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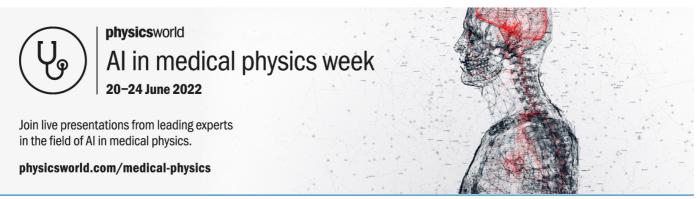
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To cite this article: Niels Janssens et al 2022 Environ. Res. Lett. 17 044069

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RECEIVED

10 October 2021

REVISED

4 February 2022

ACCEPTED FOR PUBLICATION 8 February 2022

PUBLISHED

4 May 2022

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LETTER

Rivers running green: water hyacinth invasion monitored from space

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Keywords: floating vegetation, Sentinel-2, remote sensing, invasive plant, eutrophication, hydrology, plastic

Supplementary material for this article is available online

Abstract

Water hyacinth is an aquatic free-floating plant that is highly invasive, to the extent that it is now present in most freshwater bodies in sub-tropical and tropical regions worldwide. Due to the ecological and socio-economic damages these plants can cause, monitoring their spatial coverage and seasonality is key for development of timely and efficient mitigation measures. Hyacinth patches are sufficiently large to be detectable in high-resolution satellite imagery, allowing for monitoring using freely available remote sensing data collected by platforms such as Sentinel-2. In this study, we estimated water hyacinth coverage and seasonal dynamics over three years (2018–2020) for the Saigon river, Vietnam. Using a Naïve Bayes classifier, hyacinth coverage was mapped in Sentinel-2 imagery with an accuracy of 91%. We show that the dry season (December-May) corresponds to highest water hyacinth abundance, with maximum coverage in February. Lower rainfall and relative humidity were found to be highly correlated (r = -0.56 and r = -0.64, respectively) with higher hyacinth cover. We also detected substantial interannual variability: annual means in hyacinth coverage varied by a factor of five between the 2018/2019 and 2020 yearly averages, with peak cover occurring in February 2020. The percentage of Saigon river covered by hyacinths over the entire study area peaked at 14% and reached as much as 24% for the upstream section. This confirms the prevalence of these invasive plants in the region, and the growing threat to river navigability and biodiversity. Our study provides an openly available automated workflow for long-term monitoring of hyacinth coverage, which can be scaled-up and extended to other freshwater systems. As such, it provides a step for building a large-scale monitoring tool of this highly invasive species, which may also be used for designing mitigation and reduction strategies of hyacinth and the pollutants it carries along.

1. Introduction

Tropical freshwater bodies around the world are being invaded by water hyacinth (*Eichhornia crassipes*), an aquatic plant known to cause adverse ecological, hydrological and socio-economic impacts (Vilà *et al* 2011, Dersseh *et al* 2019). Due to its rapid proliferation, water hyacinth can form dense mats at the water surface, blocking light and reducing oxygen for

fish, crustaceans, and other organisms. Severe invasions of water hyacinth can even disrupt river navigation, clogging urban waterways and dams (Lock 1988, Dersseh *et al* 2019). Recently, it has been shown that the large patches can also adsorb and accumulate pollutants such as heavy metals and macroplastics, respectively (Du *et al* 2020, Schreyers *et al* 2021a).

Free-floating aquatic hyacinth originated from the Amazon basin, and its presence is now reported in over 50 countries worldwide (IUCN 2017, CABI 2020). Despite local efforts to limit its spread, water hyacinth invasions persist in tropical freshwater bodies, and have even been recently reported at higher latitudes (Ghoussein *et al* 2019). The presence of water hyacinth is expected to further rise in the future, in the context of increased urban nutrient pollution (Kleinschroth *et al* 2021).

To plan future control and removal interventions of this floating plant in freshwater bodies, a better understanding of its dynamics in both time and space is needed (Thamaga and Dube 2018). Hyacinths have high growth rates—the plant coverage can double within 6-12 days-and mats can change position and drift at the water surface through the combined actions of currents, wind, flow velocities and tides (Ouma et al 2005). Due to these characteristics, water hyacinths are prone to rapid changes in their extent and spatial distribution, especially in river systems, and thus require frequent observations for accurate and timely monitoring. Recent studies confirm the high spatio-temporal dynamics of water hyacinth over entire freshwater bodies. Kleinschroth et al quantified annual coverage in 20 reservoirs across the world, and showed high interannual variability (of a factor of 1.2-15 depending on the sites) (Kleinschroth et al 2021). At a catchment scale, Winton et al (2020) identified seasonal oscillation patterns in hyacinth coverage in the Zambezi catchment, with annual peaks mainly governed by discharge and rainfall.

Despite the widespread presence of water hyacinth in tropical rivers and lakes, the spatial extent and seasonal dynamics of its coverage remain unknown. Large-scale monitoring of cover cannot be done through in-situ sampling, notably due to the difficulty in extrapolating point measurements to coverage estimates over an entire riverine or lacustrine system. A promising way forward includes the use of remote sensing to detect water hyacinth (Thamaga and Dube 2018, Ghoussein et al 2019, Al-lami et al 2021, Kleinschroth et al 2021). Spaceborne remote sensing and especially satellite imagery analysis is an operational tool well suited to observe vegetation dynamics in aquatic environments (Schreyers et al 2021b). Remote sensing can enable repeated and standardized observations of the same area, allowing to characterize spatio-temporal patterns of water hyacinth coverage.

