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Remote Sensing-Based Accounting of Reservoir's Water Storage for Water Scarcity Mitigation: A Case Study for Small and Medium Irrigation Dams in Vietnam

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Abstract

Integrated water resources management requires consistent and accurate data on available water storage in reservoirs as well as water stress level. Vietnam is enduring a significant deficit in collecting necessary information to manage its water resources in that manner. While reservoirs are abundant, the majority of them were constructed a long ago and often lack of regular and adequate measurement on storage volume. Furthermore, the condition of water stress is often missing or remains bias leading to certain risks in reservoir operation, e.g. during water scarcity period. This paper presents how remote sensing data can be used to acquire needed information that is fundamental to understand water resources conditions. The results indicated that Sentinel-1 and Moderate Resolution Imaging Spectroradiometer (MODIS) can be applied to determine water surface area and water stress, through vegetation health index (VHI). This information is deemed necessary to improve water resources monitoring and management and hence, ensure long-term drought resilience and water and food security.

Keywords

Remote Sensing, Water Scarcity Management, Reservoir Volume

1. Introduction

Reservoirs play an important role in provision of water during dry season and regulation of excessive flows during wet seasons (Donchyts et al., 2016). Monitoring of reservoir storage provides water managers with the ability to enhance water supply for irrigation, fisheries, hydropower, eco-tourism besides reduced risks from water-related disasters. On the other hand, the deficit of knowledge on water storage will lead to reduction in water supply capacity and potentially contribute to water scarcity and pollution. Furthermore, increased inflow into lakes might lead to overflow and flooding in the downstream area, hence impacting livelihoods (Vanthof & Kelly, 2019; Guo et al., 2017). Additional surface water storage capacity enhances the flexibility of a basin to retain and release water.

While Vietnam has more than 7800 reservoirs for water supply and electricity generation, it is struggling to ensure adequate reservoir monitoring to satisfy the increasing of water demands. Hence, a continuous monitoring and data collection of water storage in lakes are fundamental for water use planning. Nevertheless, measuring water storage in lakes, reservoirs and wetlands is still a challenge with basic information regarding geometry. Volume-level curve is missing in most of small and medium size reservoirs. While installing sensors is still costly for dam managers, dam monitoring using remote sensing (Duan & Bastiaanssen, 2017) or hydrological model (Ha et al., 2018) proves to be an effective tool.

To account for water availability for understanding the impacts of reservoir on water scarcity mitigation, reservoir's storage must be monitored systematically. While water level can be observed using water level scale, measurement of storage is more challenging as this information is often missing, especially for small and old dams. Li and Sheng (2012) used Landsat data and SRTM and ASTER DEM from SRTM to monitor storage variations in reservoirs. Nevertheless, SRTM and ASTER are only available for bathymetry measured before 2001-2008 (ASTER) and 200 (SRTM), hence are valid only for reservoirs constructed after that period. Cai et al. (2016) used Moderate Resolution Imaging Spectroradiometer (MODIS) to monitor water storage of large lakes and reservoirs in Yangtze River Basin for a consecutive period of 15 years from 2000-2014. Under this study, 230 lakes and reservoirs were monitored. Due to the coarse resolution of MODIS (250 m), the method proved to be successful to assess trend in huge bundle of reservoirs larger than 8 km^2 in surface area.

Many satellites remote sensing surface water mapping studies and applications focus on the use of optical sensors, such as Landsat (Crétaux et al., 2015), Sentinel (Markert et al., 2020), the Moderate Resolution Imaging Spectroradiometer (MODIS) (Vanthof & Kelly, 2019), Wardlow and Egbert, 2010, Pervez et al., 2014 and the Visible Infrared Imaging Radiometer Suite (VIIRS) (Usman et al., 2015; Biggs et al., 2006). These optical water mapping methods include spectral information and thresholds (Sruthi & Aslam, 2015). With areas heavily affected by cloud, Synthetic aperture radar (SAR) data have been considered a promising tool to monitor water dynamics, because they are cloud-proof. With the recent launch of the Sentinel-1 satellite and the free access to its products, SAR data have both high temporal and spatial resolution, which can be used to extract surface water extent and assess its dynamics more efficiently. In addition, radar altimeter satellites are cloud-proof and can also be used to monitor surface water area.

