff.

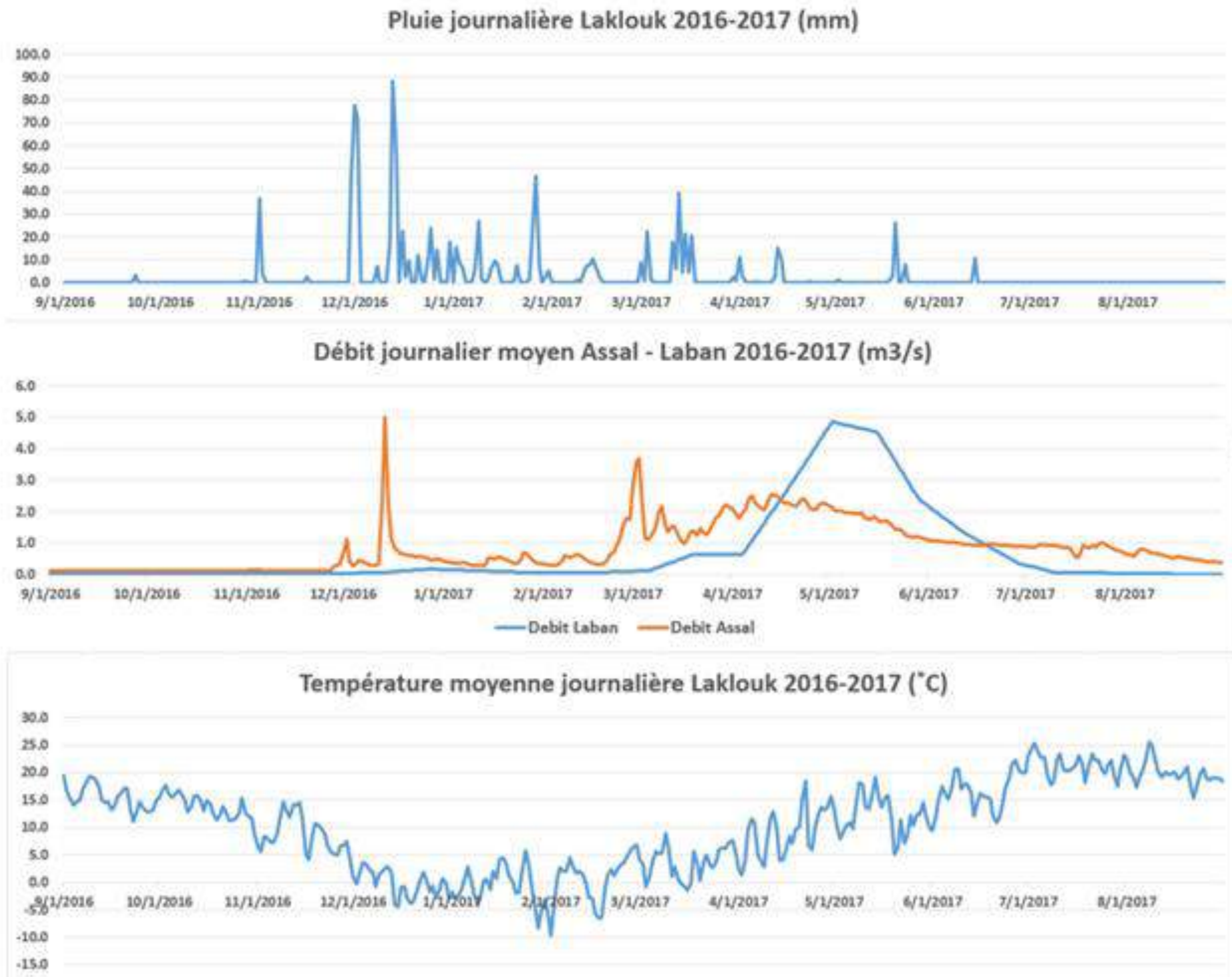


Figure 47- Daily precipitation Laklouk, Mean daily discharge Assal and Laban and mean daily temperature al Laklouk for (2016-2017)

The representation of the daily precipitation and the mean daily temperature at Laklouk station (1850 m. alt), and the hydrogram for the daily discharge of Laban and Assal springs for 2016-2017 (Figure.46) explain and confirm the results of the correlative analysis of the two springs:

a- The hydrogram of Laban is usually flat with no evidence of surface runoff. With the end of December and the low temperatures on the high mountain, the snow is accumulated in the dolines. With the elevation of the temperature and snow melting, the high discharge happens in may with a very steep recession curve. The main discharge is cumulated over two months and the yearly discharge for 2016-2017 is about 22 Millions m3.

b- The hydrogram of Assal shows evidence of rapid surface runoff, delayed subsurface runoff, and snow melting discharge. The first daily heavy rain of 77mm on 01/12/2016 and arrived on 14/12/2016 with a lag 13 days. The daily heavy rain of 88 mm on 13/12/2016 arrived on 14/12/2016 with a day lag. The recession curve is not as steep as Laban with an evidence of continuous surface runoff which is characteristic of his flow. The yearly discharge for 2016-2017 is about 27 Millions m3.

c- With a yearly precipitation of about 1012 mm, and a discharge of about 49 Millions m3, we should suggest that the common watershed of Laban and Assal would be about 50 km2.