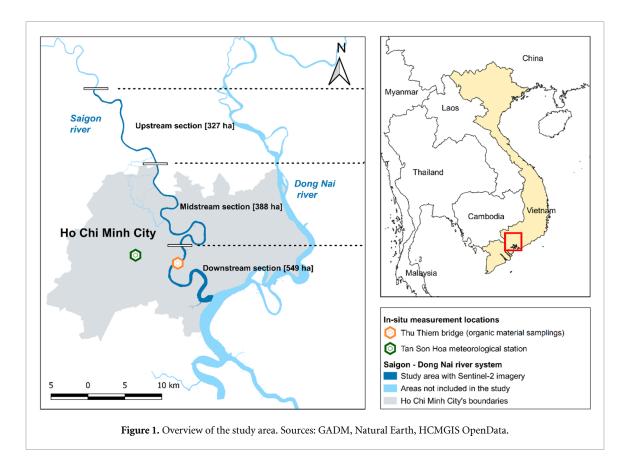
The availability of freely available satellite data can be used to continuously and cost-effectively monitor water hyacinth on broad spatial scales (Thamaga and Dube 2018, Kleinschroth *et al* 2021). As part of the Copernicus program, the launch of the European Space Agency (ESA) Sentinel-2 satellites in 2015 and 2017 has opened new avenues in environmental monitoring, thanks to its open data policy and global coverage. The Sentinel-2 A and -B constellation's high revisit time (2–5 days), spatial resolution (10–60 m

depending on bands), and its radiometric characteristics (covering the visible, near-infrared and short-wave infrared range of the electromagnetic spectrum) allow for accurate detection of vegetation.

Until recently, the long processing times of Sentinel-2 images hampered large multi-temporal analysis (Gomes *et al* 2020). The development of cloud computing systems for fast and automatic processing of satellite images, such as Google Earth Engine or Google Colaboratory, overcame this constraint (Camara *et al* 2016, Gorelick *et al* 2017, Bisong 2019, Gomes *et al* 2020). Prior to the existence of cloud-computing infrastructure, satellite images had to be downloaded and processed one by one, thus considerably limiting long time-series analysis. The emergence of automated processing platforms, in combination with reliable remote sensing data, now enables processing large quantities of remotely sensed data, which facilitates large-scale monitoring.

In this paper, we mapped the spatio-temporal dynamics of water hyacinth coverage for the Saigon river, one of Vietnam's largest river systems. We estimated water hyacinth coverage over 141 Sentinel-2 scenes over three years (2018–2020) using a Naïve Bayes classifier to distinguish water from hyacinth content at the river surface. We assessed the accuracy of our classification over a test set of Sentinel-2 water and water hyacinths pixels not previously used for training the classifier. The robustness of Sentinel-2 in detecting water hyacinth at the river surface was also assessed by comparing the results with high resolution satellite imagery (Worldview-2 scene) acquired in 2020. Additionally, monthly estimates of water hyacinths based on the Sentinel-2 classification were compared with in-situ data collected over 2018 in Ho Chi Minh City, Vietnam. Finally, we conducted a preliminary exploration of water hyacinth seasonality with hydrometeorological variables including rainfall, sunshine duration, humidity ratio and air temperature.

With this paper we aim to reveal the seasonal, spatial and interannual variation of water hyacinth coverage in the Saigon river using Sentinel-2 images. Accurate and reliable detection of floating hyacinths provides important information for monitoring this highly invasive species, which may also be used as an early warning system for operational clean-ups. Compared to previous studies, our approach improved large-scale detection of hyacinth coverage by providing hyacinth coverage estimates at both higher spatial and temporal resolutions. Our classification was automated over a large number of scenes, enabling to map hyacinth coverage almost continuously throughout the year. For the first time, we characterized hyacinth seasonality trends across a river system with remote sensing data. Our openly available workflow for hyacinth detection can also be applied to other freshwater systems for long-term and global assessments.



2. Methods

We estimated hyacinth coverage using Sentinel-2 satellite imagery. Our approach builds on previous work which mapped hyacinth coverage across freshwater systems using satellite imagery analysis (Thamaga and Dube 2019, Kleinschroth et al 2021). Kleinschroth et al (2021) automatically classified hyacinth coverage using Landsat imagery and produced yearly coverage estimates at 30 m resolution. A first effort in improving the spatial resolution was made by Thamaga and Dube (2019) by using two Sentinel-2 scenes (10 m resolution), in combination with substantive field data inputs. For our approach, we introduced technical improvements in satellite imagery-based hyacinth detection. First, we used all the spectral characteristics of Sentinel-2 bands in our classifier, in contrast to the NDVI mask approach of Kleinschroth et al (2021). Second, we conducted the analysis continuously over a large number of images and characterized seasonal dynamics. Third, we used the highest available resolution for non-commercial optical satellite imagery at the river basin scale. Overall, this approach optimized large-scale detection of hyacinths by improving both its spatial and temporal resolutions and minimizing the number of training inputs.

2.1. Study area

The Saigon river is located in Southern Vietnam, in a low elevation coastal zone, i.e. between 0 and 10 m above mean sea level. The river is approximately

225 km long with a catchment area of 4717 km² (Nguyen *et al* 2019). It originates in southeastern Cambodia, flows through Ho Chi Minh City and confluences with the Dong Nai river, and ultimately flows into the sea (figure 1). Over the year, precipitation (1800 mm of mean yearly precipitation) follows two contrasted seasons: the dry season, usually extending from December to May, and the wet season from June to November, which gathers about 80% of the total rainfall (Nguyen *et al* 2019).

The river is highly influenced by tidal regimes, with a relatively low net discharge (Camenen et al 2021). Water hyacinths coverage was mapped over a large section (115 km and 1,264 hectares) of the Saigon river with satellite imagery, amounting to approximately 20% of the total Saigon river length (figure 1). This area of interest was divided into three sections: upstream, midstream and downstream (respectively of 22, 20 and 17 km long) based on Ho Chi Minh City's urban area footprint and the city's boundaries. The upstream section extended up to the segment where the river is less than 200 m wide. We used openly available data that includes in-situ measurements of organic material, mainly composed of water hyacinths, conducted close to the Thu Thiem bridge, in the downstream section of the Saigon river (van Emmerik et al 2019) (section 2.5).