In addition to meteor-hydrological data, mapping of water scarcity areas also required information. Traditional assessment involves locally collected data at field level and from census sources. Determination of vegetation growth and level of water scarcity derived from satellite for basin scale cultivation is deemed a modern and appropriate method of mapping drought and assessing reservoir irrigation efficiency. The Moderate Resolution Imaging Spectroradiometer (MODIS) presents a considerably accurate and operational dataset to classify irrigated area at reasonable resolution. Usman et al. (2015) applied MODIS NDVI to detect temporal changes for irrigated cropland in Pakistan. Biggs et al. utilized MODIS to map land cover and irrigated pixels for small scale farming in India using MODIS and Landsat time series. Sruthi and Aslam, 2015 published drought maps for Raichur District, India using similar approaches. Luong et al. (2020) mapped irrigated paddy rice and drought using MODIS time series. This paper presents how remote sensing data can be used to 1) derive information of reservoir storage for irrigation dams and 2) combine remote sensing based-drought information for operation of dams and reservoirs.

2. Materials and Methods

2.1. Study Area

The Central Vietnam is a large area with complex terrain and extensive river network. Numerous reservoirs were constructed to improve water supply for agriculture production and other users such as industry, domestic etc. Ninh Thuan province (**Figure 1**) was selected as a case study due to having a large amount of small and medium size dams that need water storage accounting. Ninh Thuan is also prone to regular drought.

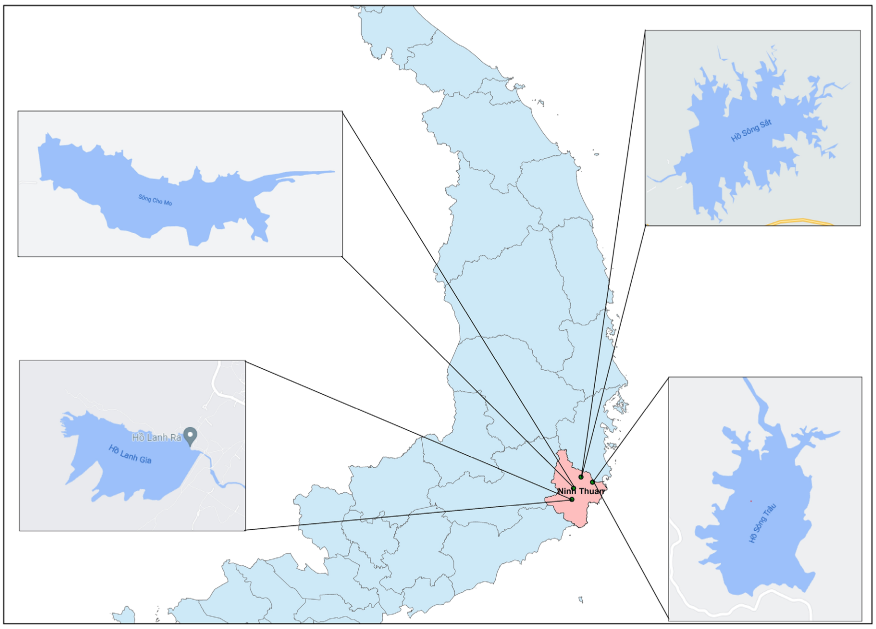


Figure 1. Four reservoirs and their locations under this study.

2.2. Satellite Data

Sentinel-1 data was used in this study to extract information on water storage. The Sentinel-1 sensor is a C-band SAR that operates in multiple acquisition modes at different ground sampling distances (GSD). For this study we used the Sentinel-1 Interferometric Wide (IW) swath mode at the 10 m GSD, which offers single and dual polarization options of vertical transmitting with vertical receiving (VV) and vertical transmitting with horizontal receiving (VH) dual-polarization. VV polarization data was used in this study. Two pre-processed versions of the ESA Copernicus Open Access Hub Sentinel 1 Level-1 IW Ground Range Detected (GRD) dataset were used for this study. This first version used, provided through GEE, was the Sentinel-1 Level 1 GRD ARD derived from the ESA data on Copernicus.

