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Toward an early warning system of barrier lakes enabled by Sentinel-1 imagery

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Toward an early warning system of barrier lakes enabled by Sentinel-1 imagery

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Keywords: barrier lake, Sentinel-1, synthetic aperture radar, time series analysis, warning system

1. Introduction

A barrier lake is the natural damming of a river by landslides, caused by an earthquake, debris flow, rock avalanche or volcanic eruption. It tends to fail catastrophically and lead to downstream flooding with high casualties, because of its loose nature and absence of controlled overflow channel. For example, over 400 death toll was reported after a devastating dam breach of a barrier lake near Siaolin Village, Kaohsiung County, Taiwan in August 2009 (Chen et al. 2013). It was formed and failed in a very short time in the upstream of Chi-Shan River caused by the heavy rainfall brought by Typhoon Morakot. As a matter of fact, most of the barrier lakes last for a short time: 44-51% are less than a week, 59-71% are less than a month, and 83% are less than six months (Yang et al. 2013, Peng and Zhang 2012). The prerequisite for detecting the emergence and providing an early warning of barrier lakes, therefore, is the timely observation of the entire area of concern.

Remote sensing from the spaceborne platform is advantageous in providing frequent and repetitive observations of a vast area. The high-spatial-resolution optical imagery acquired from satellites have been employed to delineate the boundary of a barrier lake for a long time, especially for those remote or even inaccessible areas. But all optical imagery is inevitably limited by the amount of cloudiness in the sky, which is usually rather high and persists for a long period of time. Radar imagery acquired from the synthetic aperture radar, by contrast, can penetrate clouds and serve as an ideal source of data to detect the emergence of a barrier lake. Thanks to the success of Sentinel-1 mission and the Copernicus program that adopt the free and open data policy, all Sentinel-1 data are made available systematically and freely to all registered users. They serve as an ideal and cost-effective data source for constructing an early warning system of barrier lakes.

2. Materials and Methods

There is no obscure to differentiate water from land in a radar imagery, for almost all the incident radio waves are reflected by the water surface, resulting in a much lower signal of backscattering (Gulácsi and Kovács 2020). However, in the mountainous area where the topographic surfaces are other than flat, the irregularities can have unusual geometric characteristics, namely layover and foreshortening, on the appearance of the resulting image. As a result, the dark-toned pixels in a radar image where the terrain is quite mountainous with high relief are not necessary to be waters. This research proposes a statistic analysis of the time series of Sentinel-1 imagery, with a goal to detect the emergence of barrier lakes. Figure 1 gives the flowchart of Sentinel-1 image process and statistic analysis.

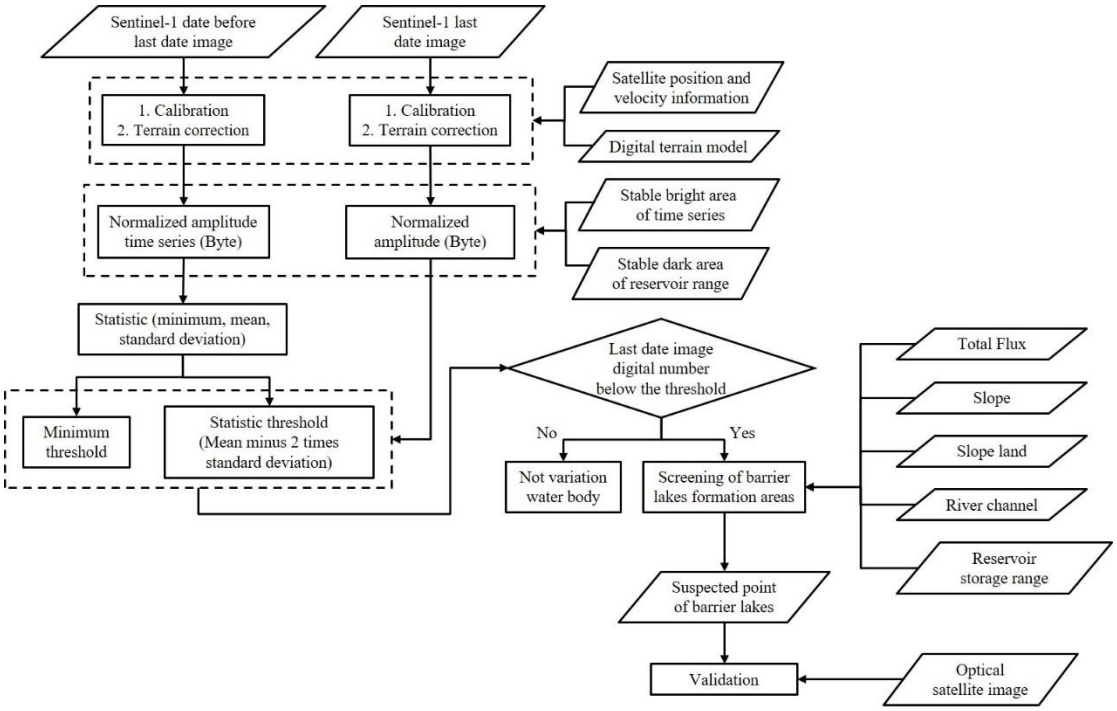

Figure 1. The flowchart of Sentinel-1 image process and statistic analysis.

All standard Level-1 Ground Range Detected (GRD) products of Sentinel-1 covering Taiwan island are downloaded from the Sentinel Hub directly. The calibration and terrain correction are processed by the Sentinel Application Platform (SNAP) tool provided by ESA to produce the (sigma nought backscatter coefficients). Note that all required parameters of orbit and attitude are referred to the meta data of GRD product, while the Digital Elevation Model (DEM) with a resolution of 20 m is made available by the Ministry of Interior Affairs of Taiwan. Based on the Sentinel-1 image is acquired from the ascending or descending orbit, all σ_0 maps are grouped and normalized by taking logarithm and digitized to the range of 0 to 255. For each pixel in the ascending or descending group, two thresholds are calculated from the minimum value (minimum threshold) and the average value deducted two times of standard deviation (statistic threshold), respectively. Note that Sentinel-1A and 1B have been operating from 2014 and 2016, respectively. The archived Sentinel-1 images cover both the rainy and drought seasons. Once a new σ_0 map is received, the same processing of calibration, terrain correction and normalization is repeated. The dark pixels are determined by comparing the DN value of each pixel to the minimum threshold and the statistic threshold, respectively.

3. Results and Discussion

Figure 2 gives one example of detecting the emergence of a barrier lake in the upstream of Beinan River in February 2021. The Sentinel-1 image acquired on 25 February 2021 was processed and the early warnings of the red polygon using the minimum threshold (Figure 2a), as well as the red polygon using the statistic threshold (Figure 2b) were alarmed immediately in the Big Geospatial Information System (BigGIS) (https://gis.swcb.gov.tw/). This result was validated later by comparing the Sentinel-2 true color images of the same region acquired on 4 February 2021 (Figure 2c) and 1 March 2021 (Figure 2d), respectively.

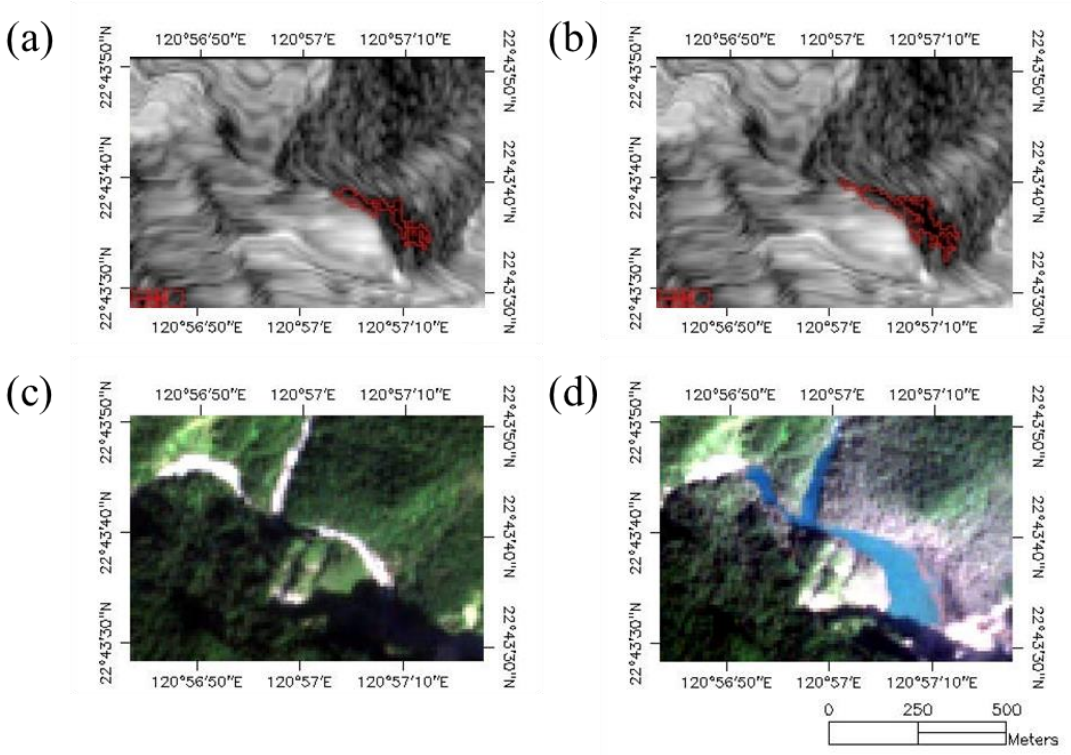

Figure 2. Early warnings of the emergence of a barrier lake in the upstream of Beinan River based on the Sentinel-1 image acquired on 25 February 2021. (a) the red polygon using the minimum threshold, (b) the red polygon using the statistic threshold. The Sentinel-2 true color images of the same region acquired on (c) 4 February 2021 and (d) 1 March 2021.

References

Chen, S.-C., K.-F. Liu, L.-K. Chen, C.-H. Wu, F. Wang & S.-C. Wei. 2013. Catastrophic deep-seated landslide at Xiaolin Village in Taiwan induced by 2009.8. 9 Typhoon Morakot. In *Progress of Geo-Disaster Mitigation Technology in Asia*, 401-419. Springer.

Gulácsi, A. & F. Kovács (2020) Sentinel-1-Imagery-Based High-Resolution Water Cover Detection on Wetlands, Aided by Google Earth Engine. *Remote Sensing,* 12**,** 1614.

Peng, M. & L. M. Zhang (2012) Breaching parameters of landslide dams. *Landslides,* 9**,** 13-31.

Yang, S.-H., Y.-W. Pan, J.-J. Dong, K.-C. Yeh & J.-J. Liao (2013) A systematic approach for the assessment of flooding hazard and risk associated with a landslide dam. *Natural Hazards,* 65**,** 41-62.

INTERPRAEVENT 2023 International Symposium

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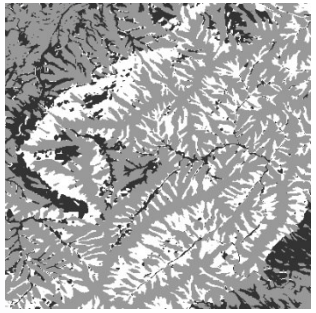
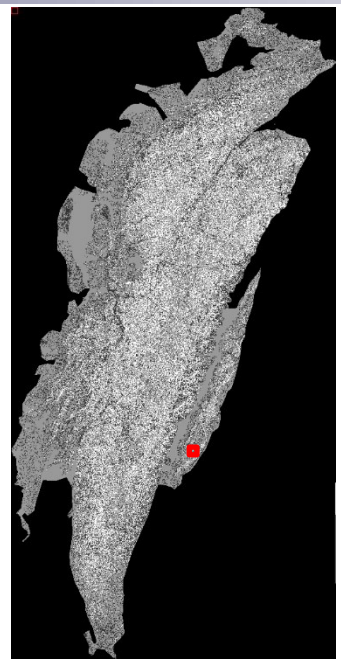
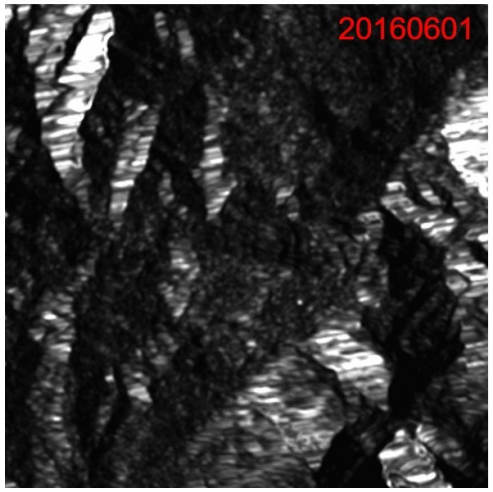
2023.04.17.