2.2. Hyacinth coverage estimates

To date, the Sentinel-2 mission provides global satellite coverage at high spatial (10–20 m depending on the bands) and temporal resolution (2–5 days)

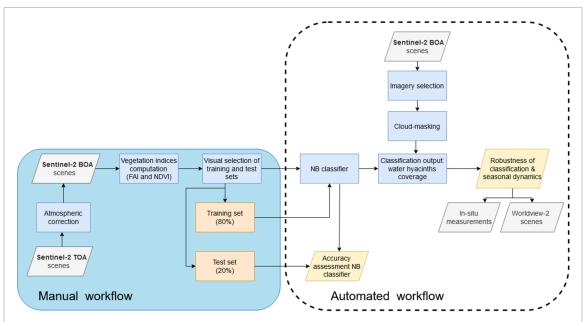


Figure 2. Workflow for estimating hyacinth coverage using Sentinel-2 imagery. The manual component enables to provide training and test sets for the classification. The automated workflow details the different steps taken to estimate hyacinth coverage over the Sentinel-2 scenes.

for terrestrial applications at no cost for the users. Sentinel-2 satellites are equipped with the Multi-Spectral Instrument, which collects reflectance values in the visible, near-infrared (NIR) and shortwave Infrared (SWIR) range of the electromagnetic spectrum, For these reasons, Sentinel-2 images were considered a good fit for consistent and long-term monitoring of water hyacinths at the river surface. The choice to analyze a time-series from 2018 to 2020 resulted from the availability of in-situ data on organic material concentrations for the year of 2018 (van Emmerik et al 2019) and that of high resolution Worldview-2 imagery for 2020. Figure 2 details the satellite imagery classification workflow, with both a manual and automatic component. The automatic workflow was entirely carried in the Google Colaboratory environment (Janssens 2021).

Training and test datasets of river water and water hyacinth were manually selected based on three atmospherically corrected Sentinel-2 scenes, using vegetation indices and remotely sensed reflectance values Using the manually identified training sets, a classification was developed to automatically differentiate hyacinth from water pixels within Sentinel-2 scenes from 2018 to 2020. This resulted in a hyacinth coverage estimate, expressed in hectares or percentage of the river surface. We detail in the supplementary material (extended methods available online at stacks. iop.org/ERL/17/044069/mmedia) both the manual workflow and the automatic classification steps.

2.3. Validation of water hyacinth coverage estimates

Ultimately, our results were assessed based on (a) the Sentinel-2 test dataset, (2b) *in-situ* data on organic

matter concentrations for the year of 2018, and (c) high-resolution Worldview-2 imagery from 2020.

The Naïve Bayes classifier was first assessed using the test set previously presented (n=120). The test data corresponds to the manually selected pixels for water and hyacinth content that were not previously used for training the Naïve Bayes classifier. A confusion matrix was derived to quantify the number of correctly and incorrectly classified pixels over the test set, also following Biermann et al's methodology (Biermann et al 2020).

Secondly, samplings of organic material in the Saigon river were used for comparison with the Sentinel-2 derived surface estimates. van Emmerik et al (2019) retrieved organic materials predominantly composed of water hyacinth using a trawl deployed from the Thu Thiem bridge in Ho Chi Minh City (figure 1). The *in-situ* measurements were conducted over a ten-month period from March to December 2018. Monthly averages of organic material concentrations were computed for comparison with the Sentinel-2 derived water hyacinth monthly estimates using Spearman's correlation coefficient. It should be noted that no *in-situ* samples were taken over the months of January, February and April, thus not allowing a comparison with Sentinel-2 surface estimates for these months.

A total of 111 *in-situ* samples were made, and 3072 kilograms of floating organic material retrieved from the sampling site in 2018. The predomninantly hyacinth material that was collected varied throughout the sampling period, with an average amount of 28 kg m⁻¹ h⁻¹ (per meter width of river) of floating organic material.

Lastly, we compared the water hyacinth classification derived from Sentinel-2 with one high resolution

Wordview-2 image. This allowed us to validate our approach, given that Sentinel-2 has a coarser spatial resolution (10 m) compared with Worldview-2 (1.84 m). Worldview-2 is a Maxar (formerly Digital-Globe) commercial satellite that acquires multispectral data in the visible, NIR and SWIR wavelengths. Only one pair of scenes were available for comparison, mainly due to the low number of Worldview-2 scenes available to us for this study, high cloud coverage, and discrepancies in overpasses between the two satellites. These scenes were taken on 1 March 2020; a day with low cloud coverage that showed noteable water hyacinth coverage from visual examination. We detail the steps taken in comparing Worldview-2 imagery and the Sentinel-2 classification outputs in supplementary material (extended methods).

2.4. Hydrometeorological variables

The derived water hyacinth monthly estimates were compared with hydrometeorological variables, namely: rainfall (mm), air temperature (°C), sunshine duration [hour per day], and relative humidity (%). These parameters are measured hourly at the Tan Son Hoa meteorological station (figure 1) and were retrieved as monthly averages from the Ho Chi Minh City Statistical Yearbook of 2019 (Ho Chi Minh City Bureau of Statistics 2019). The values were only available for the years 2018 and 2019, thus not allowing the comparison with water hyacinth coverage estimates for the year 2020. A statistical correlation analysis was performed using the Spearman's coefficient. P-values and r values are reported.

