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Evaluation of Cloud Masking Methods using Sentinel-2 Satellite Images on Google Earth Engine: A Case Study in Vietnam

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Abstract: The production of cloudless images from the optical satellite are critical in Earth surface monitoring. In 2015, Sentinel-2A was successfully launched into orbit by the European Space Agency. Sentinel-2 imagery is currently the primary source of data for Earth monitoring. There are several ways to create cloudless images from multi-temporal Sentinel-2 optical satellite imagery on the Google Earth Engine (GEE) platform. These include the Fmask (Function of mask) method, the Fmask CDI (Cloud Displacement Index) method, and the Fmask CSP (Cloud Score Plus) method. In this paper, the authors build a program and evaluate the cloud masking methods on the GEE platform in Song Hinh district, Phu Yen province, which is situated in the South-Central Coast region of Central Vietnam. The Song Hinh district is a suitable study area for the evaluation of cloud masking methods on optical satellite images due to its diverse and complex terrain, which includes numerous peaks and valleys and a variety of climatic conditions. This article illustrates the results of three cloud masking methods on Sentinel-2 images. In contrast to the Fmask method, the Fmask CDI and Fmask CSP methods provide more benefits in detecting clouds and cloud shadows, resulting in more accurate outcomes.

Keywords: Cloud masking, cloudless, multi-temporal Sentinel-2 images, Google Earth Engine.

Introduction

The utilization of optical remote sensing data is important in creating maps, disaster monitoring, and studies of the Earth's surface. Conversely, optical imagery is affected by cloud cover and atmospheric conditions. Therefore, cloud cover is a big deal when optical data is used to continuously monitor land cover objects. Cloudless optical imagery is exceedingly rare in tropical monsoon regions like Vietnam, with an annual average of only one to two sequences and a cloud coverage rate of less than 10%. Therefore, it is essential to create cloudless imagery based on optical satellite data in order to provide effective support for Earth monitoring.

Current cloud masking methods typically involve two primary processing steps: (1) Identifying the positions of clouds and cloud shadows on the image; and (2) Replacing the cloud and cloud shadow positions with cloudless pixels from images that were taken in close proximity to the test time. The application of cloud masking methods to Landsat imagery has been investigated and implemented (Zhu et al., 2015; Candra et al., 2017; Xiaolin et al., 2012). Additionally, studies and evaluations are currently ongoing regarding cloud masking for Sentinel-2 imagery (Zhu et al., 2015; Frantz et al., 2018; Cilli et al., 2020). The MCM (Multi-temporal Cloud Masking) method has been successfully implemented in a various climatic and terrain conditions (Candra et al., 2017; Mateo-García et al., 2018). This method utilizes multi-temporal imagery. Cloud masking is improved in satellite imaging based on how well the cloud and cloud shadow detection methods work. There are numerous cloud/cloud shadow detection algorithms, such as the Fmask algorithm (Zhu et al., 2015), the ACCA (Automatic Cloud Cover Assess-ment) algorithm (Scaramuzza et al., 2011), the thresh holding algorithm (Candra et al., 2017), and the ATSA (Automatic Time-Series Analysis) algorithm (Zhu and Helmer, 2018). Furthermore, the cloud and cloud shadow detection algorithms employ machine learning techniques (Francis et al., 2019; Cilli et al., 2020; López-Puigdollers et al., 2021). Cloud masking solutions are reviewed by scientists according to their targeted applications. However, in order to facilitate land cover analysis and monitoring, particularly in Vietnam, it is imperative to assess cloud detection algorithms that are capable of detecting clouds and cloud shadows in mountainous and water-shaded regions. Additionally, in order to prevent substantial image modifications, the number of multi-temporal images employed should be minimized.

The Google Earth Engine (GEE) platform is a cloud-based and web-based platform that enables the analysis and utilization of geospatial data in large-scale formats, including Landsat, Sentinel-2, and Sentinel-1 imagery, on a global scale (Gorelick et al., 2017). Furthermore, GEE is developed as an API (Application Programming Interface) application that supports data analysis through the use of Python or Java. A number of cloud masking algorithms have been evaluated on the GEE platform, and numerous researchers and developers are currently using this platform to study and create new cloud masking approaches (Mateo-García et al., 2018; Schmitt et al., 2019).

