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Monitoring and assessing the effectiveness of the biological control implemented to address the invasion of water hyacinth *(Eichhornia crassipes)* in Hartbeespoort Dam, South Africa

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ABSTRACT

Water hyacinth is one of the most aggressive alien invasive plants, which invades freshwater resources and destroys native biodiversity. The plant proliferates rapidly over a short space of time, forming thick dense layer on the surface of freshwater bodies. Monitoring and management of water hyacinth is essential to protect water resources affected by the presence of this plant. The study assessed the effectiveness of biological agent (*Megamelus scutellaris*) applied in the Hartbeespoort Dam from pre (2016–2017) and post (2018–2023) biological control to manage water hyacinth spread and proliferation. In achieving this main goal, the study used advanced cloud-computing machine learning techniques and multi date Sentinel-2 Multispectral Instrument (MSI) data to monitor the effectiveness of such biological control. During this analysis, remote sensing data was acquired for two time periods namely: pre-intervention (2016–2017) and post intervention (2018–2023) to establish variation in the spatio-temporal distribution of water hyacinth in the Hartbeespoort Dam using various machine learning techniques (Support Vector Machine (SVM), Classification and Regression Tree (CART), Random Forest (RF) and Naïve Bayes (NB)) in Google Earth Engine cloud computing platform, and assessed the spectral separability of water hyacinth from numerous land cover types, within and around the Hartbeespoort Dam using the Sentinel-2 derived spectral reflectance curves. The results indicated that the extent of water hyacinth area coverage decreased from 15% to below 6% between the period of 2018 and 2021, however, a significant increase was noted between November 2022 and April 2023, after the biological control was introduced. The significant increase observed during the time period of November 2022 and April 2023 can be attributed to nutrient rich water discharging into the dam from the Crocodile River during the time of flooding reported in November 2022. The result further indicate that RF produced the highest overall accuracies ranging between 93.42% and 98.70%. While NB produced the lowest accuracies ranging between 87.76% and 92.08%. These findings underscore the relevance of new generation satellite dataset and machine learning algorithms in monitoring the effectiveness of the biological controls of alien invasive spread provide information regarding alien plant invasion. Therefore, aligning with Sustainable Development Goals (SDG 6) emphasizing on the importance of implementing effective control measures to control invasive species and their impact on water resources thus ensuring the sustainability of freshwater ecosystems and the availability of clean water resources.

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1. Introduction

Aquatic alien invasive species have had a major impact on freshwater ecosystems across the world (Xu et al., 2012). Freshwater is a scarce and vulnerable resource to multiple stressors such as land-use changes, increasing global temperatures, eutrophication, and invasion by invasive species (Angeler et al., 2014). The decline in water quality of freshwater systems results in the ideal environment for algae and other aquatic alien species to grow and spread (Germishuys and Diamond 2022). Water hyacinth is native to the tropical regions of South America, and due it its ability to rapidly reproduce its biomass in short period of time it is regarded as highly invasive aquatic alien plant (Ajithram et al., 2021). The plant grows as a thick mat layer on the surface of freshwater bodies such as lakes, rivers, and dams. This reduces the amount of solar radiation and oxygen from penetrating the water for fish and other aquatic species, therefore causing a destruction to the freshwater ecosystem by reducing dissolved oxygen available for aquatic organisms to thrive. Moreover, large infestations of water hyacinth can also prevent river transport, fishing, damage bridges, and clog dams (Datta et al., 2021; Güereña et al., 2015), therefore, necessitating the effective management and control of the geographical spread and proliferation of this species.

The management of water hyacinth invasion has caused a significant economic burden in a number of countries such as Ethiopia, South Africa, and Kenya amongst others. In Ethiopia, it was reported that over US$100,000 have been used to control and eradicate water hyacinth between the years 2002 and 2013 (Yigermal and Assefa 2019). In Kenya, it has also been estimated that control of this alien invasive through mechanical controls could cost the country about US$60 000 000–200 000 000 (Yara, 2019), while in South Africa the reported estimate of controlling water hyacinth exceeds US$700 000, which is about 0.3% of the country's Gross Domestic Product (GDP) (Ilo et al., 2020). Although, mechanical control of water hyacinth proved to be costly, various countries have resorted to the use of cost effective approached such as chemical and biological control to manage the geographic spread and proliferation of water hyacinth. Chemical control involves the use of herbicides to control the spread and occurrence of water hyacinth. Despite being one of the cost-effective approach to manage this alien invasive species, the approach is not viable for long term purposes due to the environmental implications associated with the prolonged use of herbicides (Ilo et al., 2020).