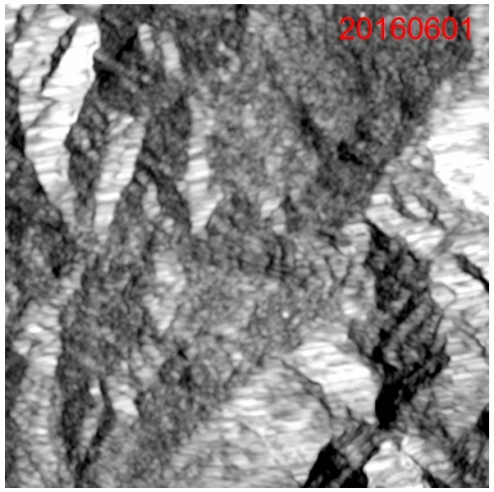
Outline

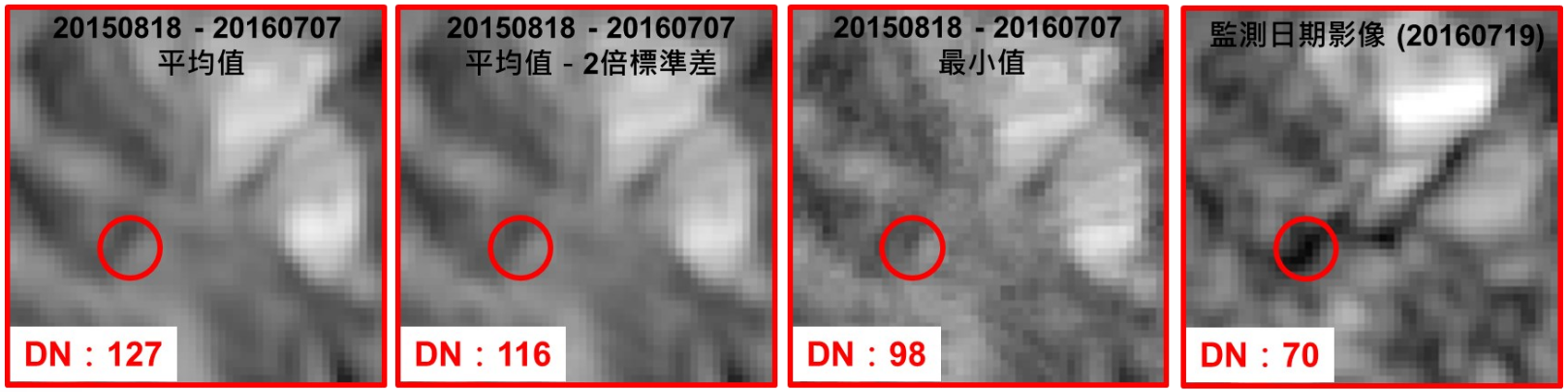
- Introduction
- Method
- Results
- Conclusion











Introduction

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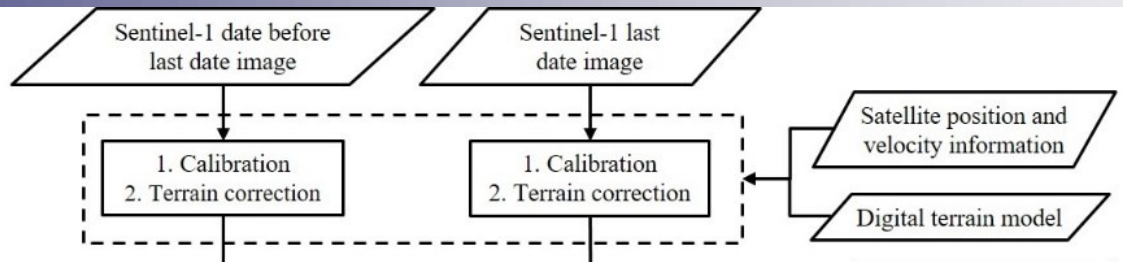
Peng, M.; Zhang, L.M. Breaching parameters of landslide dams. Landslides 2012, 9, 13-31, doi:10.1007/s10346-011-0271-y.

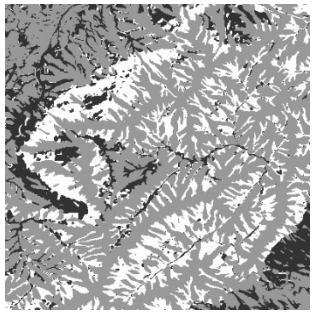
Introduction

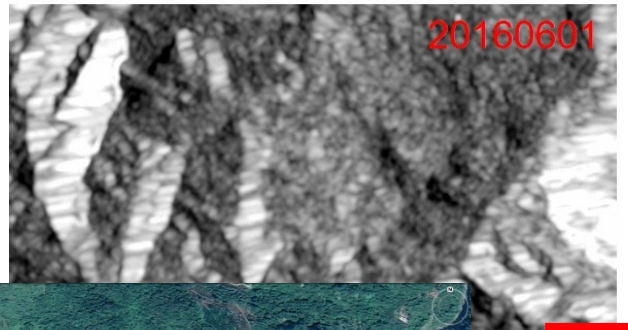
- Remote sensing from the spaceborne platform is advantageous in providing frequent and repetitive observations of a vast area.
- Radar imagery acquired from the synthetic aperture radar, by contrast, can penetrate clouds and serve as an ideal source of data to detect the emergence of a barrier lake.
- Thanks to the success of Sentinel-1 mission and the Copernicus program that adopt the free and open data policy, all Sentinel-1 data are made available systematically and freely to all registered users.

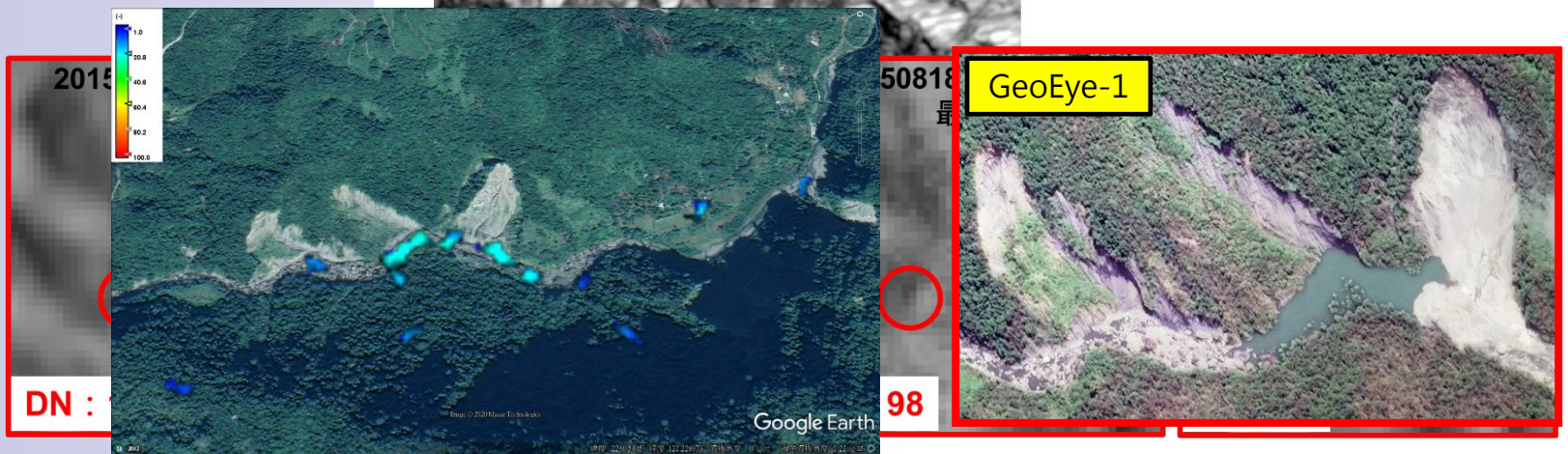
They serve as an ideal and cost-effective data source for constructing an early warning system of barrier lakes.

Method – flow chart

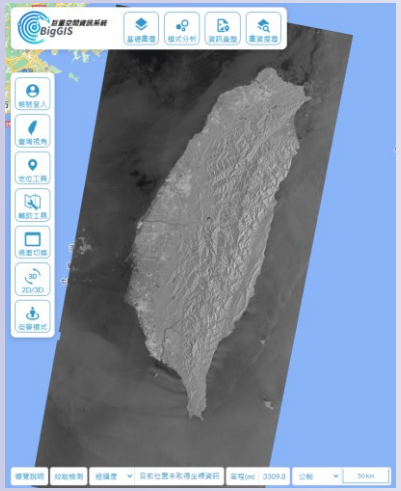








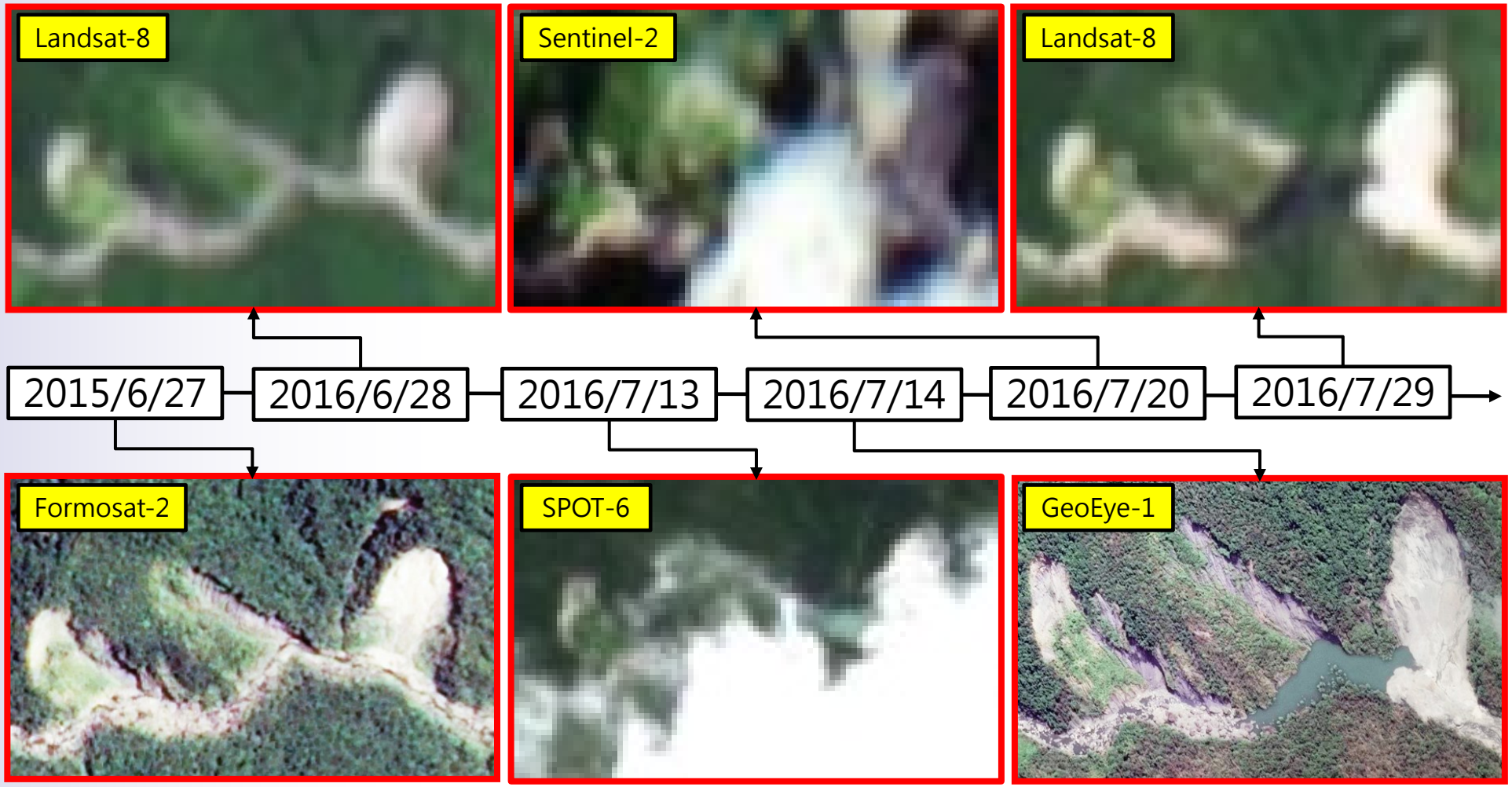
Method – Sentinel-1 imagery



BigGIS
https://gis.swcb.gov.tw/

- The Sentinel-1 mission comprises a constellation of two polar-orbiting satellites, operating day and night performing C-band synthetic aperture radar imaging, enabling them to acquire imagery regardless of the weather.
- On 23 December 2021, Copernicus Sentinel-1B experienced an anomaly related to the instrument electronics power supply provided by the satellite platform, leaving it unable to deliver radar data.
- Copernicus Sentinel-1A remains fully operational. Strong efforts have been deployed to launch Sentinel-1C as early as possible, the current plans target a launch in the second quarter of 2023.
- There are two types data, VV & VH, provided in Taiwan region.
- adopt the free and open data policy