In this study, we evaluated several cloud masking algorithms for Sentinel-2 imagery using the GEE platform. We simultaneously tested the Fmask (Function of mask) method, Fmask CDI (Cloud Displacement Index), and Fmask CSP (Cloud Score Plus) on multi-temporal Sentinel-2 images on the GEE using in Vietnam's Song Hinh district, Phu Yen province.

Materials and Methods

Study Area

The Song Hinh district is a mountainous region situated in the southwest of Phu Yen province, Vietnam (Fig. 1a). The center of study area is located at coordinates 12^{0}59N and 108^{0}52E (Fig.1b). The terrain in the Song Hinh area is extremely divided, consisting of numerous medium-high hills and mountains that gradually descend in the south-north and west-east directions. In the study area, there are three primary terrain types: low valley terrain along the Ba and Hinh rivers, with an elevation of 30-100 m; low mountainous terrain with an average altitude of 100-400 m; and ordinary mountain terrain with an elevation of 500-800 m (Department of Science and Technology of Phu Yen province, 2015). A mountainous terrain that is 800-1,528 m high and strongly divided is located to the southeast of Song Hinh district. This terrain is the beginning of rivers, streams, and natural forests. The Song Hinh district has numerous rivers and streams as a result of the high density of mountains. The monsoon climate is characterized by high temperatures and high humidity. An average annual temperature of 25°C is observed. The humidity level is quite high, at 82% and the annual precipitation ranges from 2,200 to 2,400 millimeters (Department of Science and Technology of Phu Yen province, 2015). The Hinh River region is situated in the damp region of Phu Yen province. Additionally, Song Hinh district comprises 38.9% forest land (Phu Yen Statistic Office, 2022). As a result, the Song Hinh district is well-suited for evaluating the efficacy of cloud masking methods because of its numerous suitable topographical and climatic characteristics.

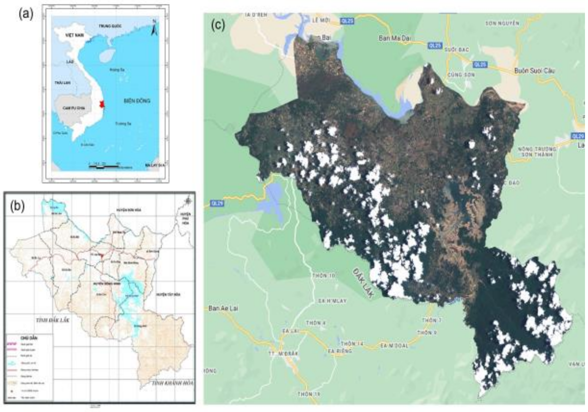

Fig. 1 Phu Yen Province (**a**); Song Hinh District (**b**); Sentinel-2 image with Cloud Cover < 20% (**c**).

Data Collection

The Sentinel-2 images that were selected are Level-2A processed data. The Level-2A data has been orthorectified to the UTM/WGS84 coordinate system with 49N zone. The spectral radiance values in these images have been converted to surface reflectance values. The ground resolutions of Level-2A products are standardized to be 10 m, 20 m, and 60 m, depending on the image band. The test image data was obtained from the Google Earth Engine data repository and downloaded from January 1, 2021, to January 1, 2022 (Fig. 1c).

Cloud masking process

The method for identifying clouds and cloud shadows in Sentinel-2 images is predicated on the spectral reflectance characteristics of cloudy and non-cloudy regions across various image bands (Fig. 2).