Use of biological controls to manage the spread and proliferation of water hyacinth is the most cost effective and environmentally friendly solution compared to the mechanical and chemical approaches. This approach involves the use of biological agents such as *Neochetina bruchi*, *Neochetina eichhorniae*, and water hyacinth borer *Sameodes albiguttalis* amongst others which directly feed on this alien invasive (Gupta and Yadav, 2020). These species are released onto the infested water bodies to feed on the water hyacinth to control its spread and growth. Although earlier studies such as Van Wyk and Van Wilgen (2002) and Sanders et al. (2014), demonstrated the effectiveness and benefits of using biological agents such as *Sameodes albiguttalis* in controlling the geographical spread and proliferation of water hyacinth, there is still controversy concerning the efficacy and economic efficiency of the use of biological control of water hyacinth in non-tropical climate regions particularly in Africa (Auchterlonie et al., 2021; Thamaga and Dube, 2018a, b). This is caused by limited post – monitoring studies caused by lack of funds to conduct such research (Coetzee et al., 2022). These studies are critical, as they provide insights on the degree to which the release of biological agents have controlled the spread of this invasive species and establishing whether is a need for the use of dual approaches when managing its proliferation.

The availability of Remote Sensing approaches and Earth Observation data offer unprecedented opportunities for assessing the efficiency of biological controls in managing the geographical spread and proliferation of water hyacinth, with input from various freely accessible satellite sensors such as Landsat and Sentinel, it is possible to monitor changes in the extent of water pre- and post-release of biological control (Dube et al., 2017; Janssens et al., 2022). Therefore, addressing the challenges associated with cost implication. Although this is the case issues such as the spatial resolution of the freely accessible remote sensing data hinders the detection and monitoring of the changes in the extent of water hyacinth in the water ways (Thamaga and Dube, 2018a,b; Oyama et al., 2015). Moreover, unavailability of seamless cloud-free remote sensing image during certain times of the year further exacerbates challenges associated with the remote sensing of water hyacinth using freely accessible satellite data. Advancements in remote sensing data analytic tools such as the introduction of cloud computing platforms like Google Earth Engine, offer unique opportunities to address such challenges, with advanced data integrations for merging strengths of various data types, data filtering approaches as well as advanced machine learning techniques, monitoring of the changes in the extent of water hyacinth can be enhanced. Despite their capabilities, such platforms according to our knowledge have been underutilised. Leveraging such platform may enhance the understanding of the effectiveness of biological agents in controlling the geographical spread and proliferation of the water hyacinth. Therefore, contributing towards the achievement of Sustainable Development Goals (SDG 6 and 15), emphasizing on the importance of implementing effective control strategies for invasive species to ensure the sustainability of freshwater ecosystems and the availability of clean water resources.

Owing to that background, the study harnessed the capabilities of Google Earth Engine cloud computing platform coupled with freely accessible remotely sensed data to assess the effectiveness of biological agents in managing the spread and proliferation of water hyacinth in the Hartbeespoort dam in South Africa. Literature suggest that Hartbeespoort dam is one of the water ways which are heavily infested by this alien invasive species, as a results the Centre for Biology Control at Rhodes University in South Africa released 350,000 water hyacinth plant hoppers (*Megamelus scutellaris*) during the year 2018 in an attempt to control the infestation. However, funding limitations hindered the monitoring of the effectiveness of the approach in managing the spread of this species in the Hartbeespoort dam. Hence thereof, the objectives of the study were 1) To evaluate the variations in the spatial and temporal extent of water hyacinth in the Hartbeespoort dam pre- and post-release of the biological control agent, and 2) To evaluate the most appropriate machine learning technique(s), for monitoring the effectiveness of biological agents in controlling the spread of the water hyacinth in non-tropical climate regions.