9. General Conclusion and Perspectives

The geomorphological analysis shows the best infiltrating zones of the land and the density of sinkholes which occupy 60% of the studied area. For their role in water recharge, they have to be preserved from any degradation.

Observation of the studied area may lead to extract terrain characteristics such as general slope, main direction of slope which could have hydrogeological importance…

The diversity of the terrain configurations on these heights covered for many months by a snowpack and the observation of the snowfields melting over the winter season offer interesting perspectives of analysis on the longevity of the snowfields according to the relief configurations. We could thus define and evaluate their roles of reservoir and protection of snow patches.

It appears that there is a good relationship between volumes and (snow) surfaces throughout the melting season. Evaluating it according to different scales or resolutions would be most interesting because if the relationship is confirmed it would imply that we can base ourselves on satellite analysis of surfaces to approximate the volume of the cover: an essential parameter for the evaluation of Snow Water Equivalent.

In the part of snow observation, we have accomplished an annual observation at 3 scales; Spatial observation, aerial observation and pilot sinkhole. For the first scale that was around 80 km2, we used the official DEM from the Lebanese Army, DEM extracted from Pleiades images provided by the CNES and 2D satellite images downloaded from Planet website. At this scale we have only calculated the snow area evolution during the snow season of 2020. Regarding the second scale, it has an area of 3 km2 on which the volume observation was done for 2020 and only based on Drone images which allow to calculate the snow volume using Pix4D for DSM and orthophoto generation and Ames Stereopipeline for ICP coregistration. The calculated snow volume plays a fundamental role to accurately calculating SWE. For the pilot sinkhole located at Jabal eL Dib, it was already monitored from 2012 until 2020. It allows the annual comparison and it also helps us to well understand the snowmelt behavior.

As per future works on snow surfaces and volumes, it is highly recommended the below:

• Observations in this study focused on karstic areas characterized by sinkholes. In fact, we were interested in estimating Snow depth, surface and volume of snow cover. On one hand, the snow cover surface could be easily estimated through 2D satellite imagery. For example, imagery provided by "Planet" website, were sufficient for high spatio-temporal resolution monitoring. On the other hand, calculating volume and snow depth on a large territory required 3D stereoscopic imagery. This latter is very expensive compared to 2D satellite imagery. In this perspective, a deeper relationship between the volumes and the surfaces of the snow cover (Figure 48) will be helpful for snow cover observation at national scale.

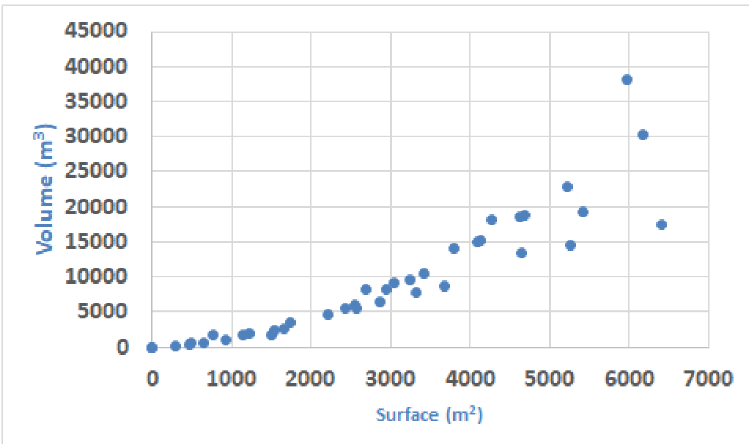


Figure 48: Relation between surface and volume of snow cover at Jabal EL dib sinkhole

• This study represents an important baseline to be applied progressively to the national level. This step requires a deep research and study about the classification of the Cenemonian territory based on the elevation, slope, aspect, spatial snow distribution. This classification leads to the prediction of total snow melt in each zone that will play a strategic role to early inform water establishment about any potential scarcity in the springs that depend on precipitation.

Correlative analysis corresponds to a functional approach to the KS based on the statistical analysis of chronological series (Jenkins and Watt, 1968; Mangin 1981). For the principle of these methods, the KS is a filter that transmits the information of an input signal. In this approach the aquifer is a "Blackbox" where the precipitation and runoff are the input and the output. The chronicles of input and output can be treated separately in the temporal domain (Simple correlative analysis SCA) or together (Cross-Correlation analysis CCA).

Single correlative analysis can test the repetitive character of the temporal series. The degree of resemblance of series with the same series lagged in time is determined by SCA

To perform this correlative analysis, it was necessary to have simultaneous data of the chronological series on Laban and Assal springs runoff, as precipitations and temperature on the Laklouk station (alt. 1850 m.) operated by IRD. This is why all the analysis was done for the year 2016-2017.

From the results of this analysis, it was possible to have information on the structure and functioning of the karstic system: inertia, memory effect, typology, as tendency on the short and long term of the system on the periodic phenomenon associated to the variation of precipitation and temperature.