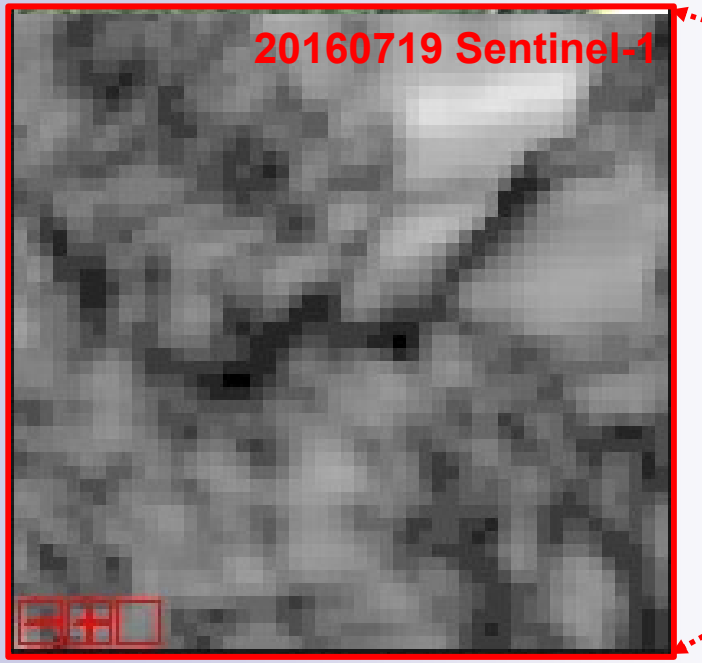
Barrier lake in Shangde Village 2016



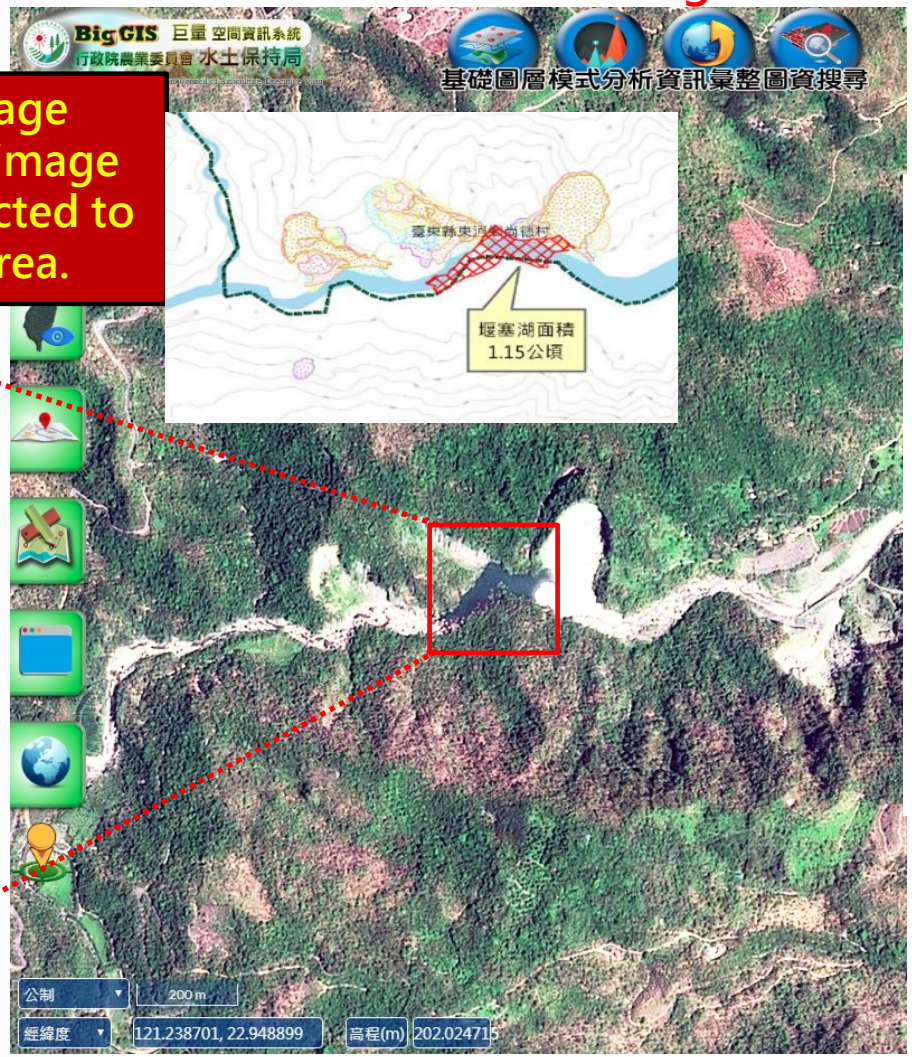
*Multi-scale satellite image analysis the barrier lake in Shangde Village, Taitung County before and after the disaster caused by Typhoon Nepartak. 2016 Multi-scale remote sensing information system data establishment, expansion and maintenance. SWCB

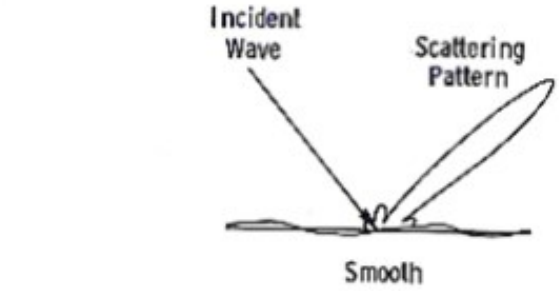
Barrier lake in Shangde Village 2016

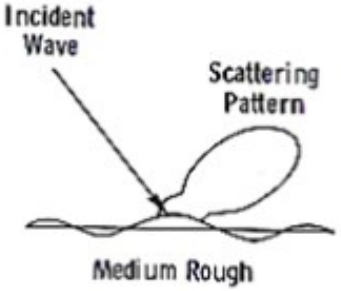
2016/07/25 SPOT image
2016/07/25 Sentinel-1 image
Water bodies were detected to be gathering in the area.

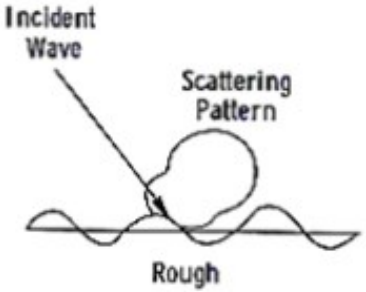


2016/07/25 SPOT image



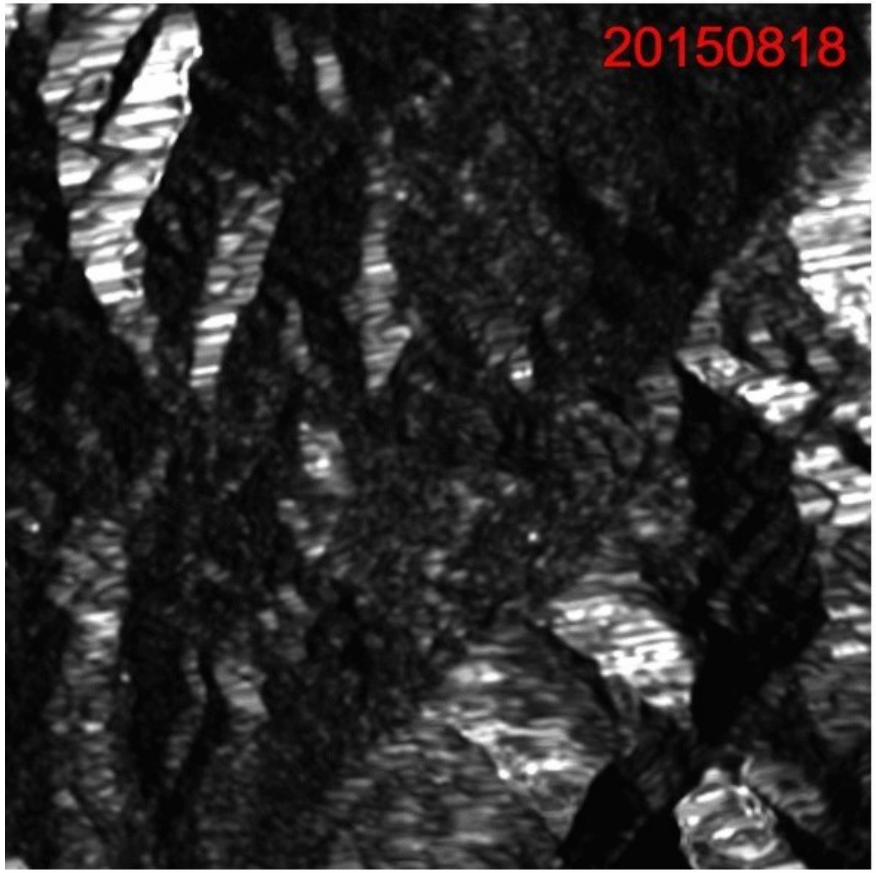






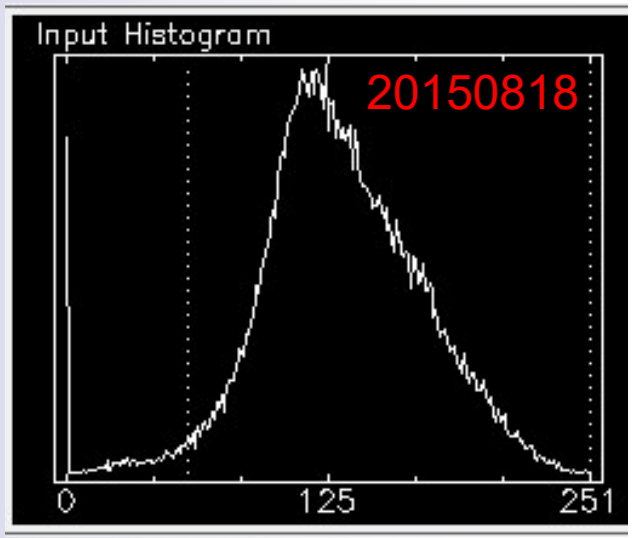
Barrier lake in Shangde Village 2016

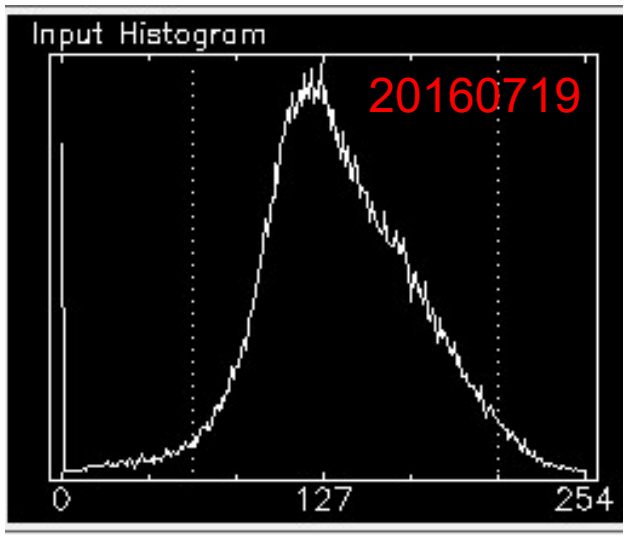
- The radar reflectivity signal strength of the water bodies in different cases can differ by up to ten times, making it difficult to establish a universal threshold value for water bodies across the entire island.
- Water body detection is performed by analyzing the changes in the reflectivity signal strength of Sentinel-1 time series images taken over the course of years, all captured in the same orbit (ascending or descending).