2. Study area

Hartbeespoort Dam, situated in the Northwest Province of South Africa (25°43′32″S 27°50′54″E), is approximately 35 km northwest of Johannesburg and 20 km west of Pretoria (Fig. 1). It is nestled amidst picturesque mountain ranges, with the Magaliesburg quartzite mountains to the south and the Witwatersberg mountains to the north. This dam serves as a crucial source of water for a variety of purposes, including irrigation, residential, and industrial use, catering to the needs of nearby communities. With a capacity of 205 million cubic meters and a depth of around 45 m, the dam was initially completed in 1923 to ensure a reliable water supply during dry seasons when natural water sources tend to decline (Mitchell and Crafford, 2016). However, in recent times, Hartbeespoort Dam has faced ecological challenges, notably the proliferation of water hyacinth (*Eichhornia crassipes*). This invasive aquatic plant has thrived in the dam's waters, creating a range of environmental, socio-economic, and tourism-related issues. The rapid growth of water hyacinth in the dam is primarily attributed to a combination of natural factors and human activities. These include elevated nutrient levels, particularly nitrogen and phosphorus, stemming from agricultural runoff and pollution sources, which act as fertilizers that promote the plant's growth. Changes in the dam's hydrology, often caused by human interference in river flow regimes, have also disrupted the natural balance and provided favourable conditions for water hyacinth to flourish. Additionally, human activities like boating and recreational pursuits inadvertently contribute to the spread of water hyacinth fragments within the dam. The impacts of this water hyacinth proliferation are far-reaching. Ecologically, it disrupts native habitats by blocking sunlight and reducing oxygen levels due to the extensive mats it forms on the water's surface. This affects aquatic life, including fish and other species, and can lead to declines in biodiversity. Furthermore, it impairs water quality as decomposing plant material consumes oxygen, causing hypoxic conditions harmful to the ecosystem.

Socio-economically, the presence of water hyacinth imposes challenges and costs on water treatment facilities, potentially resulting in increased water bills for consumers. Agricultural activities near the dam may also suffer due to impediments caused by water hyacinth, potentially leading to reduced crop yields. Additionally, tourism, a significant economic driver in the region, may be negatively affected by the unsightly appearance of water hyacinth mats and navigation obstructions, impacting activities like boating and fishing. To mitigate these adverse effects, comprehensive efforts to control and manage water hyacinth in Hartbeespoort Dam are imperative. Such measures are essential for the restoration of the ecological balance, preservation of biodiversity, and the continued socio-economic well-being of the region. The restoration of this vital freshwater resource aligns with Sustainable Development Goal 6 (SDG 6) of ensuring the availability and sustainable management of water and sanitation for all, highlighting the broader significance of addressing the issue of water hyacinth in the context of water security and freshwater management.