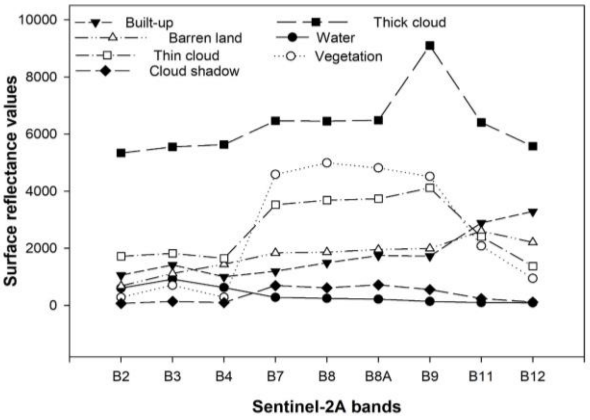

Fig. 2 Surface reflectance values of clouds and non-clouds on Sentinel-2 Images.

The spectral reflectance values of thick clouds are significantly higher than those of other objects, and they reflect powerfully across all bands. Thin clouds display a high degree of reflectance in the water vapor band (B9-Water vapor) and the Near-Infrared (NIR) bands (B7, B8, B8A). In comparison to other non-cloudy objects, cloud shadows exhibit low reflectance values in the B2 (Blue), B3 (Green), and B4 (Red) bands. The reflectance characteristics of cloud shadows are comparable to those of barren land. However, the spectral reflectance values of cloud shadows are low, similar to those of water reflection. Bare soil and other objects exhibit extremely high spectral reflectance values at the Short-wave infrared (SWIR) wavelengths (B11 and B12), whereas cloud estimates exhibit extremely low reflectance values.

This study will employ multi-temporal Sentinel-2 data stored on the GEE platform to demonstrate cloud masking approaches. The GEE platform will carry out the processing steps for cloud detection, cloud shadow detection, and cloud masking in accordance with the flowchart depicted in Figure 3.

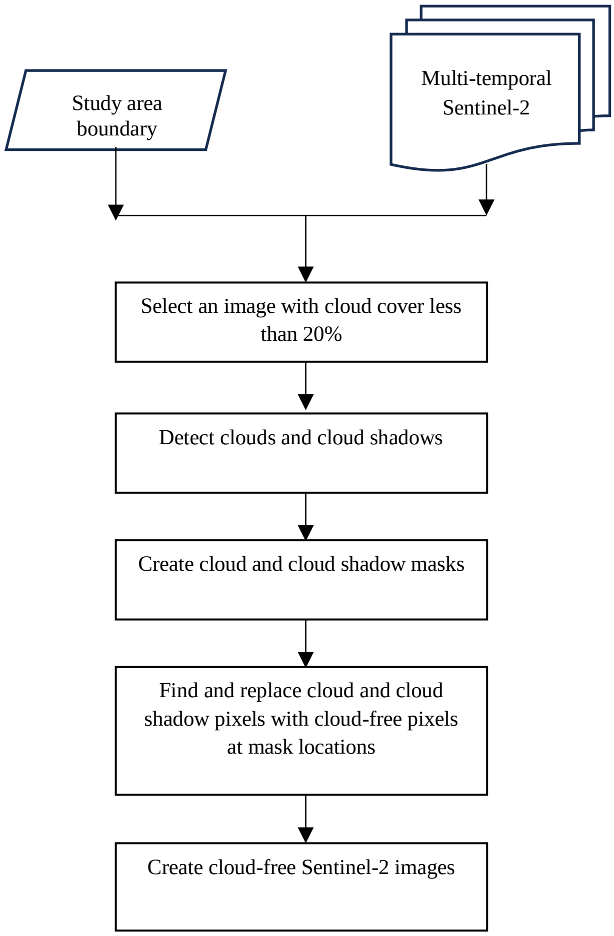

Fig. 3 Cloud Masking Process Using Multi-Temporal Sentinel-2 Images on GEE.

The cloud masking program using multi-temporal Sentinel-2 satellite images on the GEE platform consists of three main steps:

1. Detect clouds and cloud shadows using Fmask, Fmask CDI, and Fmask CSP algorithms.
2. Create a mask of clouds and cloud shadows.
3. Replace the pixels in the cloud and cloud shadow mask regions with cloudless pixels from multi-temporal Sentinel-2 images. This results in cloudless Sentinel-2 images

Fmak cloud masking

Clouds are pixels with a cloud probability higher than 99%, as defined by the Fmask (Function of mask) method (Zhu et al., 2015). For Sentinel-2 data, the Fmask method depends on cloud information that is contained in the QA60 band of the Sentinel-2 image data file on GEE. The QA60 band is a quality assessment band that provides encoded bit values that illustrate the attributes and quality conditions of each pixel in the image. The QA60 band in Sentinel-2 images contains data on factors such as fog, cirrus clouds, clouds, sun angle, snow and ice cover, and other elements that may impact the quality and reliability of the image.