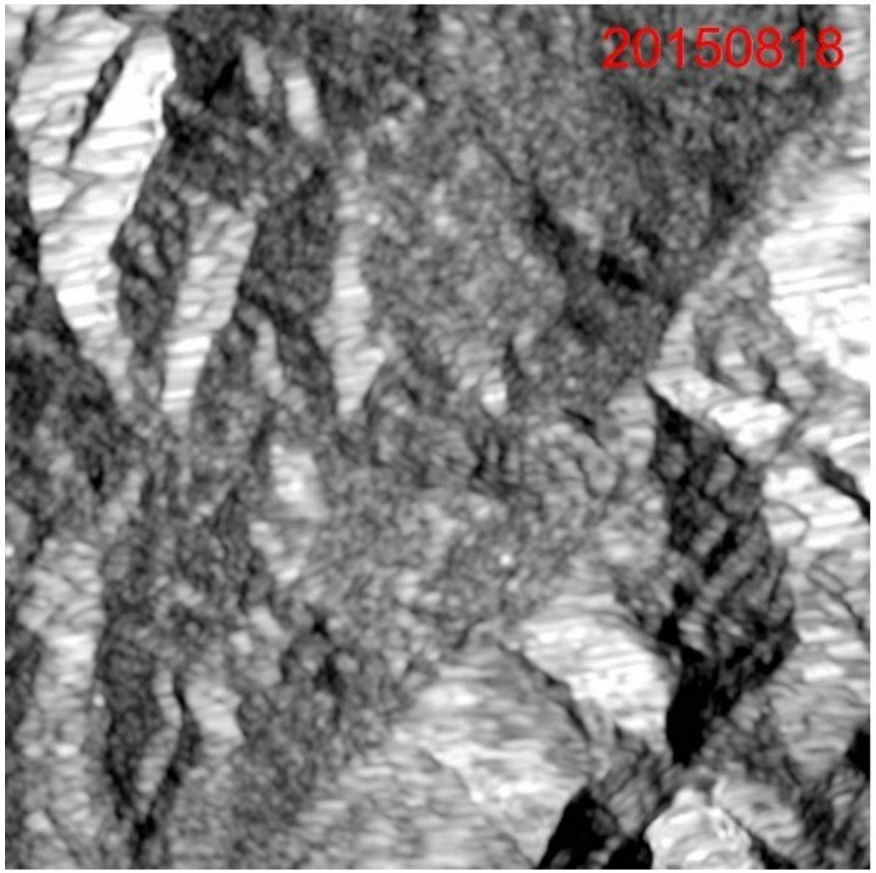


Barrier lake in Shangde Village 2016

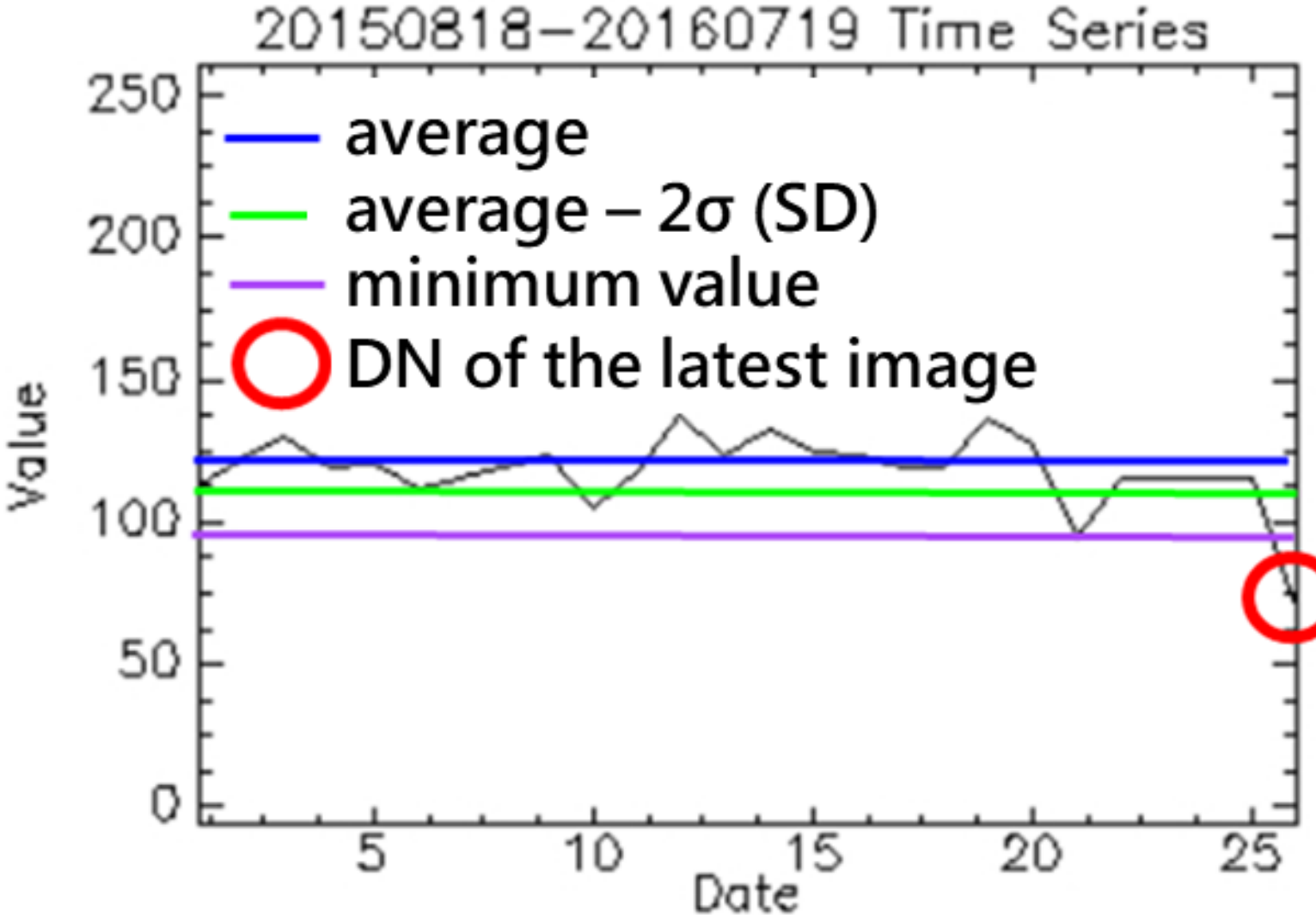
- The reflectivity signal strength of radar images exhibits exponential changes, and the data range of the images differs for different dates.
- Convert the data to logarithmic scale and stretch it to the range of 0-255.

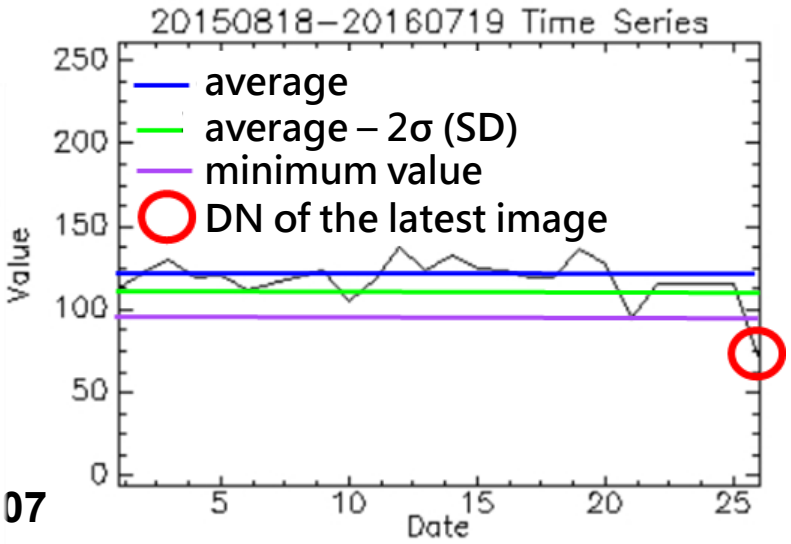






Barrier lake in Shangde Village 2016





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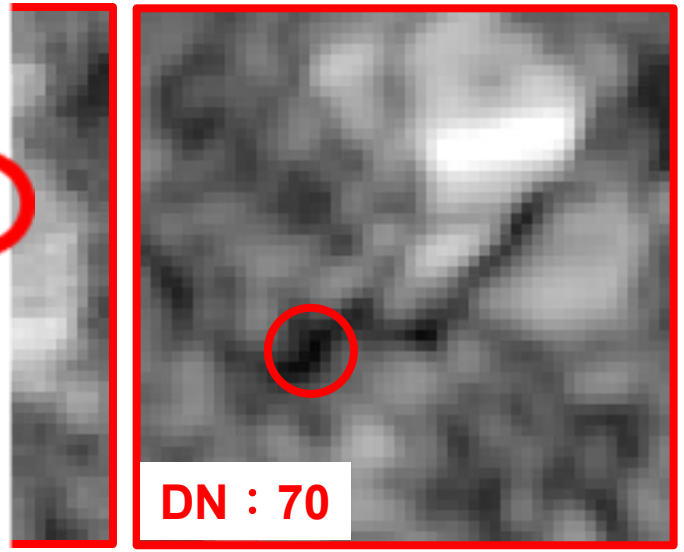
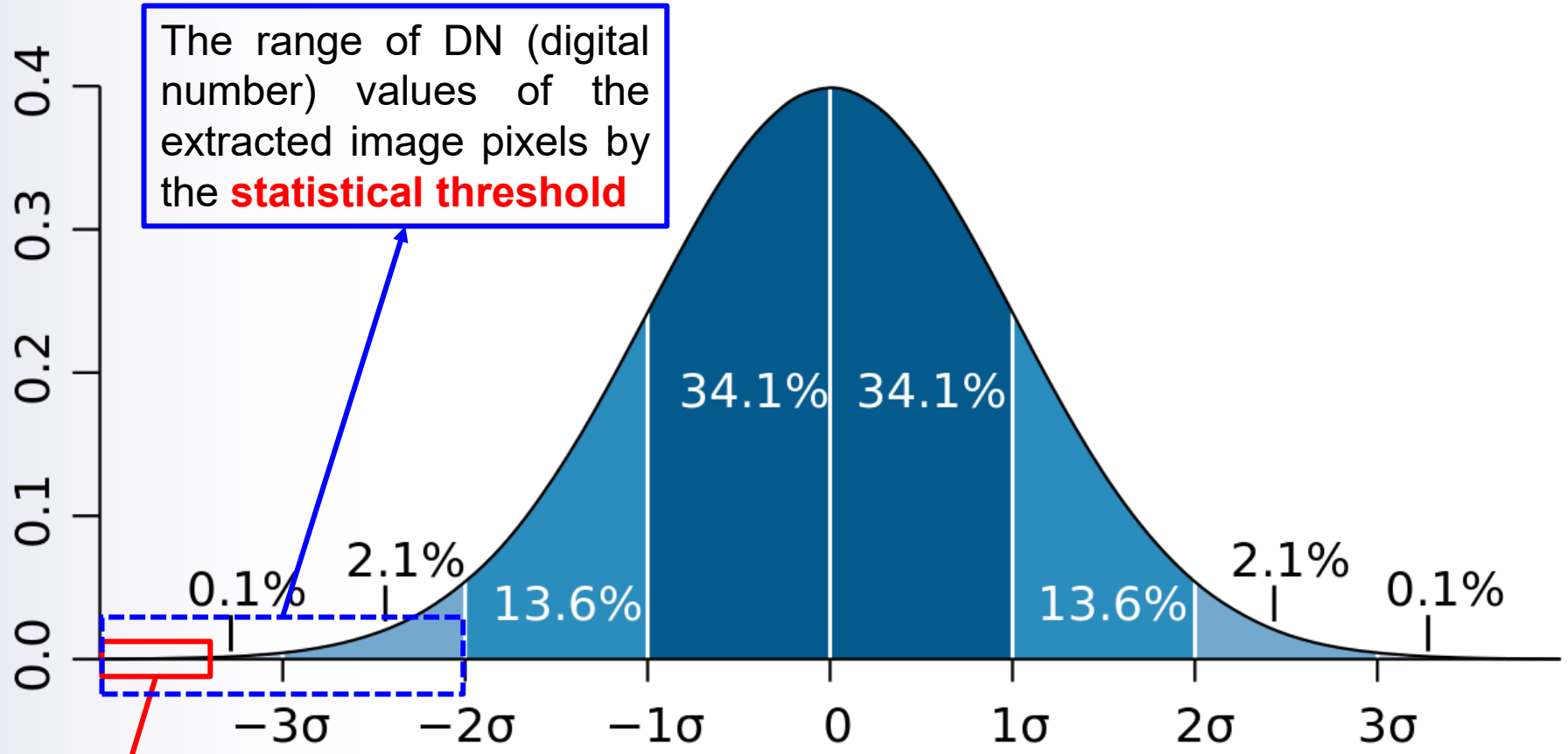
Monitoring date (20160719)