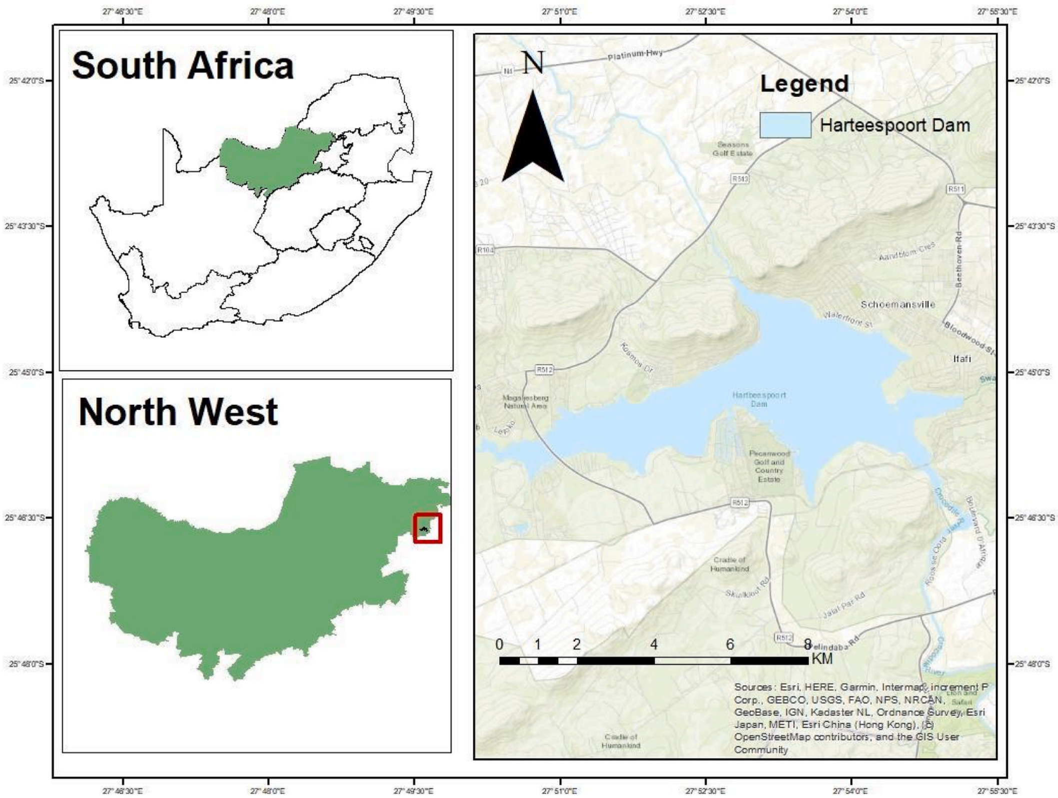

Fig. 1. Hartbeespoort Dam sight area map.

3. Methods and materials

3.1. Field data collection for model training and validation

Field data collection in these study involved the gathering of ground control points representing the geographical location of various Land cover types found within the region of interest. These points were collected from the review of record of other Land cover mapping studies conducted within the areas. Further, the collected points were supplemented by ground control points generated from Google earth for the same classes identified from the review of record using the high-resolution image corresponding to the dates of the remote sensing data. A total of 300 points were gathered from studies conducted, and these included 105 points representing water hyacinth, 50 points representing bare land, 50 points representing open water, 55 points representing vegetation as well as 40 points representing built up areas at the proximity of the Hartbeespoort Dam. The bare land class included roads, agricultural land which is not planted during the period of analysis and exposed bare mountainous surfaces such as rocks. The vegetation class included several types of vegetation namely agricultural vegetation, grass, forest trees and urban trees. Built-up land class included residential buildings, tall hotel buildings and other man-made structures located in close proximity to the Hartbeespoort Dam. The collected points were randomly split to 70/30% ratio, and the 70% data was used to train the machine learning models while 30% were used to validate the model output.

3.2. Spatial data acquisition and pre-processing data

For this study, multi date composite images of the Sentinel-2 Multispectral Instrument (MSI)) were used to study the changes in the extent of water hyacinth pre- and post-release of biological control in the Hartbeespoort Dam following the steps in Fig. 2. The selected images were collected between 2016 and 2017 for the pre-release and between 2018 and 2022 for the post release period. The study used images with less than 5% cloud cover proportion. During this process, the images were firstly filtered by the boundaries of the region of interest, followed by the dates as well as the cloud cover proportion. The obtained images were then sorted by dates representing both the pre and post release of biological control. The sorted images were then cloud masked to remove pixels contaminated by clouds. During this process Quality Assurance (QA60) bands containing information about pixels impacted by cloud cover were extracted. The QA60 bands were then used to create a masking function which was then applied on the image stack of each time period to remove pixels that are contaminated by clouds. The cloud masked images were then composited using the median composite algorithm in GEE cloud computing platform. Median composite algorithm function as an image stack reducer which calculates a median across the matching pixels and bands of a particular image stack, and the output will be a single composite image representative of the entire stack. The algorithm also assists in minimising the cloud and shade effects (Mahdianpari et al., 2020). The composite images representing the pre and post release of biological control were later used to compute the selected band ratios used to enhance the classification.