Information on drought was derived using Vegetation Health Index (VHI) from MODIS, which can be used to monitor the growth of vegetation cover and water stress. VHI value reflects the concentration of green biome in vegetation leaf and hence, indicates vegetation health and dynamics. Regional and global spatially determination of irrigated lands conducted earlier using MODIS dataset Luong et al. (2020). In this study, VHI dataset was calculated from MODIS Global MOD13C2. MOD13C2 is cloud-free spatial composites of the gridded monthly 1-km geographic (lat/lon) Climate Modeling Grid (CMG). Cloud-free global coverage is achieved by replacing clouds with the historical MODIS time series climatology record.

2.3. Calculation of Reservoir Volume

Detailed calculation step to derived reservoir storage is illustrated in **Figure 2**. Remote sensing data from Sentinel-1 was processed in Google Earth Engine to extract water surface area (F). Water area was subsequently combines with water level (Z) monitored at the reservoirs to estimate water volume. This information together provides knowledge on reservoir remaining storage capacity.

Reservoir volume calculation is estimated using following equation:

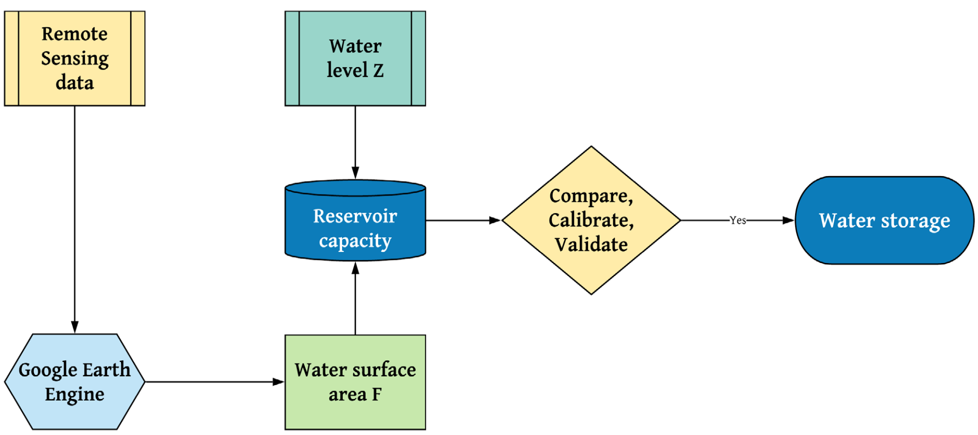


Figure 2. Step-wise calculation of reservoir storage volume.

$$W_{t+1} = \frac{\left(F_i + F_{i+1} + \sqrt{F_i \cdot F_{i+1}}\right) \cdot \left(Z_{i+1} - Z_i\right)}{3}$$

In which:

W_{i+1}, W_i: Reservoir storage at the time step i and i + 1

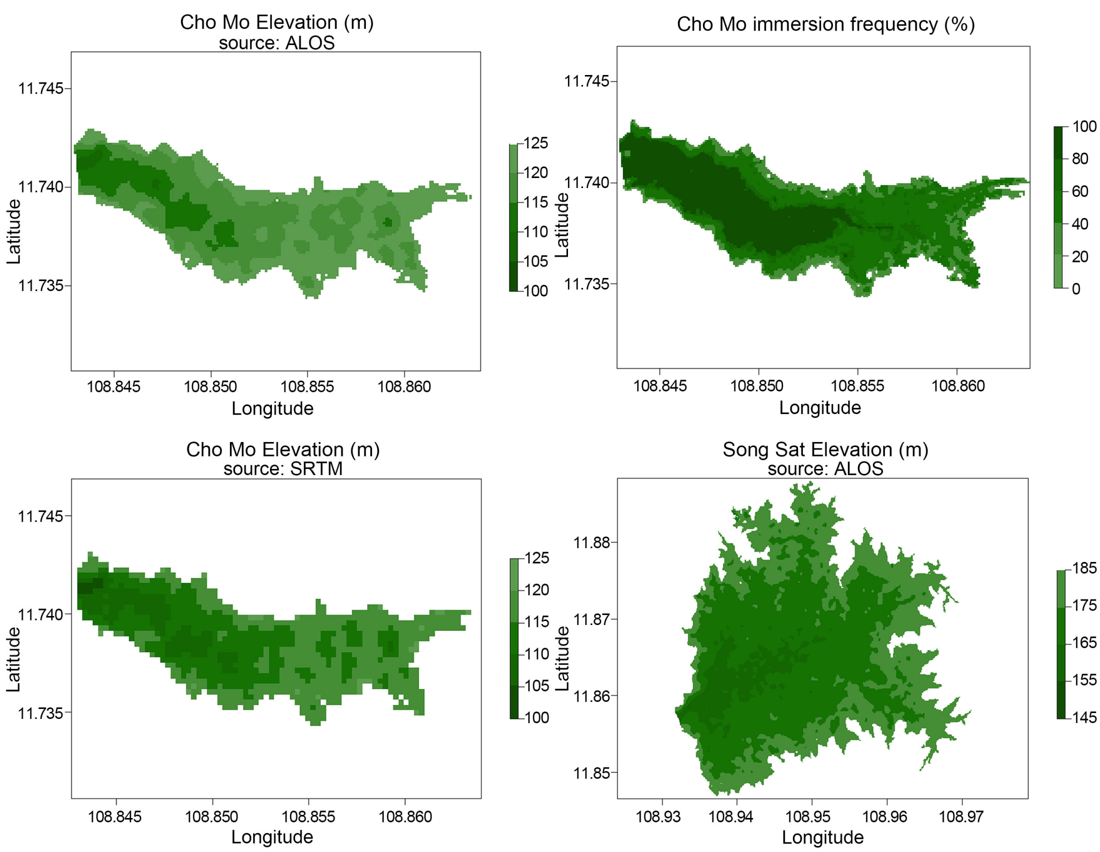
F_{i+1}, F_i: Reservoir surface area the time step i and i + 1 calculated from Sentinel-1

Z_{i+1}, Z_i: Reservoir water level at the time step i and i + 1 measured at the reservoir

3. Results and Discussions

The bathymetry for seven reservoirs was provided in **Figure 3** as immersion frequency (%). DEM data from ALOS and SRTM was shown as comparison of the result. It is shown that reservoir volume can be estimated using Sentinel-1 with good agreement.

Figure 4 indicates VHI calculated for the year 2020, which is a drought year. The value was normalized from 0 - 100 to reflect better the water stress level with 100 is the highest level while 0 describes no water stress at all. The VHI time series for 2020 show two distinguished periods following a wet-dry climatic condition. The period from March until May is the most critical period of water scarcity while the remaining months enjoy a more relaxed water resources condition.