3. Results and discussion

3.1. Seasonal variation of water hyacinths

Due to their distinct spectral characteristics, water hyacinth patches can be detected through satellite imagery (text S3) and their coverage estimated. Between 2018 and 2020, water hyacinth coverage shows high interannual and intrannual variability over the Saigon river. Plant coverage varied within four orders of magnitude over the entire period (from 2×10^{-2} to 2×10^{2} ha equivalent to 0%–14% of the entire study area). The time-series of water hyacinth cover shows that days with water hyacinth coverage peaks can be preceded and/or followed by days with low water hyacinth abundance. For instance, water hyacinth coverage over the entire study area increased by a factor of 6 between 16 and 21 January 2020 $(1.5 \times 10^{1} - 9 \times 10^{1} \text{ ha})$ then dropped by half just two days later $(4 \times 10^1 \text{ ha})$.

Considering monthly averages, water hyacinth coverage varied by two orders of magnitude, ranging from $1\times10^\circ$ to 10×10^2 ha (corresponding

to 0.06% and 8% of the total study area respectively). Figure 3 details the absolute and relative water hyacinth monthly coverage estimates between 2018 and 2020. The entire time-series can be found in the supplementary materials.

The highest monthly peak in water hyacinth coverage (1 \times 10² ha) was reached in February 2020. The upstream section was the major contributor for this peak in water hyacinths, with 75% of the total water hyacinth coverage. Accordingly, this peak corresponds to approximately 8% (1 \times 10² ha of 1.2 \times 10³ ha river surface) of the entire study area and 24% $(8 \times 10^1 \text{ ha of } 325 \text{ ha river surface})$ of the upstream section. Over the monitored period, this peak was 3-5 times higher than in previous years $(2 \times 10^1 \text{ ha})$ in 2018 and 3 \times 10¹ ha in 2019). Potential factors explaining this large outbreak could be related to drier conditions than in previous years, but this could not be ascertained due to the lack of hydrometeorological data for the year 2020. Water hyacinth coverage was much higher for the year 2020 (max = 2×10^2 ha, correspond to 14% of the total area studied) than the two previous years (2018, max = 4×10^1 ha/3%, 2019, $max = 8 \times 10^1 \text{ ha/6\%}$).

Water hyacinth extent is higher in the upstream section (both relative and absolute values) compared to the downstream and midstream ones. The lower coverage in water hyacinth within Ho Chi Minh City urban area could result from the break-down of water hyacinth mats due to higher stream flow velocity and/or increased salinity levels (Muramoto et al 1991, Petrell and Bagnall 1991). Field measurements conducted at Thu Thiem bridge in 2020 registered an average flow velocity of 0.54 m s⁻¹, above the threshold level (0.40 m s^{-1}) at which water hyacinth patches become unstable and break down (Petrell and Bagnall 1991, Schreyers et al 2021b). The role of boat activity, buoys, piers and bridge columns in the mechanical break-down of patches also need to be further investigated.

The monthly estimates of water hyacinth coverage reveal a clear seasonal cycle in hyacinth cover (figure 4). A high abundance period is observed during the dry months (December–May), followed by a decreasing and low abundance period over the wet season (June–November).

The highest water hyacinth abundance period typically occurs between February and May, and is at its peak in February. From June to November, hyacinths coverage is lower on average, although a small increase in coverage was identified in July. From December onwards, water hyacinth abundance increases again. These observed trends are consistent for all monitored sections, especially when considering the maximum coverage values. The availability of numerous cloud-free scenes (figure S2) during the dry months enabled us to capture the peak

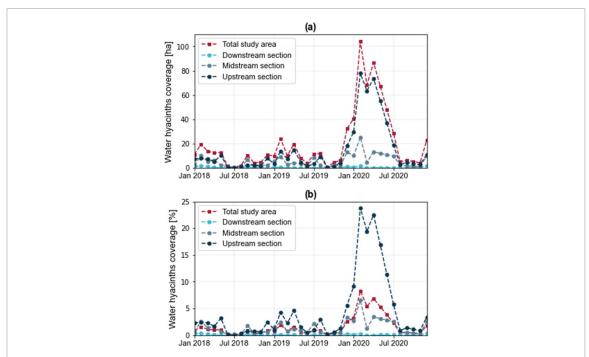


Figure 3. Water hyacinth monthly coverage over the Saigon river. (a) Expressed in hectares (ha). The entire study area is the sum of all the separate sections here (b) expressed percentage of the section surface (%).

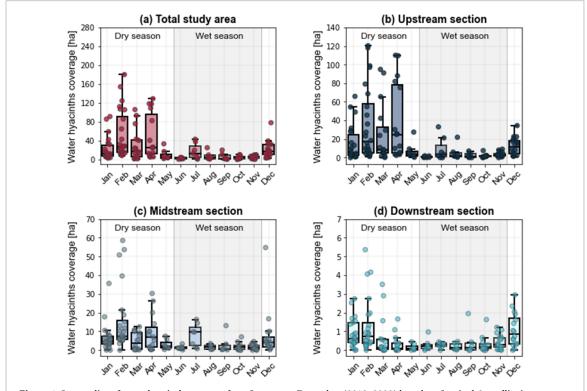


Figure 4. Seasonality of water hyacinth coverage from January to December (2018–2020) based on Sentinel-2 satellite imagery analysis. Note the different *y*-axis scales between subplots: (a) 0–200 ha (b) 0–140 ha (c) 0–70 ha (d) 0–6 ha.

hyacinth season well, and suggests that Sentinel-2 is an excellent tool for accurate, near-real time monitoring in this region. High abundance coverage of water hyacinths during the dry season was also observed for the Maramba river in Zambia and the Shagashe river in Zimbabwe (Winton *et al* 2020, Chapungu *et al*

2018). Other studies however found that the maximum hyacinth coverage was reached during the rainy and post-rainy season for the Greater Letaba river in South Africa and Laka Tana in Ethiopia, respectively (Thamaga and Dube 2019, Dersseh *et al* 2020). To establish the main factors accountable for these

diverging trends across tropical freshwater systems, the drivers for water hyacinth proliferation need to be further studied at more locations worldwide.