The QA60 band is typically employed to identify pixels that are obscured by clouds, cirrus clouds, or other undesirable factors when the Fmask method is employed to perform cloud masking. A mask is subsequently generated to cover the pixels in the input image that are obscured by clouds and cirrus clouds. The Fmask method employs two bits in the QA60 band to identify pixels that are obscured by clouds and cirrus clouds (specifically bits 10 and 11).

The Fmask method consists of the following main steps:

1. Select the QA60 band from the input image, which contains information on cloud and atmospheric conditions.
2. Define bitmasks to identify cloud and cirrus cloud pixels from the QA60 band information.
3. Create a mask by combining the two bitmasks (bits 10 and 11) for cloud and cirrus cloud pixels.
4. Apply the mask to the input image.
5. Divide the pixel values by 10,000 to convert them back to their original reflectance values.

Fmask CDI (Cloud Displacement Index)

The Fmask-CDI method is an improved version of the Fmask cloud masking method, which includes an additional Cloud Displacement Index (CDI) defined by Equation (1) (Frantz et al., 2018):

$$CDI = (V_{8A,8} - V_{8A,7}) / (V_{8A,8} + V_{8A,7}) \qquad (1)$$

Where: $V_{8A,8}$, $V_{8A,7}$ are the surface values determined from the corresponding near-infrared (NIR) band ratios $V_{8A,8} = B_8/B_{8A}$ and $V_{8A,7} = B_7/B_{7A}$. Bands B_8, B_{8A}, and B_7 are near-infrared bands of Sentinel-2.

This technique is employed in the processing of remote sensing images to detect and eliminate clouds. The CDI index is determined by the displacement of clouds between successive images of the same region. By comparing these changes, CDI is able to detect and mask clouds from the images (Frantz et al., 2018). CDI is typically calculated from Sentinel-2 image datasets on the Google Earth Engine platform using previous algorithms, such as *ee.Algorithms.Sentinel2.CDI()*. The pixels that are impacted by clouds are typically labeled and can be masked during the development of composited images or other analyses after CDI is applied. The Fmask CDI method enhances the detection of clouds by utilizing the parallax phenomenon of NIR bands of Sentinel-2 images as bands B_8, B_{8A}, and B_7 (Frantz et al., 2018). The parallax between the NIR bands is determined by the viewing angle in order to obtain a reliable separation between the surface and clouds in Sentinel-2 data. This is primarily employed to locate low-level clouds and objects on the ground that are obscured by low-level clouds. In addition, it compensates for the absence of thermal infrared bands in Sentinel-2 data. Additionally, this technique employs the *directional Distance Transform()* function, a built-in function on GEE, to calculate cloud shadows in order to enhance filtering capabilities. The following are the five primary steps in the Fmask CDI method:

1. Select input image datasets:
    - Copernicus/S2
    - Copernicus/S2_Cloud_Probability
    - Copernicus/S2_SR
2. Calculate indices:
    - Cloud Displacement Index (CDI)
    - Cloud Probability
    - Cirrus Value (B10)
3. Create Cloud Mask. Identify cloud pixels based on the following conditions:
    - Cloud probability greater than 65% and CDI less than -0.5.
    - Cirrus value greater than 0.01.
    - The cloud mask is a combination of one or both conditions.
4. Refine the cloud mask.
5. Predict cloud shadows by calculating the cloud shadow direction using the solar azimuth angle.
6. Create a cloudless image by searching for cloudless pixels within the cloud mask.