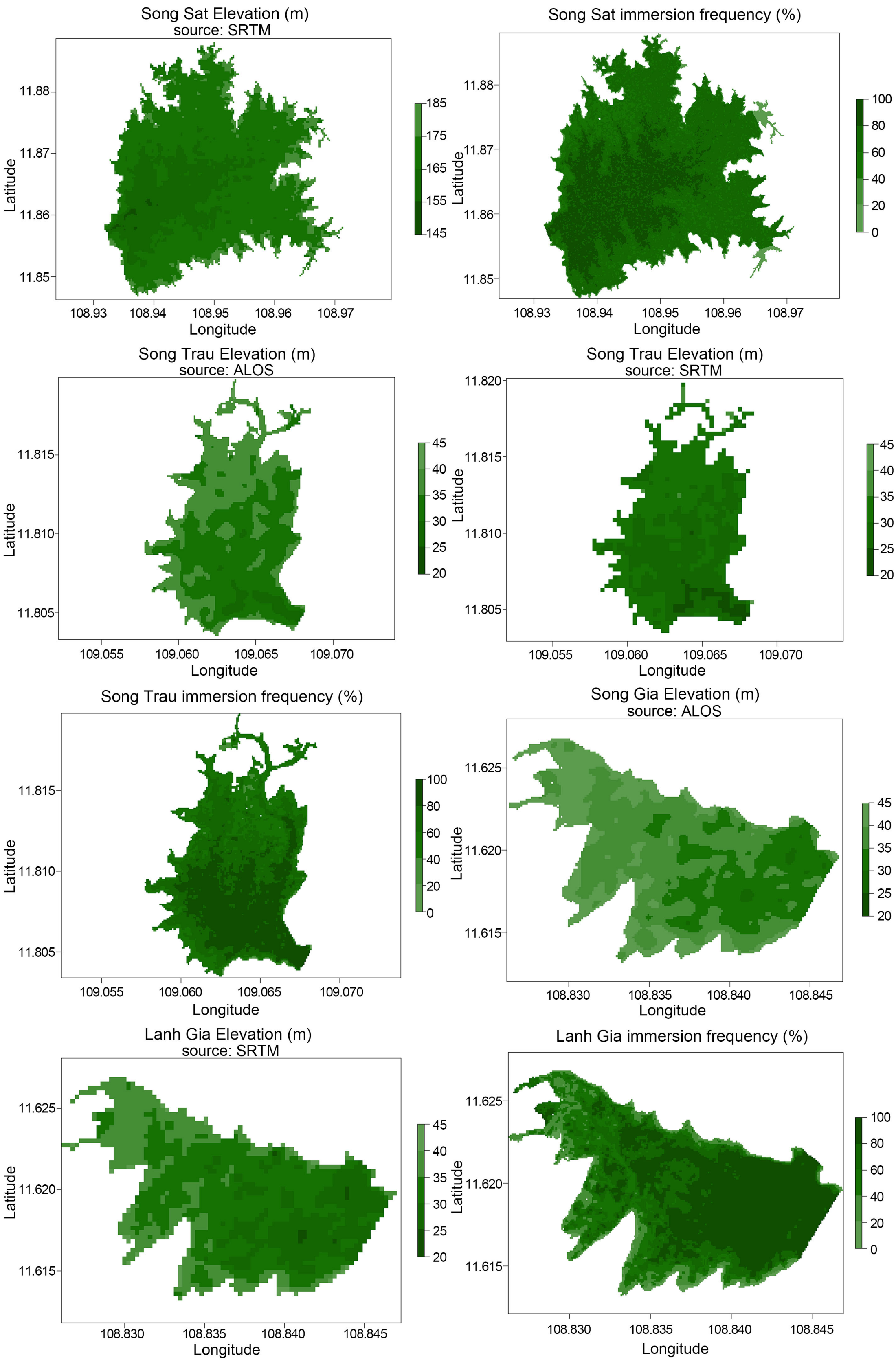


Figure 3. Reservoirs storage and bathymetry derrived from remote sensing and DEM for Cho Mo, Song Sat, Song Trau and Lanh Gia reservoir.