We identified a seasonal cycle in water hyacinth coverage over the Saigon river. Monthly averaged humidity rates and rainfall showed high negative correlations with water hyacinth coverage (r = -0.58, p-value 0.003 and r = -0.61, p-value = 0.001 for rainfall and humidity, respectively). A significant positive correlation was found between water hyacinth monthly coverage (r = 0.51, p-value = 0.01). No significant statistical correlation was found between hyacinth coverage and air temperature in the Saigon river. These results indicate that water hyacinth proliferation is optimal during the dry season in the Saigon river. The reduced water flows, higher water stability and higher concentrations of nutrients during that period cause water hyacinth blooms (Harun et al 2021).

During the wet season, higher rainfall and increased flow velocities that favor instability may lead to higher disintegration rates of the mobile water hyacinth patches. Extending this preliminary exploration of the influence of hydrometeorological factors to other years and with higher level of details (daily estimates for instance instead of monthly) is needed to better understand the role of these parameters in governing water hyacinths proliferation at the river system scale. Additional hydrological and climatic factors such as flow velocities, currents, tidal regimes, salinity, as well as wind speed and direction should also be considered in addition to those investigated. These might indeed influence the drifting and spread of water hyacinth patches along the river system as well as their spatial distribution across the river width. The limited number of available Sentinel-2 scenes from May to October (five scenes for the year 2020) calls for cautious interpretations of the average estimates for these months. A way to increase data availability would be to integrate Sentinel-1 scenes. Thanks to the difference in backscatter values between aquatic vegetation and water (Simpson et al 2020), active radar data can successfully be used to detect water hyacinth without interference from cloud. The ESA Sentinel-1 satellites carry a C-band synthetic aperture radar imaging instrument that enables acquisition of data through haze or cloud (day or night), and with a revisit time of six days in this area. This presents an additional opportunity for large-scale and long-term monitoring of water hyacinths over tropical regions, given the persistence of cloud coverage at such latitudes. Combining Sentinel-1 and 2 would provide very high frequency observations, but requires first calibration between the remote sensing methods for estimating water hyacinth coverage.

3.2. Robustness and accuracy of Sentinel-2 derived classification

Applying the classifier to Sentinel-2 data not previously used for training resulted in a good agreement. Considering the satellite scenes used for the training dataset, suspected water hyacinths were correctly classified correctly by the Naïve Bayes model with an accuracy of 91%. Overall, the in-situ dataset and Sentinel-2 surface estimates showed a good agreement in terms of observed trends (figure 5). Strong significant correlations between the two datasets were found for the total study area (r = 0.78 and p-value = 0.01), the upstream section (r = 0.68 and p-value = 0.04), the midstream section (r = 0.73, p-value = 0.02). This was not the case however for the downstream section (r = 0.43, p-value = 0.24). The *in-situ* measurements were taken in the northern part of the downstream section, at a site where hyacinth coverage is more abundant compared to its southern part. Thus, hyacinth coverage at the midstream section can be considered a better reference for the concentrations of organic material that can be found at the *in-situ* sampling site. Discrepancies between organic material concentrations and Sentinel-2 derived hyacinth coverage were also noted. For instance, relatively high concentrations in organic material were measured for June 2018 and are not reflected in hyacinth coverage. Three main factors could explain the discrepancies in the trends of hyacinth coverage and organic material concentrations. First, the in-situ measurements offer a snapshot view of the water hyacinth content at the in-situ measurements site and are thus not representative for the entire area monitored by the satellite imagery. Second, in-situ measurement dates did not always coincide with Sentinel-2 available scenes. Given the high temporal variability of hyacinth coverage (also within months), this temporal mismatch could (partially) explain differences in the monthly trends of hyacinth coverage and organic material concentrations. Third, Sentinel-2 imagery does not allow to detect small water hyacinth patches due to the relative coarse spatial resolution of this data (10 m \times 10 m). This last factor most likely explains the between the hyacinth coverage and in-situ samplings for the downstream area, where patches likely break down due to boat traffic and higher flow velocities, especially in its southern most part.

The visual comparison between Worldview-2 and Sentinel-2 imagery on 1 March 2020 (figure 6) shows similar detection of water hyacinths for two areas at the Saigon river. Overall, the classification of water hyacinths with Sentinel-2 seem to detect water hyacinth content accurately. The pattern of water hyacinth patches is similar across both sensors, as is

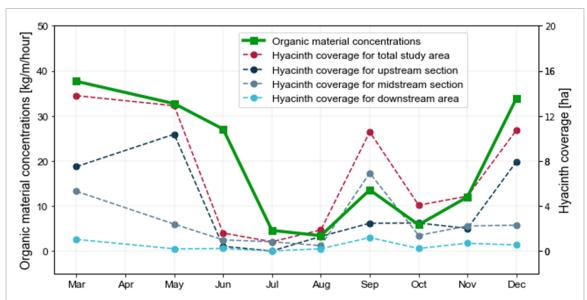


Figure 5. Monthly averages for organic material concentrations and hyacinth coverage for 2018. Significant positive correlations were found for all sections except the downstream area. Total study area: r = 0.78, p-value = 0.01. Upstream section: r = 0.68, p-value = 0.04, midstream section: r = 0.73, p-value = 0.02, downstream section: r = 0.43, p-value = 0.24.