Fmask CSP (Cloud Score Plus)

Inspired on the original Cloud Score method, Cloud Score Plus (CSP) is a sophisticated method in GEE enhanced to offer more precise cloud probability estimates (Pasquarella et al., 2023). In order to comprehend CSP, it is necessary to examine both the original Cloud Score method and the enhancements that have been implemented in CSP. The SimpleCloudScore algorithm (Candra et al., 2017) was initially employed to detect clouds in the original Cloud Score method, which was tested on Landsat images. The method selects image bands that correspond to the spectral reflectance characteristics of clouds. In optical images, clouds are typically white, brilliant, and moist. Cloud objects are identified by examining the cloud score image. Initially, a value of 1 is allocated to each pixel values. Using the Equation (2), the cloud score image is determined:

$$S = \min\left(\max\left(\frac{S-a}{b-a},0\right),S\right) \tag{2}$$

Where S is the current cloud score image that is defined within the range [a, b]. The bands used to determine the cloud score on Sentinel-2 images include B2 (Blue band) with a threshold of [0.1, 0.5]; B1 (Aerosol band) with a threshold of [0.1, 0.3]; B10 (Cirrus+Aerosol band) with a threshold of [0.5, 0.7]; B4, B3, B2 (Red, Green, and Blue bands) with a threshold of [0.2, 0.8]; B8, B11, B12 (NIR, SWIR1, and SWIR2 bands) with a threshold of [0.3, 0.8]; NDMI (Normalized Difference Moisture Index) with a threshold of [-0.1, 0.1]; and NDSI (Normalized Difference Snow Index) with a threshold of [0.8, 0.6]. The authors used a morphological algorithm with a radius of 1.5 to 3 pixels to eliminate single pixels on the cloud score image. The global thresholding method and mask creation, with a threshold range of [0, 1], guided the selection of cloud locations on the cloud score image.

The CSP method was created to overcome some of the constraints of the original Cloud Score technique. To identify clouds and cloud shadows in satellite images, CSP employs machine learning models and more intricate principles that are influenced by a variety of factors, including color, brightness, and image structure. The CSP method helps to precisely identify and remove areas covered by clouds or cloud shadows by providing a cloud probability score for each pixel.

The "Cloud Score+ S2_HARMONIZED V1" dataset is recommended for use in the CSP method by GEE. This is a dataset or version of the CSP method that is intended to identify and filter clouds from processed and harmonized Sentinel-2 data. Clouds are typically identified and concealed in this version through the use of a variety of indices and specific bands, which enables the development of cloudless composites.

The main steps in the CSP method are as follows:

1. Select the input image data.
2. Choose the CS band (Band CS): "CS" may represent a specific band in the remote sensing data, such as a band containing cloud probability information (Cloud Score). The CS band typically assigns a value to each pixel, indicating the likelihood of cloud coverage or another image quality index.
3. Select the CS_CDF band (Band CS_CDF): "CS_CDF" may represent the CS band's cumulative distribution function (CDF). The

cumulative distribution function represents the cumulative probability of a certain value in a data series. In this case, it may represent the cumulative probability of values in the CS band.

4. This study uses both the CS band and the CS_CDF band to compare differences, choosing a threshold of 0.6 to create the cloud mask.
5. Next, use the *link Collection()* function to merge Cloud Score+ bands from the Cloud Score+ collection, and then apply a function to create a binary mask for each image based on the chosen Cloud Score+QA threshold value.
6. Create the cloudless Sentinel-2 image.

Results and Discussion

The study evaluated three cloud masking algorithms (Fmask, Fmask CDI, and Fmask CSP) to produce cloudless Sentinel-2 images. The data included Sentinel-2 images with a cloud cover of less than 20% from January 1, 2021, to January 1, 2022. Figure 4 illustrates the results by displaying the input image (Sentinel-2 natural color composite), the detected clouds and cloud shadows, and the cloud-masking results.

The accuracy of the cloud masking algorithms was assessed using 200 randomly distributed check points, as illustrated in Figure 5.