3.3. Spectral band ratios computation

To further enhance the classification of water hyacinth using the Sentinel-2 data, band ratios such as the Normalised Difference Vegetation index (NDWI), Normalised Difference Water Index (NDWI) as well as Modified Soil Adjusted Vegetation Index (MSAVI) were computed and integrated to the selected spectral bands from the composite images. These were then used during the classification process. The NDVI was selected because it is sensitive to photosynthetically active biomass, this is beneficial in differentiating between the aquatic vegetation and non-vegetated areas (Liu and Huete, 1995; Gxokwe et al., 2022). Moreover, the index was selected because it has proven to be successful in enhancing aquatic vegetation in a number of studies such as Dlamini et al. (2021) NDWI was chosen because of its sensitivity to open water, therefore, improving the segregation of water from, non-water pixels (McFeeters, 1996). MSAVI was selected to improve the limitations of the NDVI.

3.4. Remotely sensed data processing

The composite images with integrated band ratios were then subjected to Object-Based Image Analysis (OBIA). This approach considers contextual characteristics in addition to the spectral reflectance during the classification process, therefore minimising the 'salt and pepper' effects on the final classified images (Dlamini et al., 2021). Moreover, the integration of these contextual characteristics enhances the discrimination between target classes. The approach was selected because of its superiority to pixel-based analysis in a number of studies such as Mahdianpari et al. (2020) . The initial step to OBIA is image segmentation. During this process, the image is partitioned to a multiple discreet and non-overlapping objects based on a specific criterion. In this process the individual pixels are combined to form Superpixels which are used to compute their respective contextual characteristics (Pixel Area, Texture, Height, Size). These are then integrated to the original image to enhance the identification of the land cover features. In this study, we used a Simple Non-Iterative Clustering (SNIC) in GEE to segment the images. The approach was selected because of its simplicity, memory efficiency and its ability to maintain connectivity between the merged pixels (Mahdianpari et al., 2020). During the implementations of SNIC, the centroids were initiated on a cluster of pixels with the same colour and texture on a gridded image, then distance relative to the centroids and the candidate pixels was the computed in five-dimensional space of colour and coordinates. The next candidate pixel to be added on the cluster was decided based on the shorted distance to the centroid. During this process, the seed grids were set to 5 and this was decided based on a number of iterations, where the seed grid that yielded high overall accuracy was selected. In addition to the seed grid parameters such as "compactness factor" which affects the object shape, "connectivity" which defines the type of contiguity to merge adjacent objects as well as "neighborhoodSize" which assisted in avoiding the tile boundaries artifacts were set to 30, 1, 8 and 60, respectively. These were also decided on a number of iteration, where a combination that yielded the highest overall accuracy was chosen. The outputs from SNIC were Superpixels, which were then used to compute their respective contextual char-