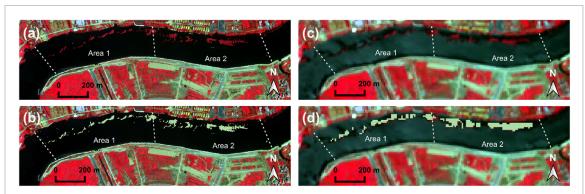


Figure 6. Worlview-2 and Sentinel-2 water hyacinth classification on 1 March 2020. (a) Worldview-2 input scene (b) Worldview-2 classification output of water hyacinths (c) Sentinel-2 input scene (d) Sentinel-2 classification output. Red pixels suggest water hyacinth content in the top panel. The satellite scenes are displayed in false color composite. Green pixels in the lower panel indicate pixels classified as water hyacinths based on the input scenes. ©2020 DigitalGlobe.

the cover distribution. However, the Sentinel-2 classification tend to overestimate water hyacinth coverage compared to Worldview-2 imagery (table 1). The classification output of Sentinel-2 estimated that 8% and 15% of the river was covered with water hyacinth patches for the area 1 and 2, respectively. In comparison, Worldview-2 found a coverage ratio of 6.3% and 9.9%, respectively. This over-estimation of water hyacinth coverage by Sentinel-2 might be the result of the relatively large pixel size compared to Worldview-2 resolution. It is therefore advised to refine the classification to take into account the percentage of subpixel ratio between water and water hyacinth.

3.3. Outlook

Water hyacinth coverage over the Saigon river showed high temporal variability: minimum and maximum daily coverage over the three year period varied by an order of magnitude of four $(2 \times 10^{-2} - 2 \times 10^2 \text{ ha})$, monthly averages by an order of magnitude of two

 $(1 \times 10^{\circ} - 1 \times 10^{2} \text{ ha})$ and annual averages by a factor of five $(1 \times 10^1 - 5 \times 10^1 \text{ ha})$. Our application over the Saigon river used a high number of images (n = 141) spread over three years, thus providing good confidence in the seasonality trends observed. The seasonality in hyacinth coverage over rivers is best captured by frequent observations and multi-year monitoring. Indeed, the high variability in coverage within months generates outliers within each season (e.g.: a peak in hyacinth coverage during a season with overall low coverage). As a result, assessing the hyacinth coverage at a few dates over one year could lead to inaccurate interpretations of seasonality trends. The highly dynamic hyacinth coverage in rivers further emphasizes the importance of continuous and longterm monitoring, which can be achieved with satellite imagery such as Sentinel-2.

A higher frequency of observations could be obtained with the addition of imagery collected with Sentinel-1 radar data, given that imagery acquisition

Table 1. Comparison between Worldview-2 and Sentinel-2 derived water hyacinth coverage estimates on the 1 March 2020.

	Worldview-2	Sentinel-2
Spatial resolution [m]	1.84	10
Date and time	1 March 2020-10.36.42	1 March 2020-10.16.39
Water hyacinths coverage estimate [ha]	Area 1: 0,75	Area 1: 1,2
	Area 2: 1,1	Area 2: 2,1
Water hyacinths coverage ratio [%]	Area 1: 6.3	Area 1: 8.0
	Area 2: 9.9	Area 2: 15

is not hampered by cloud coverage. Combining Sentinel-1 and 2 would increase the frequency of observations and build an effective early warning system to guide water hyacinths mitigation and clean-up efforts.

Other developments may include refining the classification method to estimate the ratio of water hyacinth content for each pixel, rather than provide a binary classification of it belonging to the water or water hyacinth class. Another advantage of this approach would be to take into consideration small water hyacinth patches. In the Saigon river, large water hyacinth patches break down when passing through Ho Chi Minh City, possibly due to navigation, salinity or higher flow velocity in that portion of the river. A recent field campaign conducted at Thu Thiem estimated that almost all the observed water hyacinth patches had a size of less than 5 m² (Schreyers et al 2021c), well below the minimal resolution of Sentinel-2. However, most patches were found drifting next to each others, probably filling a larger portion of a 10×10 m pixel. Overall, estimating the percentage of a Sentinel-2 pixel covered by water hyacinths would enable to better account for heterogeneity in patch size and density across a river system.

Kleinschroth et al looked at water hyacinth presence in 20 reservoirs and their associated river sections around the world, and found an increase in water hyacinth coverage for all studied sites (except one) from 1984 to 2018 (Kleinschroth et al 2021). This increase in water hyacinth presence in rivers is often associated with trends in urbanization, which is in turn also correlated with plastic abundance in rivers (Best 2019). For instance, the Chao Phraya river in Thailand has a high abundance in both water hyacinth coverage and plastic pollution concentrations (Ta and Babel 2020, Kleinschroth et al 2021). Considering that water hyacinths in the Saigon river accumulate the majority of floating plastic debris (Schreyers et al 2021a), estimates on water hyacinth coverage could be used as a proxy to quantify riverine plastic transport and accumulation.

Despite challenges associated with detecting small hyacinth patches and seasonal cloud coverage, the method used here is highly suitable for large-scale monitoring and to provide a first order estimate of hyacinth coverage. Another benefit of the method is its replicability, as it uses freely available Sentinel-2 imagery within the Google Colaboratory environment. Such an approach can be extended to other freshwater bodies invaded by water hyacinths for long-term and large-scale monitoring. This is particularly relevant due to a rise in the number of affected rivers and lakes worldwide, as well as an increase in hyacinth coverage in affected systems (Kleinschroth et al 2021). However, several uncertainties remain regarding the transferability of this approach to other river systems. As mentioned in section 3.1, in other water bodies the hyacinth peak season occurs during the wet season when cloud coverage is more persistent, thus limiting the number of satellite scenes suitable for analysis. Under different flow conditions, small hyacinth patches might not be detectable with the Sentinel-2 sensor, thus requiring the use of higher resolution sensors for accurate mapping of hyacinth coverage.