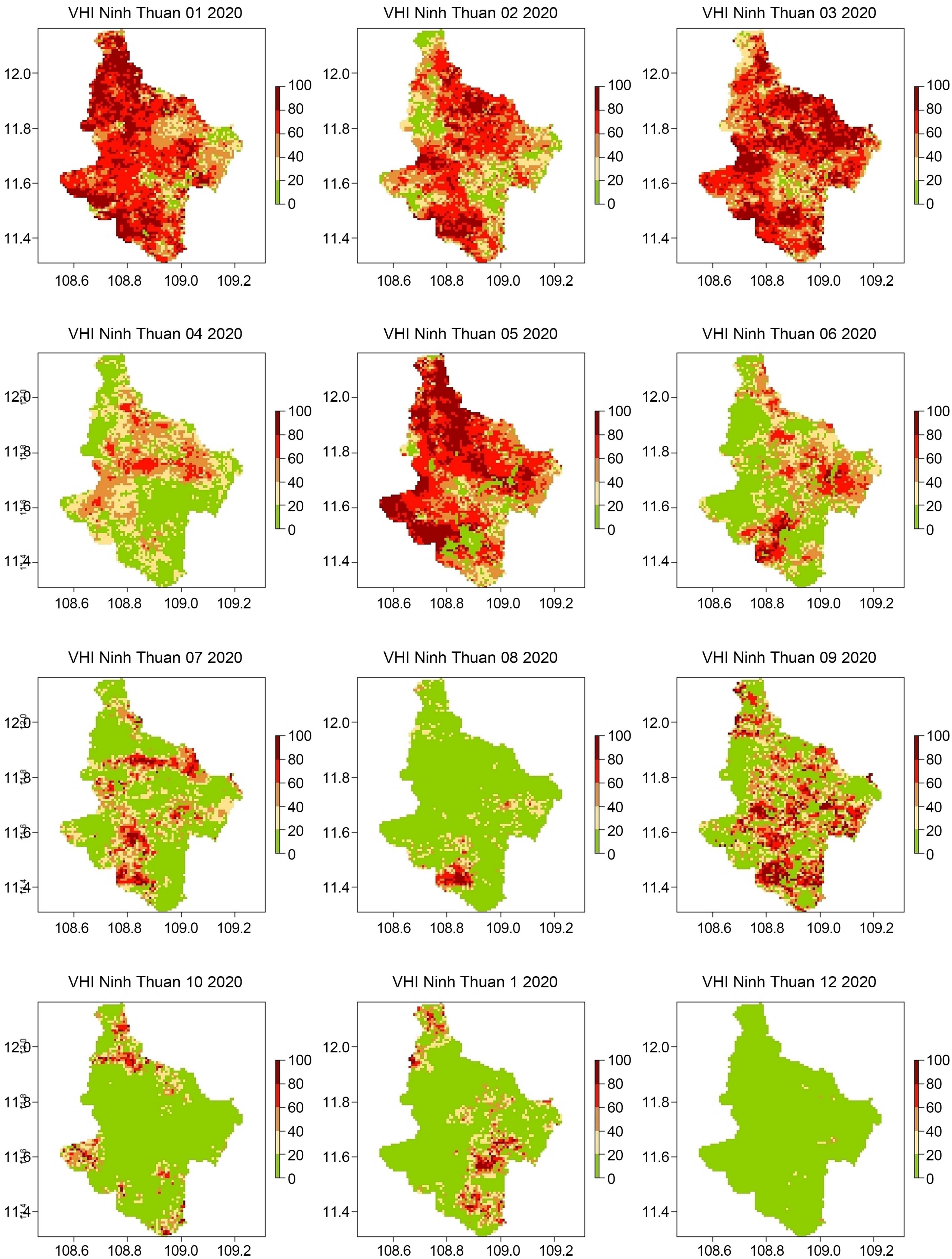


Figure 4. VHI calculated for Ninh Thuan province during the drought year of 2020.

4. Conclusion

This study presents a comprehensive and step-wise calculation of reservoir storage and implication to water scarcity management in Central Vietnam. It was demonstrated that remote sensing-derived reservoir information and water stress level has a good potent and agreement with theory and field observation. The data on reservoir storage offers exciting insights for reservoir operator and water users to have continuous information on available water for their use and therefore, promote more effective water resource management strategies in the study area.

While this study shows specific results from satellite data, the role of *in-situ* measurement should not be underestimated. The new generation of elevation data available through altimetry sensors will provide a medium to substitute field measurement. Furthermore, is should be noted that all analyses strongly rely on the quality of the satellite data and algorithm to extract necessary information map.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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