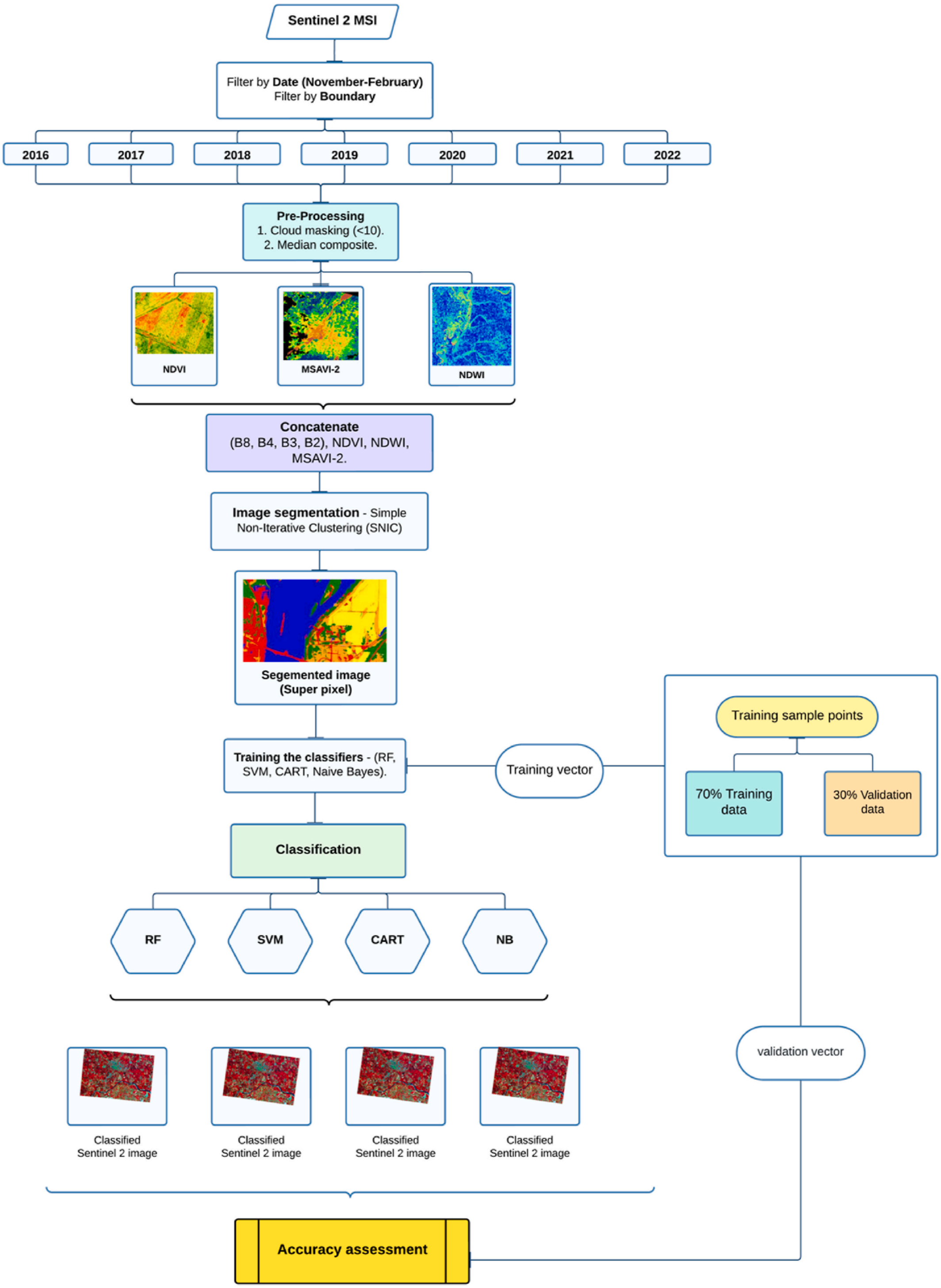

Fig. 2. Flow chart outlining methodology.

acteristics. The computed contextual characteristics were then integrated to their respective image composites, and these were later subjected to Machine Learning classification.

3.5. Machine learning classification

To perform image classification the study adopted four machine learning techniques namely: the Random Forest (RF), Classification and Regression Tree (CART), Naïve Bayes (NB) and Support Machine Vector (SVM), and the superior was selected for further analysis. The detailed explanation on these classifiers is provided in Gxokwe et al. (2022) and Simioni et al. (2020). During the implementation of these algorithms, the 70% ground control points were used to train the classifiers. In training the classifiers, the 70% ground control points were used to sample out regions corresponding to the geographical locations of the ground control points on the image composites. These were then used as inputs to train the classifiers, then these were used to classify the image composites. The classifier which yielded the highest overall accuracy was then used for further analysis.

3.6. Accuracy assessment

To validate the model output in this study, accuracy matrices such as Overall Accuracy (OA), Producer's Accuracy (PA) as well as User's Accuracy (UA) were used. OA measures the proportion of the correctly classified pixels, while PA and UA measure accuracy of the correctly classified individual classes, representing the likelihood that a classified pixel corresponds to the actual feature on the ground (Mtengwana et al., 2020). To compute the above matrices, the 30% remaining ground control points were used. In computing these, the data were overlain of the classified image composites, then areas corresponding to the location of those points were extracted then used to generate confusion matrix. The generated confusion matrix was then used to compute the OA, PA, and UA.