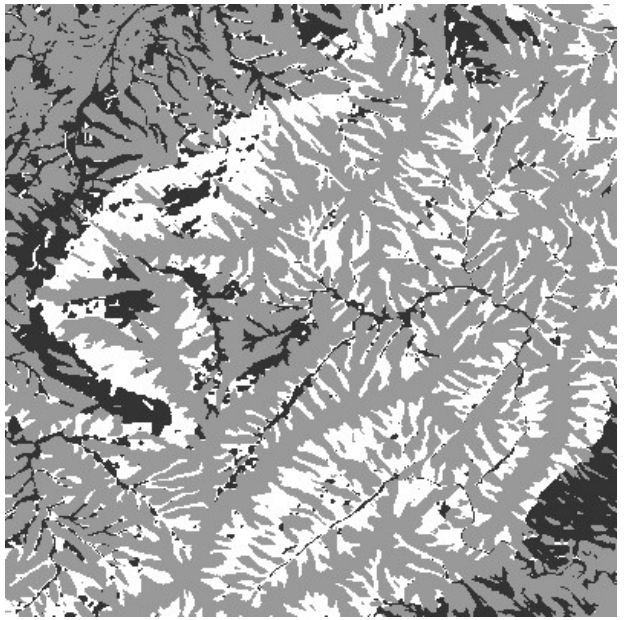


Barrier lake in Shangde Village 2016

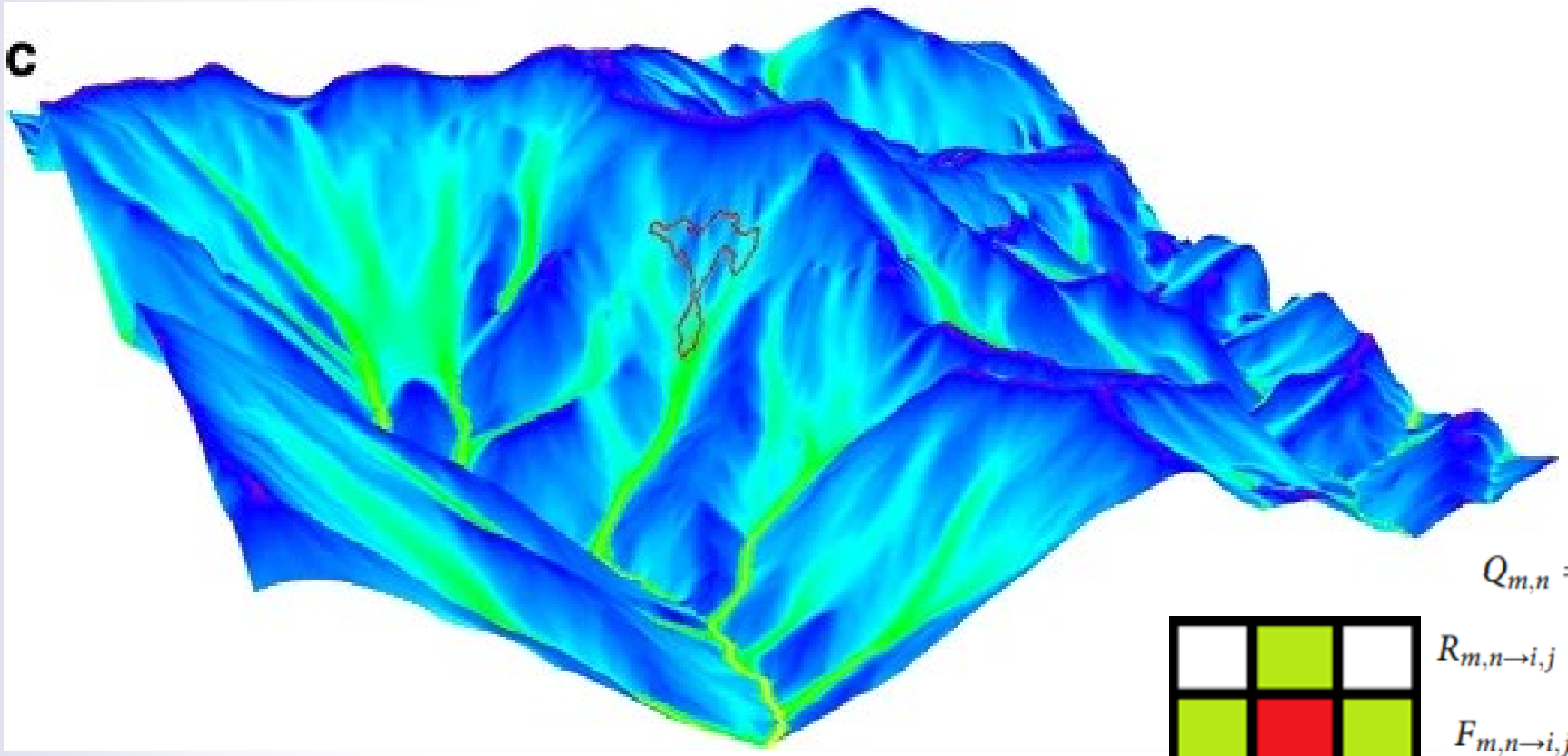


Environmental Factors

- Minimum Threshold Method ：
  - the minimum value in historical series imagery
- Statistical Threshold Method：
  - the average value deducted two times of standard deviation
- According to the selection criteria for potential formation areas of barrier lakes
  - mountainous area
  - in the river channel or total flux greater than 3
  - Slope angle less than 30 degrees
  - Not within the range of static water bodies such as reservoirs or lakes



Environmental Factor – Total Flux



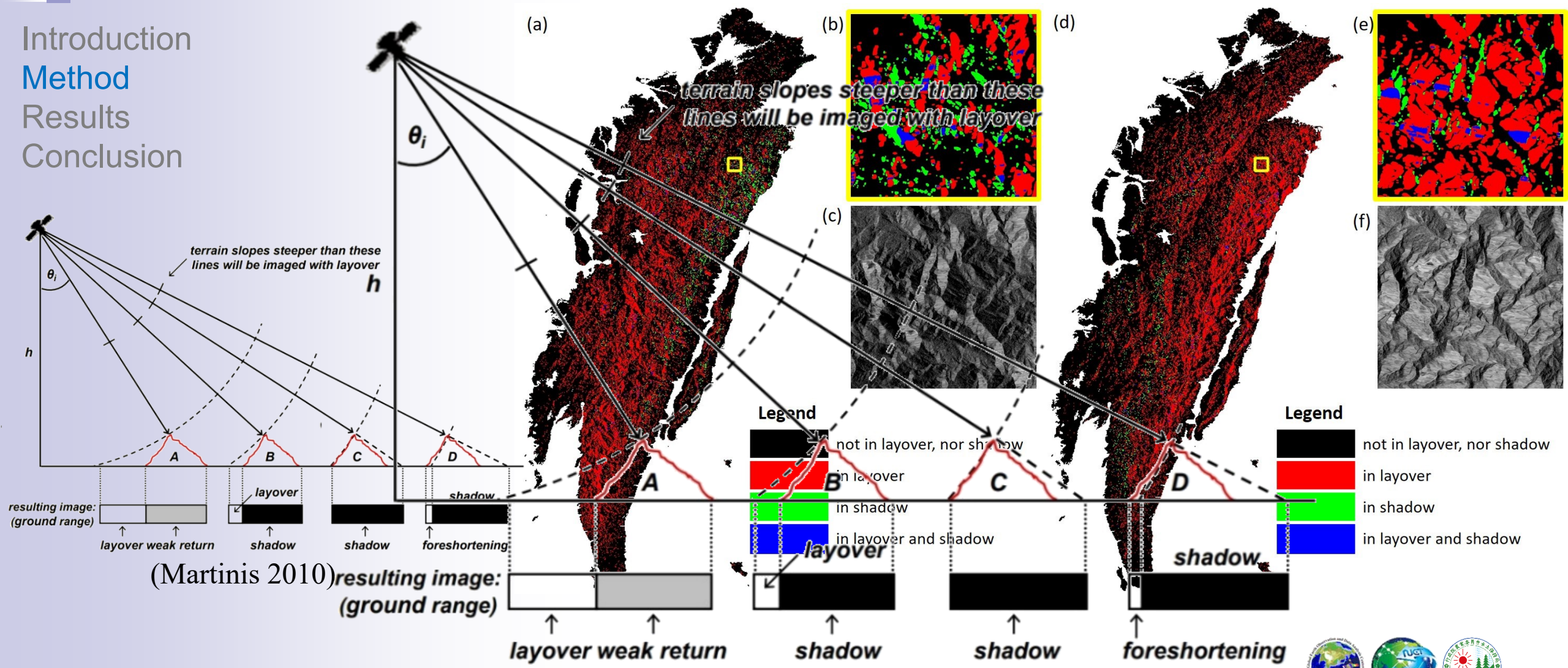
$$Q_{m,n} = P_{m,n} + R_{m,n}.$$

$$R_{m,n \to i,j} = Q_{m,n} \times F_{m,n \to i,j}$$

$$F_{m,n \to i,j} \equiv \frac{G_{m,n \to i,j}}{\sum G_{m,n \to i,j}},$$

*** Liu, C.C., Luo, W., Chen, M.C., Lin, Y.T. and Wen, H.L. (2016) A new region-based preparatory factor for landslide susceptibility models: the total flux. *Landslides*.**

Limitations of radar satellite imagery



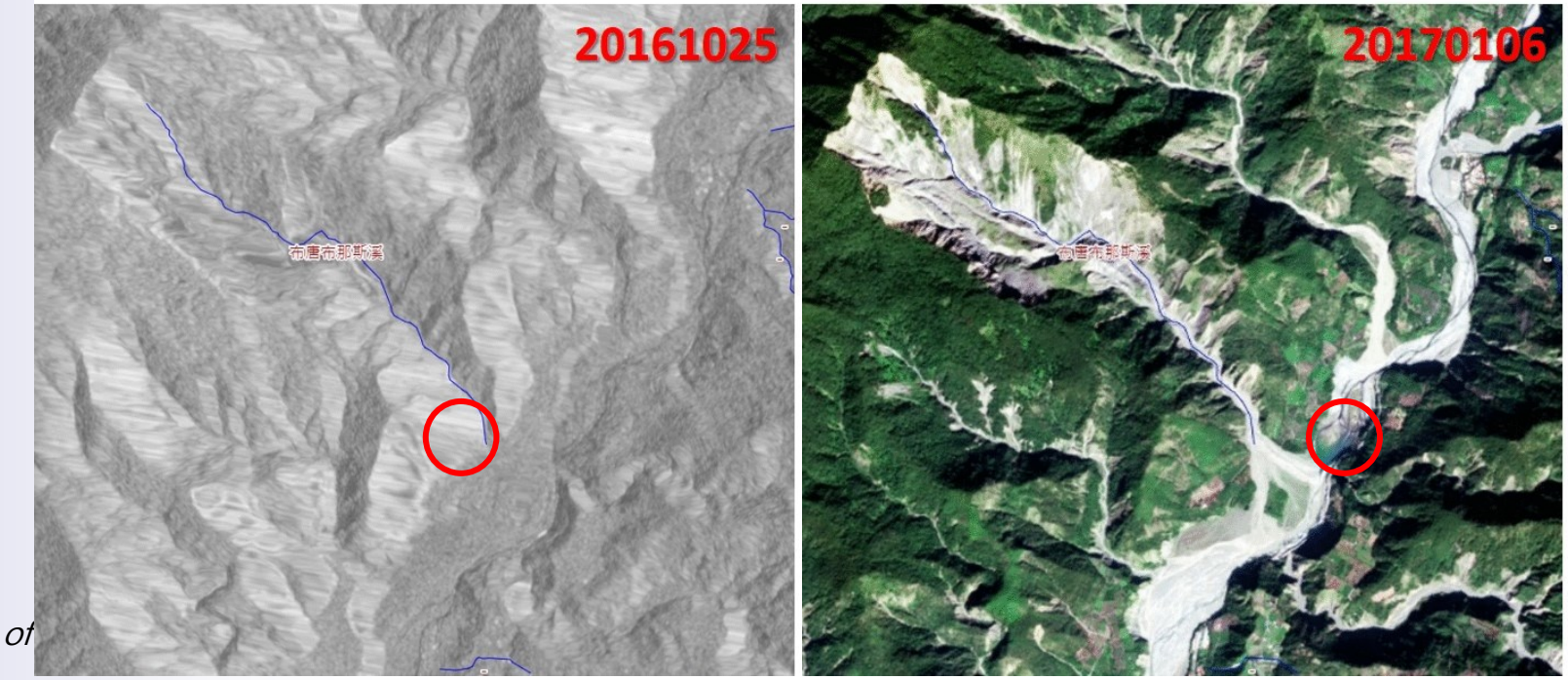
(Martinis 2010)

Results of historical case studies

- 2016 Barrier lake in Shangde Village
- 2017 Barrier lake in the Laonong River
- 2019 Barrier lake in the Zhile River
- 2020 Barrier lake in Enshi City, Hubei Province, China
- 2021 Barrier lake in the Beinan River
- 2022 Barrier lake in the Nanao South River

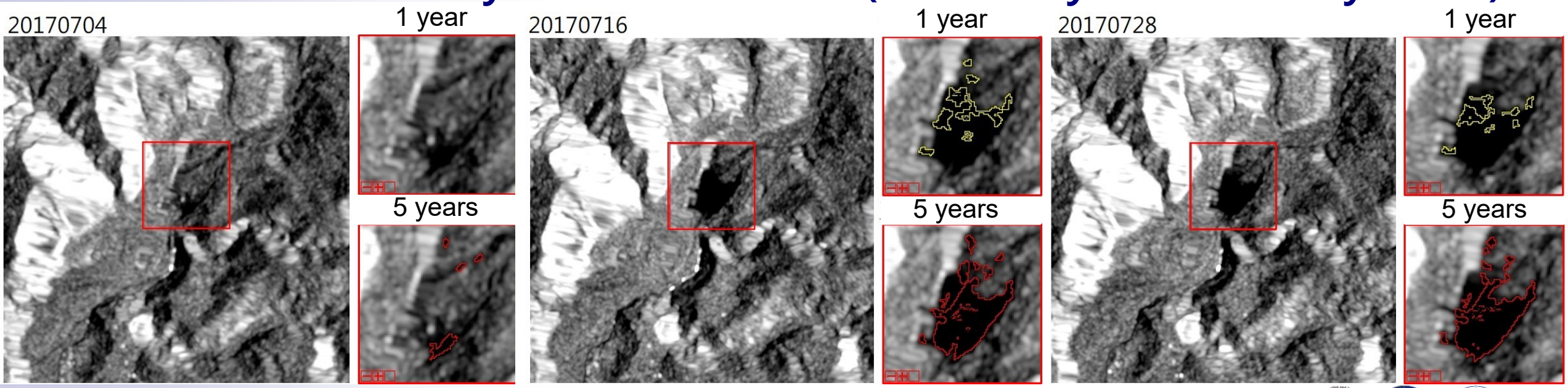
2017 Barrier lake in the Laonong River

- Located at the confluence of the Laonong River and the Pu-Tun-Pu-Nas River, the Pu-Tun-Pu-Nas River often experiences debris flows during typhoons and heavy rains, obstructing the Laonong River and forming a barrier lake.