Monthly water hyacinth coverage showed strong, negative and significant correlations with relative humidity (r = -0.61) and rainfall (r = -0.58), suggesting that annual seasonality in hyacinth coverage might be linked to a reduction in water flows and levels. It remains unclear whether hydrological factors also affect daily and yearly variations in water hyacinths coverage. Further research into the role of hydrological parameters is needed for better understanding of hyacinth spatiotemporal variability, and to design control measures. Hydrological factors affect water hyacinths both in their proliferation and their movement within the river (Mugidde and Naro 2002). Flow velocity is an important factor regulating the growth of aquatic macrophytes, with increasing flow velocities typically corresponding to lower coverage and biomass (Chambers et al 1991). Additionally, wind, flow velocities and flash floods affect the movement of water hyacinths at the water surface. In the case of the Saigon river, it should be noted that the hydrological seasonality is further complexified by both tidal regimes and water release from the Dau Tien reservoir (Nguyen 2015). Other factors, such as reduced water flows in meanders and lower levels of water close to the banks likely promote the establishment of hyacinth patches. Therefore, additional in-situ measurements on the hydrometeorological conditions, as well as water quality indicators of the Saigon river are needed for a comprehensive understanding of the main drivers for hyacinths proliferation and transport.

4. Conclusion

Water hyacinths are highly dynamic and vary significantly along the river length and throughout the seasons. We characterized seasonality trends over a river system using the highest temporal and spatial resolutions non-commercial available satellite data. Our automated classification can be transferred to other river systems affected by hyacinth invasion.

For one of Vietnam's largest river, we revealed the spatial and temporal dynamics of water hyacinths over a three year period (2018–2020). We identified a clear seasonal cycle, with the dry season (December–May) corresponding to a period of higher hyacinth coverage. Water hyacinth coverage was also found to be strongly negatively correlated with rainfall and humidity (r=-0.58 and r=-0.61, respectively). In addition, we showed high interannual variability in water hyacinth coverage (10–50 ha in annual mean coverage over 60 km of river). Our study also highlights that hyacinth coverage can be particularly severe for the Saigon river, reaching as much as 14% of the total area monitored.

In this paper, we demonstrate the added value of using satellite imagery for long-term and large-scale detection of hyacinths in rivers. Understanding the seasonality and spatial variation are crucial for the design of mitigation strategies.

Data availability statement

The data that support the findings of this study are openly available. The code for water hyacinth Sentinel-2 based estimates can be accessed via https://github.com/n-janssens/Water-hyacinth-monitoring-tool. All statistical data used in this study can be accessed at: https://doi.org/10.4121/19229472.v1

Author contribution

Conceptualization: T V E, L B, N J; Data curation: N J, L B, L S; Formal Analysis: N J, L S; Funding acquisition: T V E, L B; Investigation: N J, L B, L S, T V E; Methodology: N J, L S, L B; Project administration: T V E, L B, L S; Resources: N J, L B, L S; Software: N J, L S; Supervision: T V E, L B; Validation: L B, T V E, M V D P; Visualization: N J, L S; Writing – original draft: L S, N J; and Writing – review & editing: all authors

Acknowledgments

We thank the two anonymous reviewers for their careful revision of our paper and helpful comments. We thank Martin Herold for his help in defining the scope of this study.

Funding

The work of T V E was supported by the 4TU. Federation Plantenna project, and the Veni research program The River Plastic Monitoring Project with project number 18211, which is (partly) funded by the Dutch Research Council (NWO). The work of L S was supported by NWO Open Mind Grant 18127. This study is part of the Plastic Plants project, supported by the Discovery Element of the European Space Agency's Basic Activities (ESA Contract No. 4000132682/20/NL/GLC).

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References

Al-lami A K, Abbood R A, Al Maliki A A and Al-Ansari N 2021
Using vegetation indices for monitoring the spread of Nile
Rose plant in the Tigris River within Wasit province, Iraq
Remote Sens. Appl.: Soc. Environ. 22

Best J 2019 Anthropogenic stresses on the world's big rivers *Nat. Geosci.* 12 7–21

Biermann L, Clewley D, Martinez-Vicente V and Topouzelis K 2020 Finding plastic patches in coastal waters using optical satellite data *Sci. Rep.* **10** 5364

Bisong E 2019 Google colaboratory Building Machine Learning and Deep Learning Models on Google Cloud Platform (New York: Apress) pp 59–64

CABI 2020 Eichhornia crassipes (water hyacinth) *Invasive Species Compendium* (Wallingford: CAB International) (https://www.cabi.org/isc/datasheet/20544)

Camara G, Assis L F, Ribeiro G, Ferreira K R, Llapa E and Vinhas L 2016 Big earth observation data analytics *Proc. 5th ACM SIGSPATIAL Int. Workshop on Analytics for Big Geospatial Data—BigSpatial '16* (https://doi.org/10.1145/ 3006386.3006393)

Camenen B, Gratiot N, Cohard J-A, Gard F, Tran V Q, Nguyen A-T, Dramais G, van Emmerik T and Némery J 2021 Monitoring discharge in a tidal river using water level observations: application to the Saigon River, Vietnam *Sci. Total Environ.* **761** 143195

Chambers P A et al 1991 Current velocity and its effect on aquatic macrophytes in flowing waters Ecol. Appl. 1 249–57

Chapungu L, Mudyazhezha O C and Mudzengi B 2018 Socio-ecological Impacts of Water Hyacinth (Eichhornia Crassipes) Under Dry Climatic Conditions: The Case of Shagashe River in Masvingo, Zimbabwe J. Environ. Sci. Public Health 2 36–52

Dersseh M G, Melesse A M, Tilahun S A, Abate M and Dagnew D C 2019 Water hyacinth: review of its impacts on hydrology and ecosystem services—lessons for management of Lake Tana Extreme Hydrology and Climate Variability (Amsterdam: Elsevier) pp 237–51