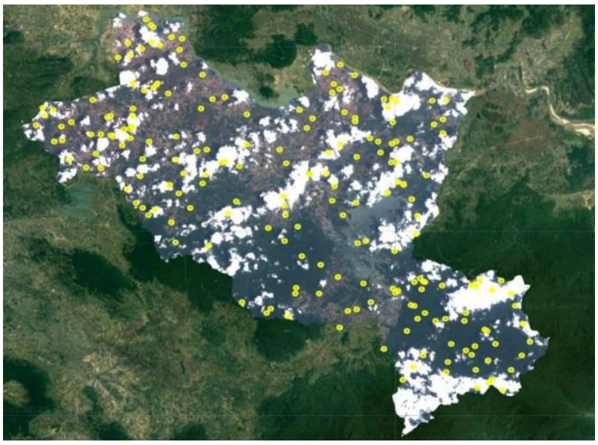

Fig. 5 The location of the checkpoints.

The outcomes of each approach (Fmask, Fmask-CDI, Fmask-CS, and Fmask-CDF) on cloud/cloud shadow detection images will be compared to the original image's visual interpretation at each checkpoint. The cloud masking algorithms accuracy will be assessed by utilizing the confusion matrix, Kappa index, and overall accuracy. The accurate assessment results are presented in Table 1.

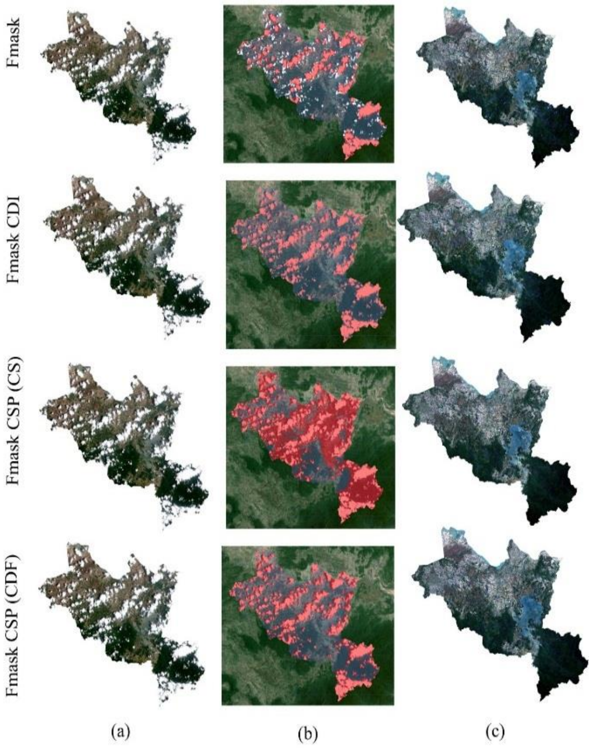

Fig. 4. Comparison of cloud masking results of the methods. (a) The original image; (b) The detected cloud and cloud shadows; (c) The cloud-masking results.

The Fmask-CDF method has the highest accuracy of 97%, as indicated by the results in Table 1. The accuracy of the Fmask technique is the lowest, at 81%. The accuracy of the Fmask CDI and Fmask CSP methods is comparable. In addition, the experimental results illustrated in Figure 4 indicate that the cloud masking algorithms accuracy is comparable to the results presented in Table 1.

Table 1. The assessment of the accuracy of cloud/cloud shadow detection methods using the checkpoints**.**

Methods	Fmask	Fmask CDI	Fmask CSP (CS)	Fmask CSP (CDF)
Kappa indexs	0.581	0.823	0.818	0.938
Overall accuracy	81%	91.5%	91.5%	97%

Cloud coverage is a significant concern in optical remote sensing because it obstructs continuous monitoring of the Earth's surface. In this study, we studied three cloud masking methods on Sentinel-2 satellite images in GEE, including Fmask, Fmask CDI, and Fmask CSP, and assessed their strengths and weaknesses in Table 2.

Table 2. Evaluation of the effectiveness of cloud masking methods on Sentinel-2 images.