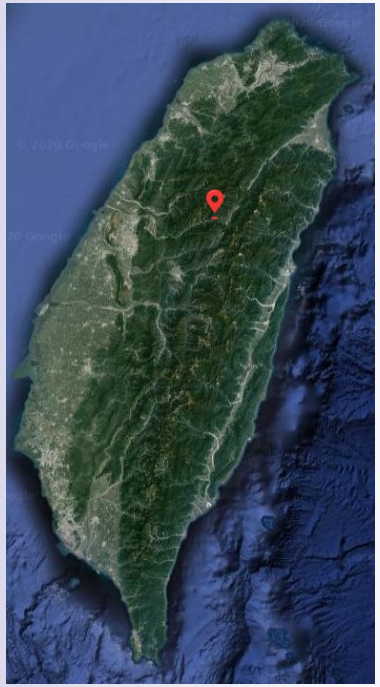


2017 Barrier lake in the Laonong River

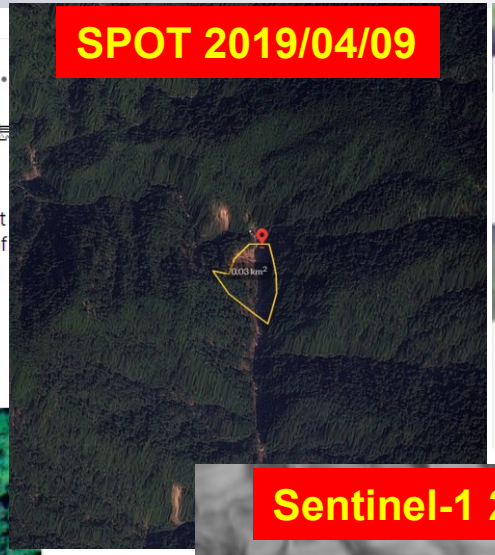
- Comparing the detection results of the one-year time series and the five-years time series.
  - one-year time series (From June 2016 to June 2017)
  - five-years time series (From July 2015 to July 2020)

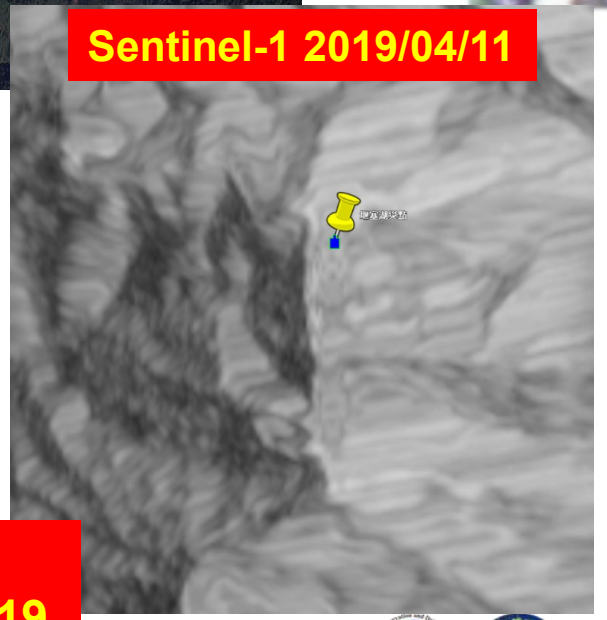


2019 Barrier lake in the Zhile River



Information provided by Face Book

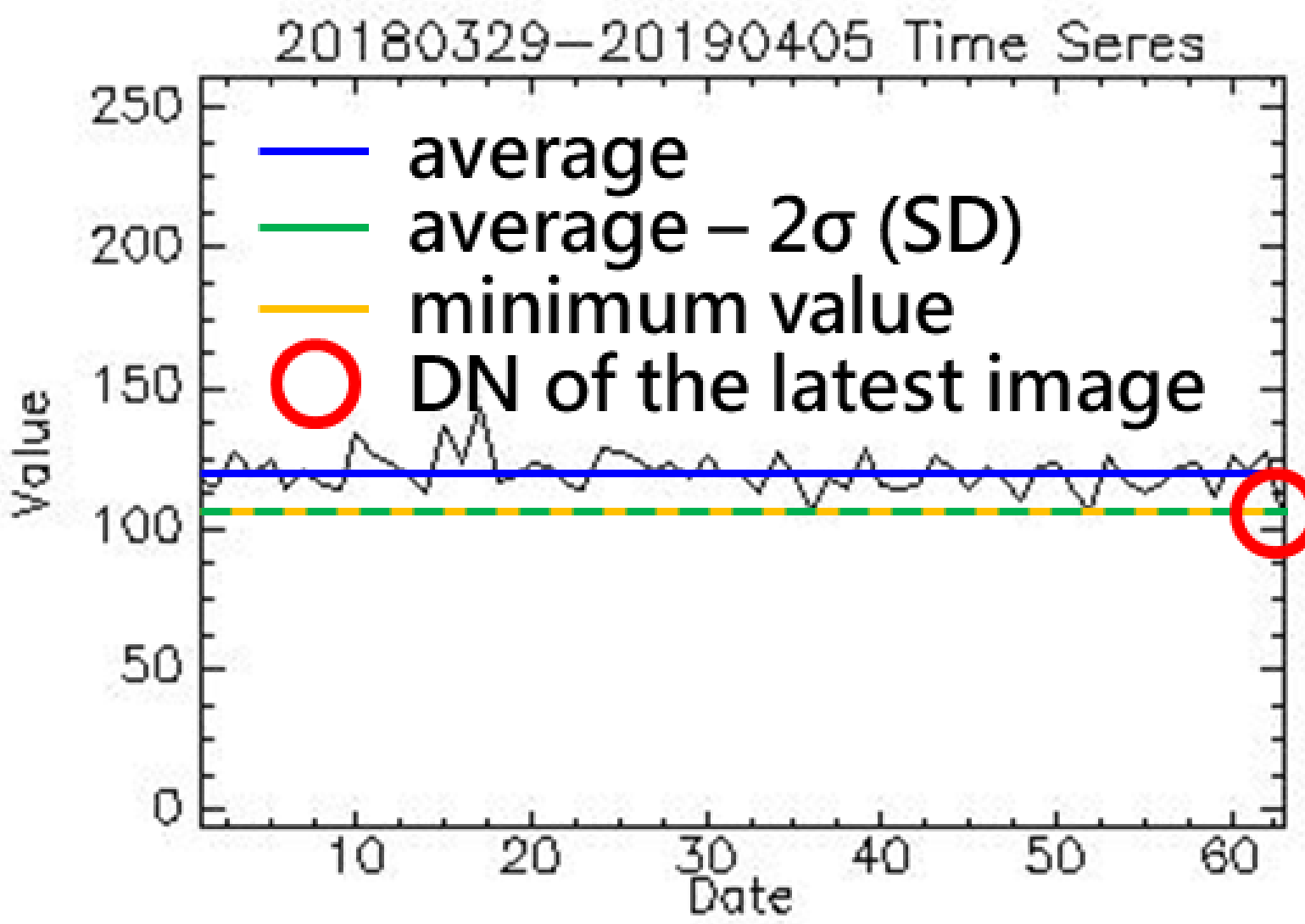


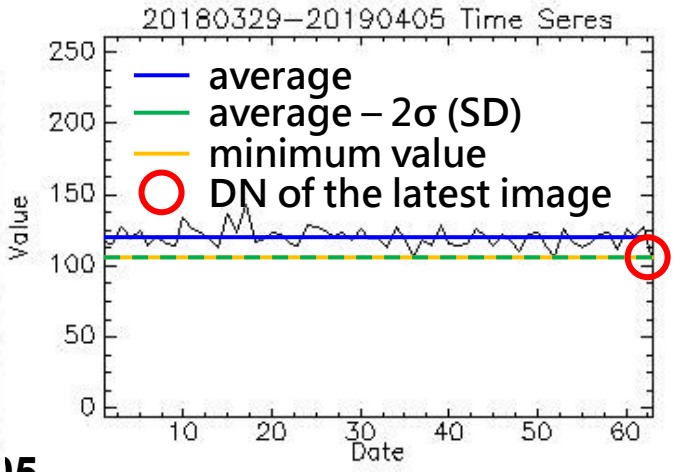


By using optical and radar satellite images, the date of the formation of the barrier lake was successfully traced back to between April 9th and 11th, 2019.

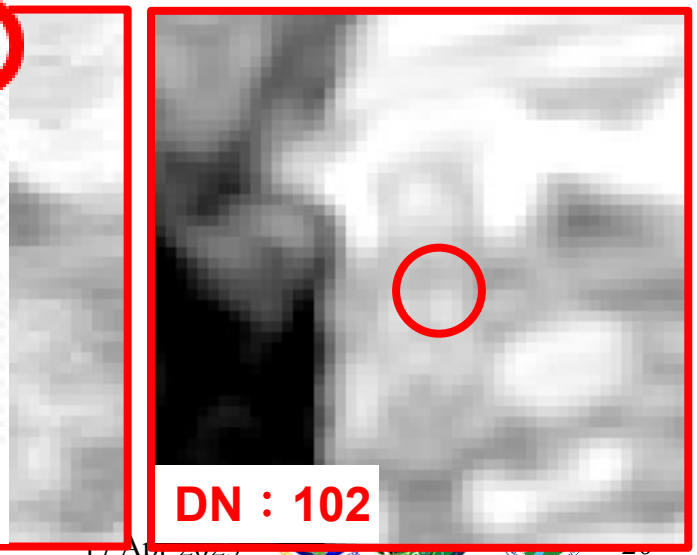
2019 Barrier lake in the Zhile River

using the detection technology developed in this study, the barrier lake information could be successfully extracted based on a threshold value.



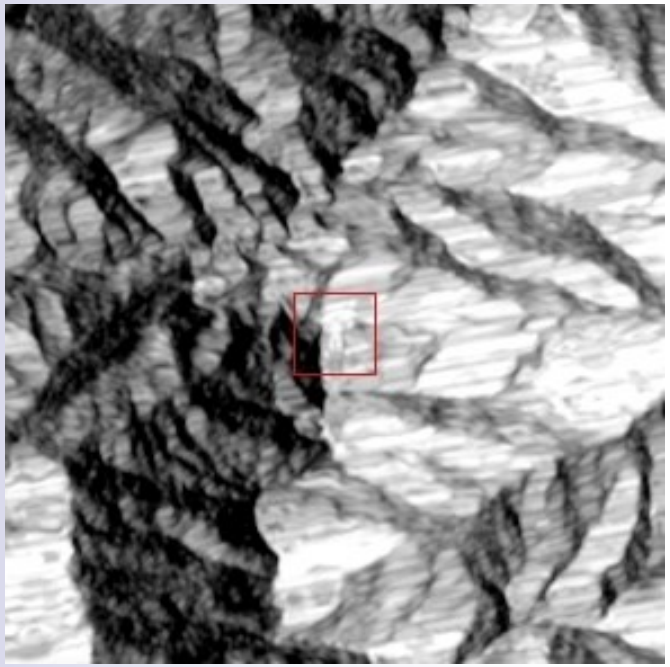


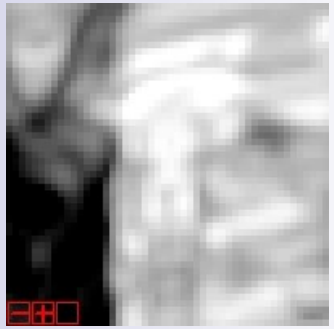
Monitoring date (20190411)