Dersseh M G, Tilahun S A, Worqlul A W, Moges M A, Abebe W B, Mhiret D A and Melesse A M 2020 Spatial and temporal dynamics of water hyacinth and its linkage with lake-level

- fluctuation: Lake Tana, a sub-humid region of the Ethiopian highlands *Water* **12** 1435
- Du Y, Wu Q, Kong D, Shi Y, Huang X, Luo D, Chen Z, Xiao T and Leung J Y S 2020 Accumulation and translocation of heavy metals in water hyacinth: maximising the use of green resources to remediate sites impacted by e-waste recycling activities *Ecol. Indic.* 115 106384
- Ghoussein Y, Nicolas H, Haury J, Fadel A, Pichelin P, Abou Hamdan H and Faour G 2019 Multitemporal remote sensing based on an FVC reference period using sentinel-2 for monitoring *Eichhornia crassipes* on a Mediterranean River *Remote Sens.* 11 1856
- Gomes V, Queiroz G and Ferreira K 2020 An overview of platforms for big earth observation data management and analysis *Remote Sens.* 12 1253
- Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D and Moore R 2017 Google earth engine: planetary-scale geospatial analysis for everyone *Remote Sens. Environ*. 202 18–27
- Harun I, Pushiri H, Amirul-Aiman A J and Zulkeflee Z 2021 Invasive water hyacinth: ecology, impacts and prospects for the rural economy *Plants* 10 1613
- Ho Chi Minh City Bureau of Statistics 2019 Statistical Yearbook of Ho Chi Minh City 2019 (Ho Chi Minh City: General Publishing House) pp 26–27
- IUCN 2017 Water hyacinth, an invasive plant in the lake tanganyika basin (available at: www.iucngisd.org)
- Janssens N 2021 Water hyacinth monitoring tool (available at: https://github.com/n-janssens/Water-hyacinth-monitoring-tool)
- Kleinschroth F, Winton R S, Calamita E, Niggemann F, Botter M, Wehrli B and Ghazoul J 2021 Living with floating vegetation invasions Ambio 50 125–37
- Lock J M 1988 Water hyacinth *J. Tropical Ecol.* 4 92–93 Mugidde R and Naro L 2002 Environmental factors influencing composition, abundance and distribution of water hyacinth (available at: http://hdl.handle.net/1834/35528)
- Muramoto S, Aoyama I and Oki Y 1991 Effect of salinity on the concentration of some elements in water hyacinths (eichhornia crassipes) at critical levels *J. Environ. Sci. Health* A 26 205–15
- Nguyen T N T2015 Risk of eutrophication in the Saigon River: impacts of the Ho Chi Minh City Megacity (Vietnam)
- Nguyen T T N, Némery J, Gratiot N, Strady E, Tran V Q, Nguyen A T, Aimé J and Peyne A 2019 Nutrient dynamics and eutrophication assessment in the tropical river system of

- Saigon—Dongnai (southern Vietnam) *Sci. Total Environ.* **653** 370–83
- Ouma Y O, Shalaby A and Tateishi R 2005 Dynamism and abundance of water hyacinth in the Winam Gulf of Lake Victoria: evidence from remote sensing and seasonal-climate data *Int. J. Environ. Stud.* **62** 4
- Petrell R J and Bagnall L O 1991 Hydromechanical properties of water hyacinth mats *Aquac. Eng.* 10 133–47
- Schreyers L *et al* 2021c A field guide for monitoring riverine macroplastic entrapment in water hyacinths *Front. Environ.* Sci. 9
- Schreyers L, van Emmerik T, Biermann L and Le Lay Y-F 2021a Spotting green tides over brittany from space: three decades of monitoring with landsat imagery *Remote Sens.* 13 1408
- Schreyers L, van Emmerik T, Thanh Nguyen L, Castrop E, Phung N-A, Kieu-Le T-C, Strady E, Biermann L and van der Ploeg M 2021b Plastic plants: water hyacinths as driver of plastic transport in tropical rivers *Front. Environ. Sci.* 9
- Simpson M, Marino A, Nagendra Prabhu G, Bhowmik D, Rupavatharam S, Datta A, Kleczkowski A, Sujeetha J A R P and Maharaj S 2020 Monitoring water hyacinth in Kuttanad, India using Sentinel-1 sar data 2020 IEEE India Geoscience and Remote Sensing Symp. (Ingarss) (1 December) (https://doi.org/10.1109/InGARSS48198.2020.9358977)
- Ta A T and Babel S 2020 Microplastics pollution with heavy metals in the aquaculture zone of the chao phraya river estuary, thailand *Mar. Pollut. Bull.* **161** 111747
- Thamaga K H and Dube T 2018 Remote sensing of invasive water hyacinth (eichhornia crassipes): a review on applications and challenges *Remote Sens. Appl.: Soc. Environ.* 10 36–46
- Thamaga K H and Dube T 2019 Understanding seasonal dynamics of invasive water hyacinth (eichhornia crassipes) in the Greater Letaba river system using Sentinel-2 satellite data *GISci. Remote Sens.* 26 1355–77
- van Emmerik T, Strady E, Kieu-Le T C, Nguyen L and Gratiot N 2019 Seasonality of riverine macroplastic transport *Sci. Rep.*
- Vilà M, Espinar J L, Hejda M, Hulme P E, Jarošík V, Maron J L, Pergl J, Schaffner U, Sun Y and Pyšek P 2011 Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems *Ecol. Lett.*
- Winton R S, Kleinschroth F, Calamita E, Botter M, Teodoru C R, Nyambe I and Wehrli B 2020 Potential of aquatic weeds to improve water quality in natural waterways of the Zambezi catchment *Sci. Rep.* **10** 15467