	Fmask	**Fmask CDI**	**Fmask CSP**
Strengths	The proposed technique efficiently masks cloud and cirrus cloud pixels in Sentinel-2 satellite images, therefore allowing the creation of cloudless composite or single images. This approach is distinguished by its simplicity, clarity, and ease of use. The technology is highly efficient in processing images and enables direct downloading on GEE.	This method allows for cloud/cloud shadow identification. The use of CDI indices, cloud probability, and cirrus cloud values helps ensure accuracy in cloud/cloud shadow detection. Using the time series images increases the accuracy in cloud/cloud shadow detection and masking. This method includes an algorithm for calculating cloud shadows based on the solar azimuth angle, which aids in cloud shadow detection and masking. Compared to the Fmask method, the cloud/cloud shadow detection and masking capability is significantly higher.	This method allows for better cloud/cloud shadow detection compared to the Fmask and Fmask CDI methods. Machine learning on large image datasets improves the accuracy and clarity of cloud/cloud shadow classification and detection. The CSP method helps create cloudless images quickly. The image processing time for display on GEE is fast. The capability for cloud/cloud shadow detection and masking is higher compared to the Fmask and Fmask CDI methods. There are two bands available for masking clouds, depending on the study area.
Weaknesses	This method may not be effective in regions with a high cloud density, and cloud masking may not be able to detect and mask all cloud/cloud shadow pixels. Dividing pixel values by 10,000 may result in a loss of some detail in the reflectance data, especially in areas with low reflectance.	The method is complex and has a high level of difficulty. Processing time to display images directly on GEE is quite long, and it may not be able to display result images on machines with lower specifications. The method uses the *reproject* algorithm for reprojections of the image data, which slows down processing and consumes a lot of memory.	To make appropriate choices, selecting thresholds and bands for cloud masks necessitates substantial experience and empirical data.

Although all the applied methods showed effectiveness in cloud masking, Fmask demonstrated lower performance under testing conditions in the mountainous and highly fragmented terrain of Song Hinh district. Fmask calculates spectral variation, temperature, and cloud shadow probability to capture the "white," "cold," and "high" characteristics of clouds over land. It performs well with Landsat images, but it has issues with Sentinel-2 images. Sentinel-2 doesn't have any thermal bands, so it might not be able to see low-level clouds in the cirrus band or bright land surfaces. This is especially true for architectural structures that are often mistaken for clouds when only spectral information is used (Zhu et al., 2015).

On the other hand, the cirrus band is a water vapor absorption band, and higher altitudes correspond to shorter water vapor paths, leading to higher Top of Atmosphere (TOA) reflectance. These effects can easily cause cloud misclassification in high mountain regions, and they are difficult to resolve without incorporating a Digital Elevation Model (DEM) to correct for them. Recently, Qiu et al. (2017) developed the MFmask (Mountain Mask) algorithm to mitigate the elevation impact on thermal bands using DEM, but it fails to consider the impact on the cirrus band. Meanwhile, Fmask CDI observes three highly correlated NIR bands at various viewing angles, enabling the observation of high-altitude objects like clouds under parallax and reliable separation from ground objects (Frantz et al., 2018).

Conclusion

The GEE platform provides a large data repository and various support methods for solving spatial analysis problems with large datasets. The cloud masking method on the GEE platform uses multi-temporal Sentinel-2 images to quickly make cloudless optical imagery that can be used for research, monitoring resources, and large-scale natural observations. Currently, there are several methods for detecting clouds and cloud shadows on Sentinel-2 imagery, such as the Fmask, Fmask CDI, and Fmask CSP methods built using JavaScript on the GEE platform. The authors determined the effectiveness of these cloud masking methods in Vietnam, based on experimental results and analysis in the study area. The accuracy results of the assessment indicate that the Fmask CSP (CDF) approach has the highest accuracy of 97%. The Fmask, Fmask CDI, and Fmask CSP (CS) methods have an accuracy of 81%, 91.5%, and 91.5%, respectively. Additionally, each methodology is assessed for its strengths and weaknesses. The analysis of the cloud/cloud shadow detection results demonstrates the effectiveness of the cloud masking proposed methods, thereby producing cloudless Sentinle-2 images in Vietnam. On the other hand, it is essential to select an appropriate reference dataset with a suitable number of images and cloud cover ratio to ensure cloudless areas for compensation. To achieve maximum effectiveness, it is also necessary to research and choose the appropriate method for each study area and purpose.

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