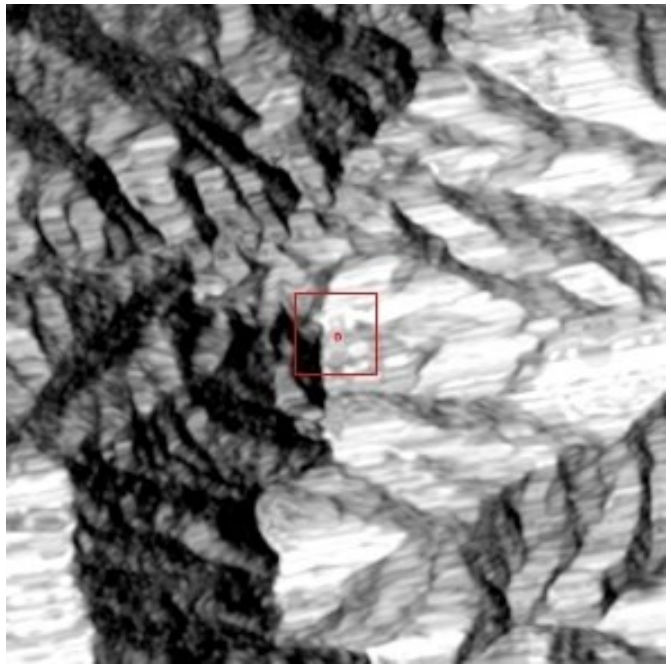
2019 Barrier lake in the Zhile River

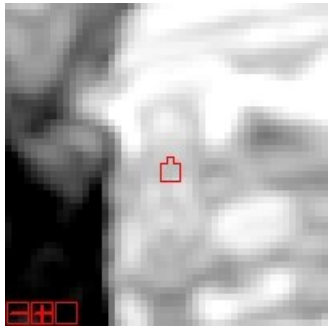
Before 20190405



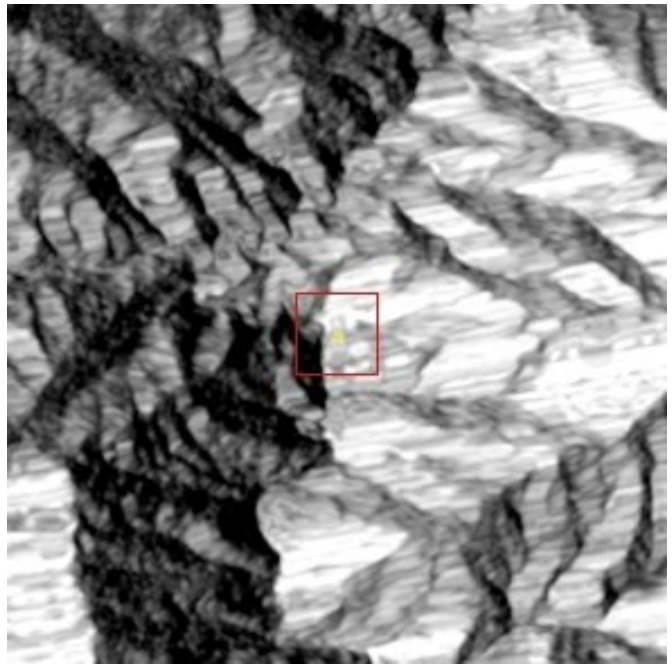


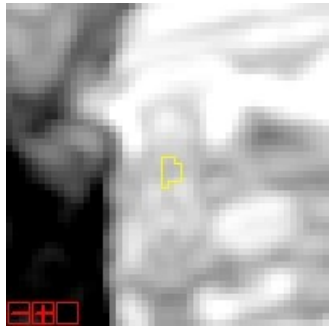
After 20190411 minimum



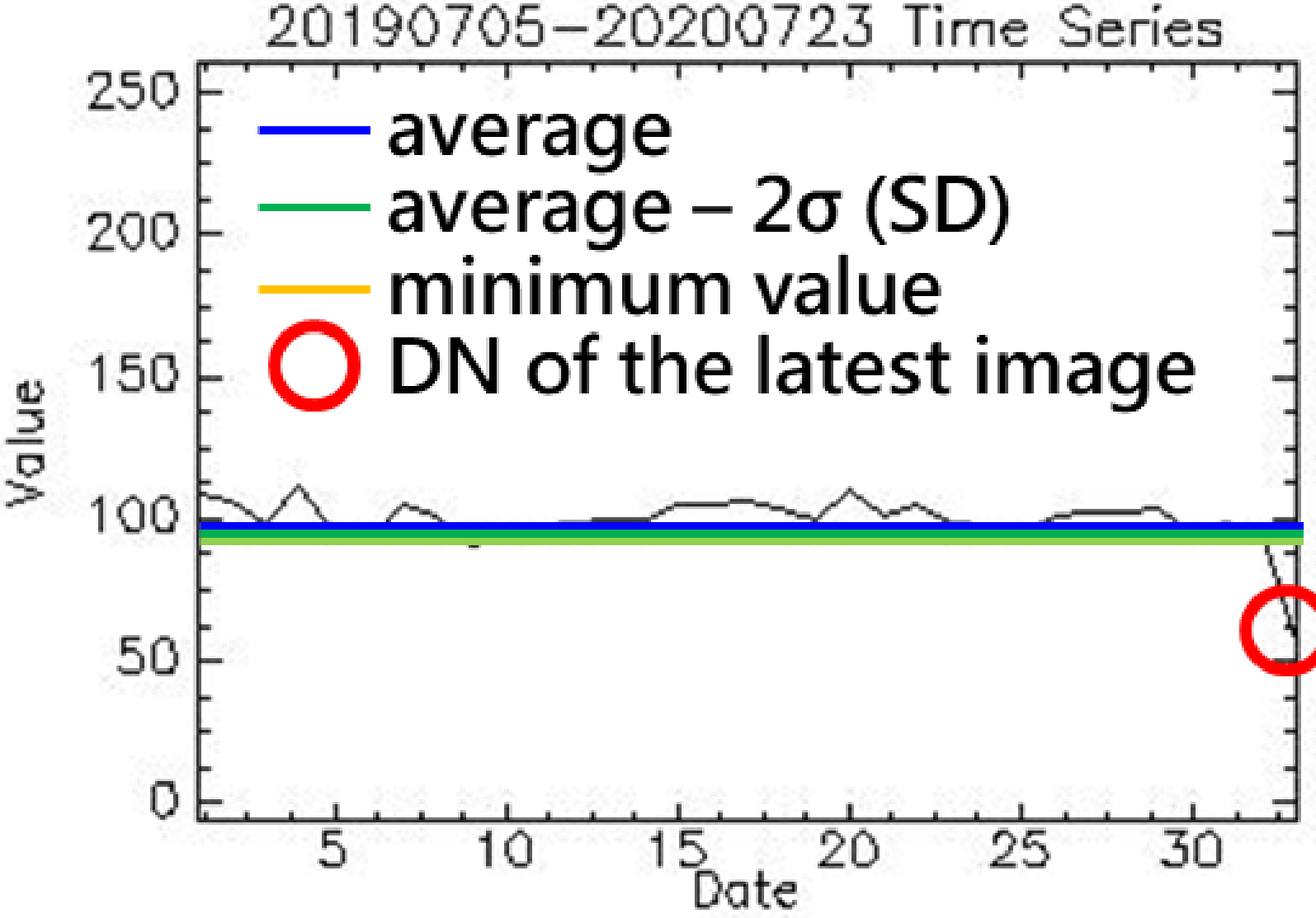


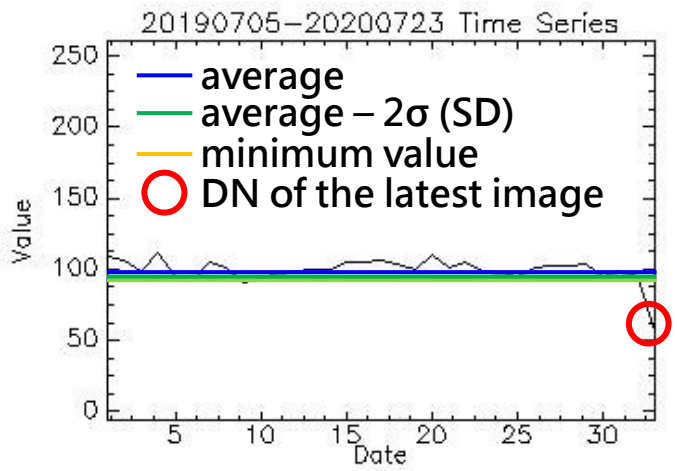
After 20190411 statistical



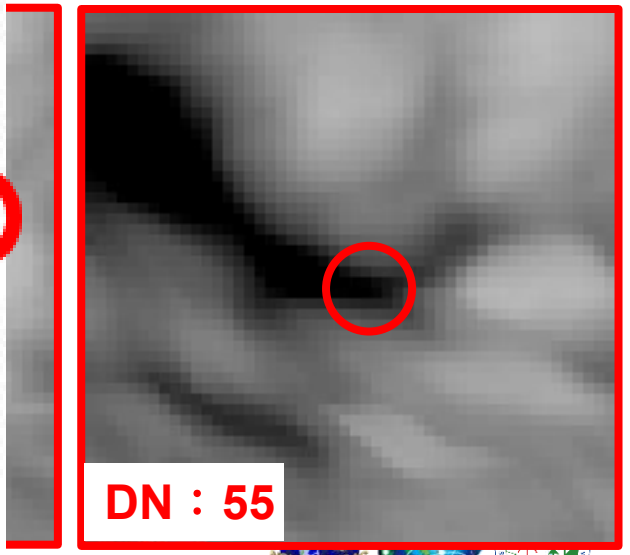


2020 Barrier lake in Enshi City, Hubei, China



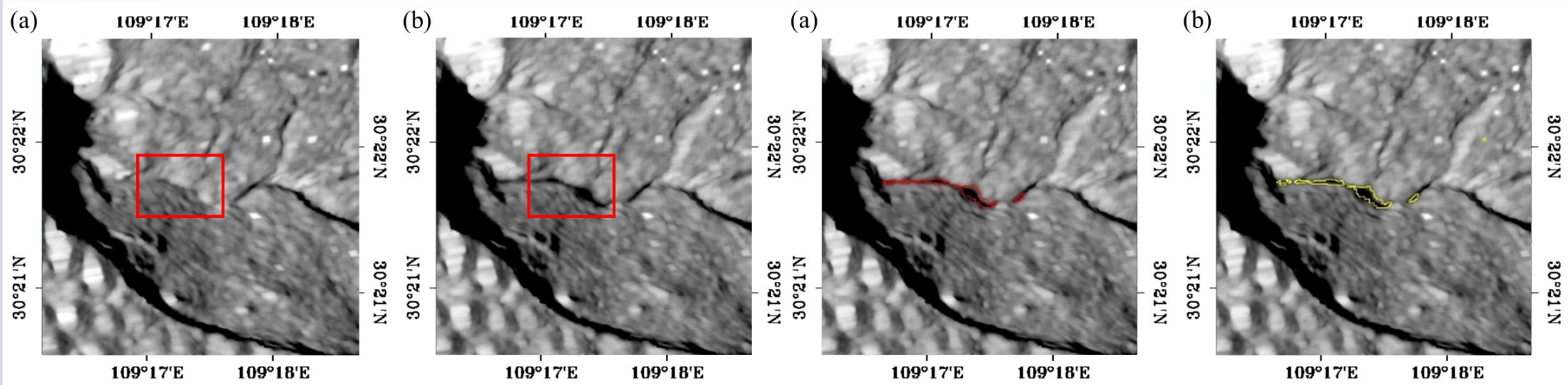


Monitoring date (20200723)



2020 Barrier lake in Enshi City, Hubei, China

http://www.xinhuanet.com/english/2020-07/21/c_139228978.htm

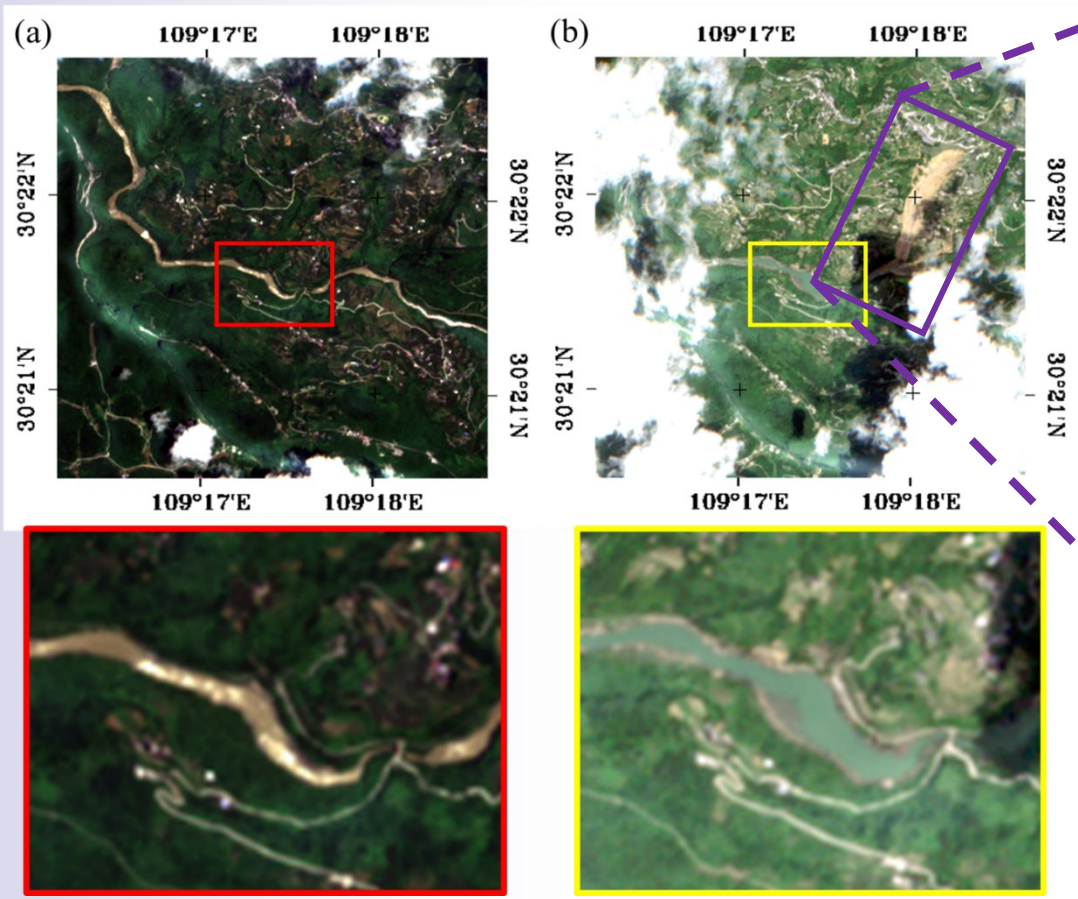


Through the Sentinel-1 images captured (a) before disaster on July 11, 2020, and (b) after disaster on July 23, 2020, it can be observed that the dark areas (water) have significantly expanded.

(a) The red region indicates the detection results using the minimum value threshold method, and (b) the yellow region indicates the detection results using the statistical threshold method.

2020 Barrier lake in Enshi City, Hubei, China

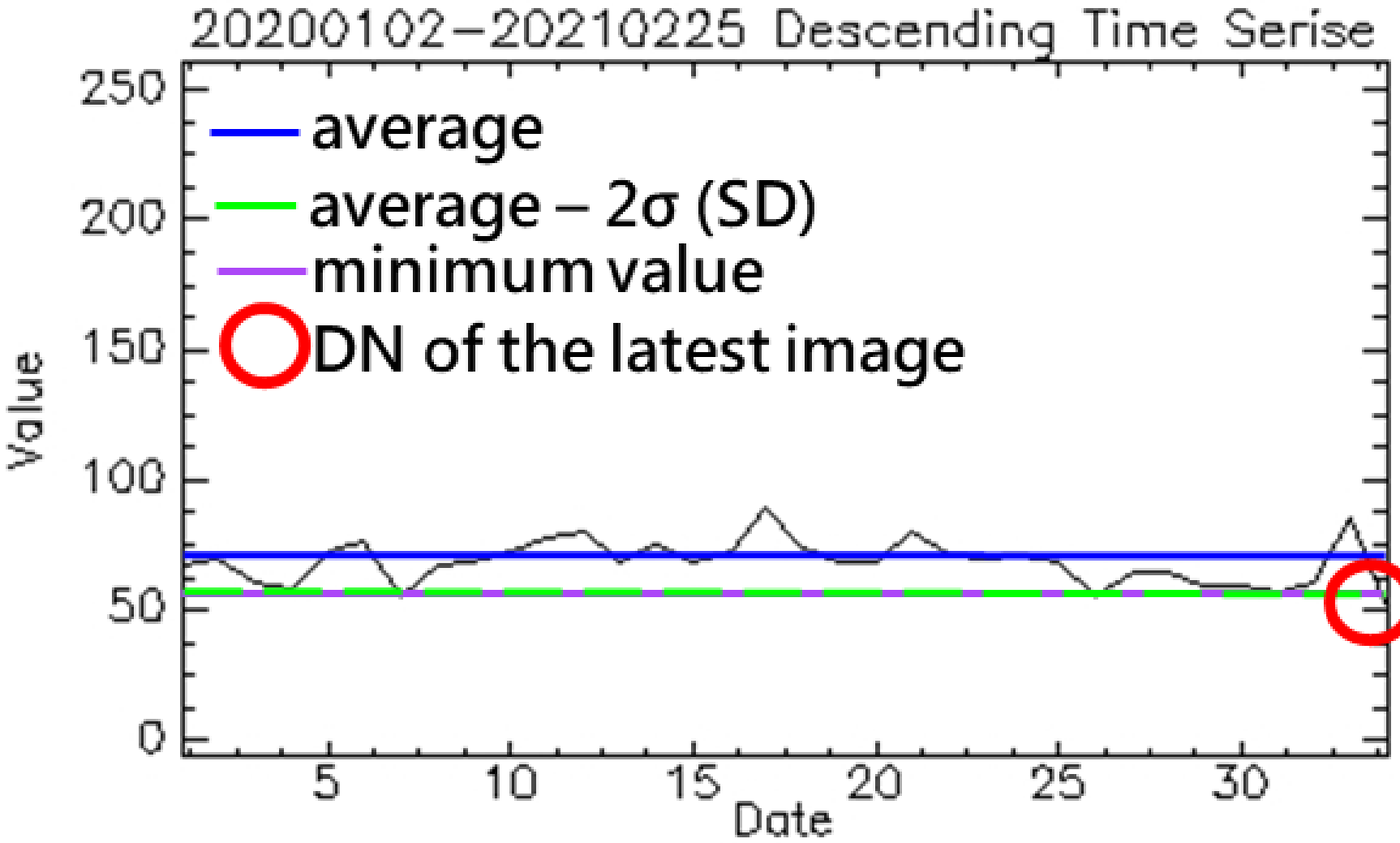
http://www.xinhuanet.com/english/2020-07/21/c_139228978.htm

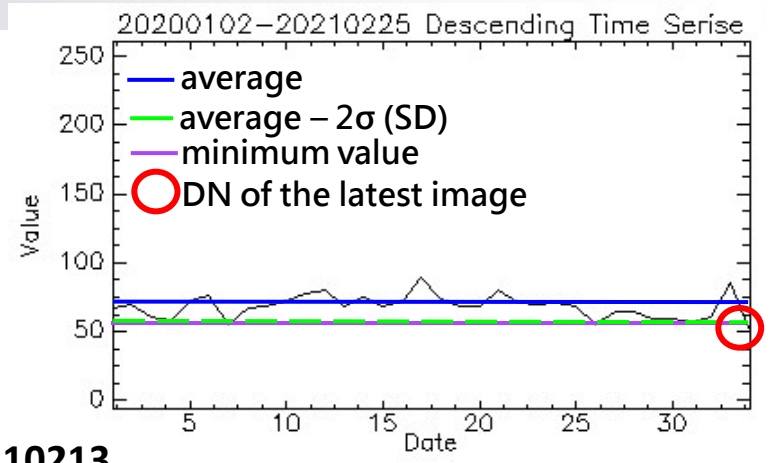


Through (a) Sentinel-2 before the disaster on July 9, 2020, and (b) after the disaster on August 3, 2020 (c) aerial image from a news report on Xinhua News Agency

Area of the barrier lake is approximately 2.5 hectares

2021 Barrier lake in the Beinan River

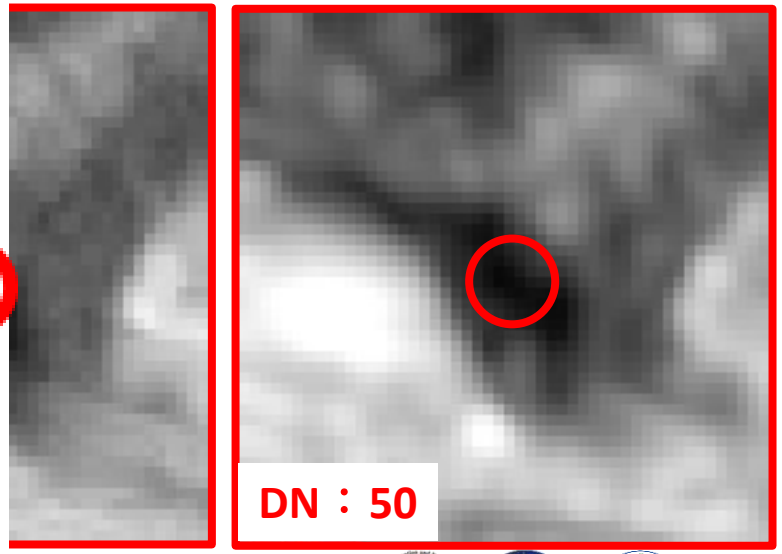




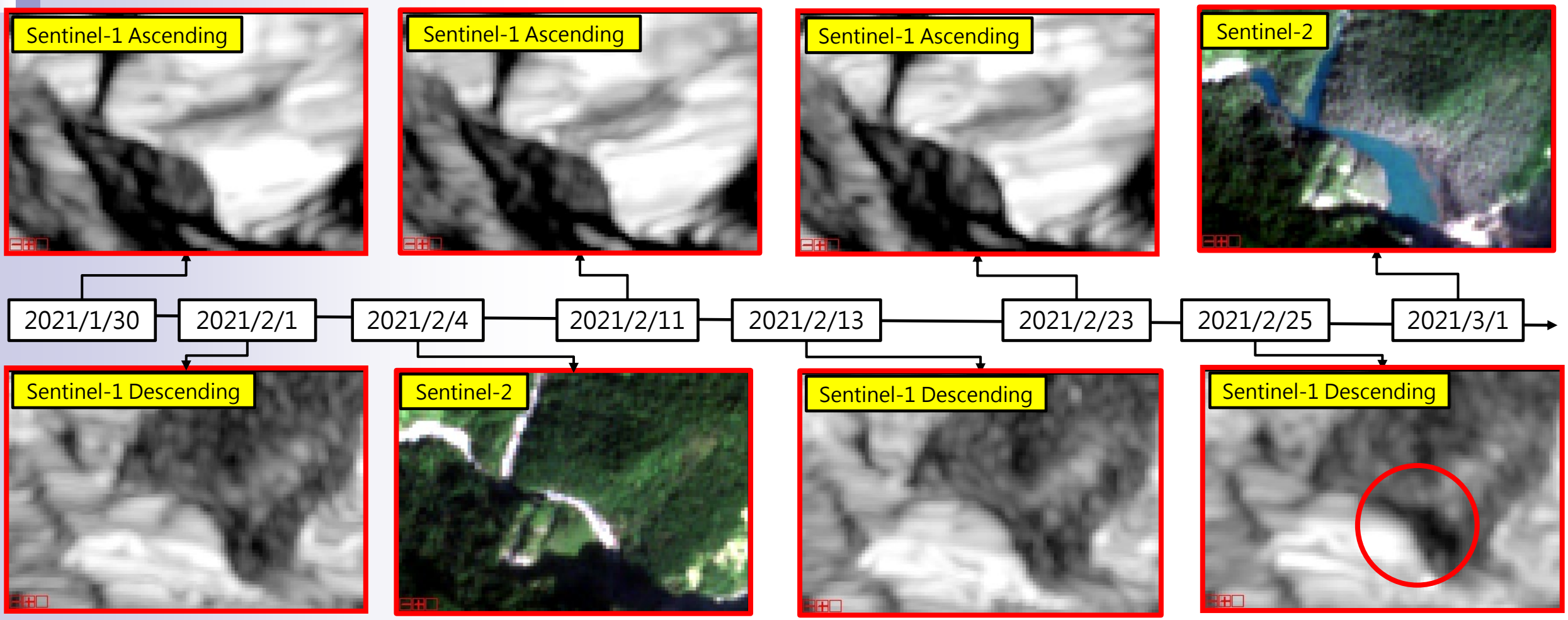
:10213

/alue

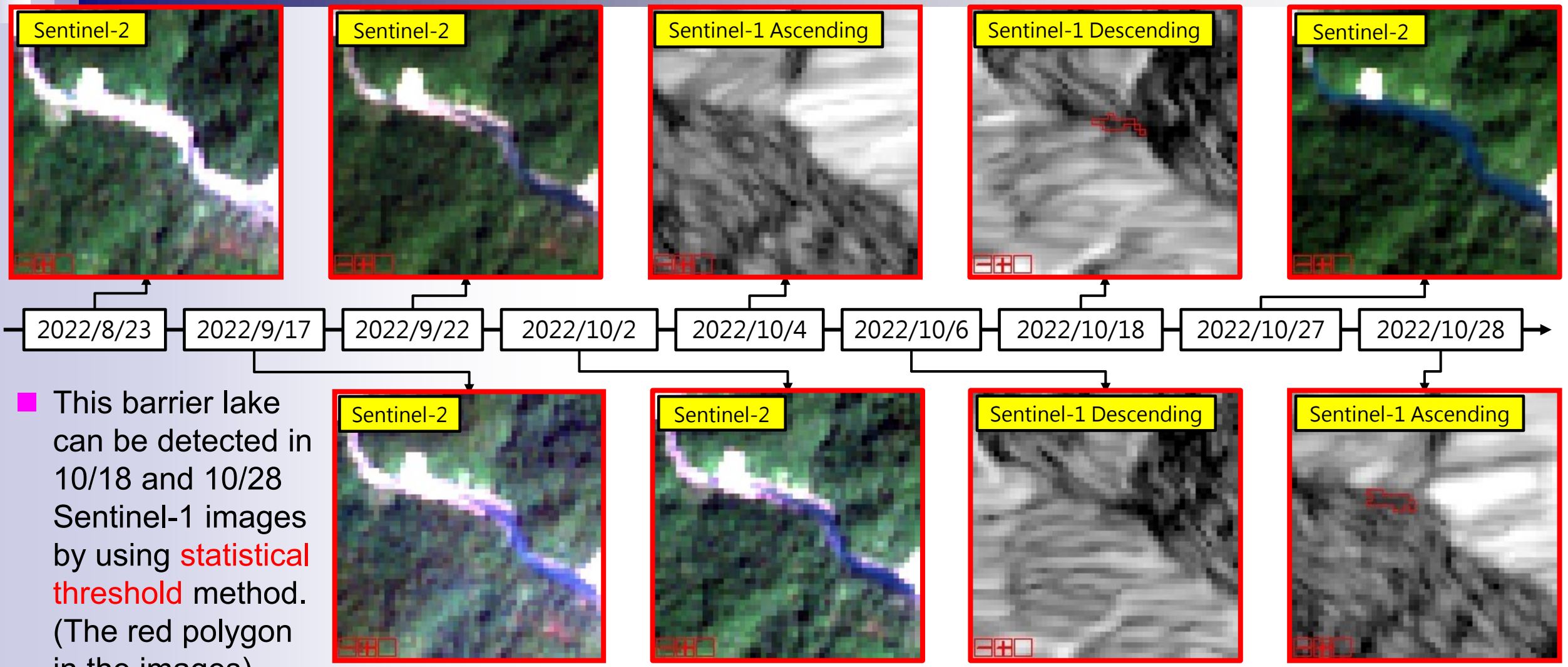
Monitoring date (20210225)



2021 Barrier lake in the Beinan River



2022 Barrier lake in the Nanao South River



- This barrier lake can be detected in 10/18 and 10/28 Sentinel-1 images by using statistical threshold method. (The red polygon in the images)

Conclusion

	Minimum Threshold Method	Statistical Threshold Method
Advantage	The sensitivity of water body extraction is high, because the DN values of the extracted pixels are all lower than the record in the past year.	It is less prone to the phenomenon of extraction passivation, and the reliability of the threshold will increase as the statistical time increases.
Disadvantage	With the elongation of statistical time, extraction passivation is prone to occur. For example, if the rainfall in the previous warning event was relatively high, the DN value (water body signal) of subsequent images would hardly be lower than the threshold, which may cause water bodies to be undetected.	The sensitivity of water body extraction is lower, and the area to be screened is relatively large, resulting in an increase in misjudgment rate.

The two methods of extracting water have their own advantages and disadvantages, and are currently used in parallel at this stage.

Conclusion

- Compared with the detection of flooding in plain areas, there is a blind spot in the application of radar images to the detection of barrier lakes, which is the influence of terrain.
- Referring to the relationship between the radar incidence angle and the terrain, there will be shadow areas on the image. If the barrier lake exists in the shadow area, it cannot be detected.
- It is recommended to refer to optical images for disaster assessment in disaster prevention.
- To improve the accuracy of detecting barrier lakes, this study will introduce data on historical landslides of river slopes in the future.

Thanks for your attention!

ご清聴(せいちょう)ありがとうございます

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2023.04.17.