4. Results

4.1. Land cover class separability

The spectral reflectance curves of the land cover class (water hyacinth, bare land, vegetation, built up and water) within and around Hartbeespoort Dam from sentinel-2 data are shown in Fig. 3. The different land cover classes show a variety of spectral reflectance with Water hyacinth showing a higher reflectance value at the red edge 2 (B6), red edge 3 (B7), near-infrared (B8), and red edge 4 (B8A) regions of the electromagnetic spectrum when compared other classes, making it more separable to other land cover classes in these regions, for all the time periods, This was expected because water hyacinth is known to strongly reflect light in the Near-infrared and red edge regions, particularly at its healthiest stage (Cho et al., 2008). Comparative reflectance between pre- and post-release of the biological control revealed that in the year 2020 November to April 2021 the spectral reflectance of water hyacinth was lower compared to other years. This was expected because, the biological control was implemented around these years therefore causing the reduction in the health status of water hyacinth around this time. Although this was the case towards the end of the monitoring period April 2023, a spike in the reflectance was observed for this alien invasive. This was expected because the Hartbeespoort dam received an increased inflow of water from the Crocodile River which has been confirmed in a study by Germishuys and Diamond (2022) that the water had elevated faecal coliforms and *Escherichia coli* values. This may have contributed to the growth in this invasive since elevated *E. coli* favours its growth.

4.2. Spectral ratios for water hyacinth detection

Fig. 4 demonstrates the NDVI variation within the Hartbeespoort Dam used to identify the regions which have water hyacinth. Pixels with highly dense water hyacinth were found to have NDVI values which are around 0.82 and areas with lower densities demonstrate NDVI values which are slightly lower. Regions with no water hyacinth coverage lie on the lower end on the NDVI scale. This was expected because a study by Thamaga and Dube (2018) revealed that NDVI for water hyacinth typical ranges between 0.65 and 0.85.

Fig. 5 demonstrates the variation in NDWI values across the dam. Water hyacinth infested areas demonstrated lower values compared to areas with no water hyacinth present. Clear water has NDWI values around 0.5 and areas infested water produced values around −0.6. Where the water hyacinth is not significantly dense the NDWI value is moving towards zero on the negative side of the NDWI scale.

The MSAVI-2 is an index that was also used in this study to improve the classification of water hyacinth as an additional layer to concatenate before image segmentation (Fig. 6). This index was used because it helps overcome limitations of NDVI. Areas where water hyacinth is highly dense the MSAVI value is around 0.9 and areas with no water hyacinth is close to −0.6. Where the water is not entirely clear the MSAVI value is closer to zero.

4.3. Classification accuracies for water hyacinth detection

Table 1 demonstrates the overall accuracies of different machine learning algorithms (i.e. SVM, RF, CART, NB). For the study period of 7 years different classifiers were used to distinguish water hyacinth from four other land cover classes. All the classifiers produced overall classifications range between 87.76% and 98.70%. The RF and SVM classifier produced high accuracy results compared to CART and NB. NB had the lowest accuracies where the overall accuracies range between 87.76% and 92.08%. RF produced the highest class accuracies which ranged between 93.42% and 98.70% respectively, therefore was used for further analysis (see Table 2).

4.4. Spatial and temporal variations of water hyacinth before and after biological control

In Figs. 7 and 8 the distribution of water hyacinth is represented alongside other land cover classes around the dam. Water hyacinth coverage in the dam varied from year to year as the biological control is implemented. The least abundance was in 2021 and the most was in 2022. The plant is formed on the border of the dam compared to the centre.

The annual spatial coverage of water hyacinth in the Hartbeespoort dam varies from 2016 to 2022. For each year, the area was determined for water hyacinth coverage for the summer and spring months (November to April) from the year 2016–2023. For 2016, 2017, 2018, 2019, 2020, 2021, 2022 the percentage of area coverage was 10%, 12%, 15%, 9%, 7%, 6% and 37%, respectively. The

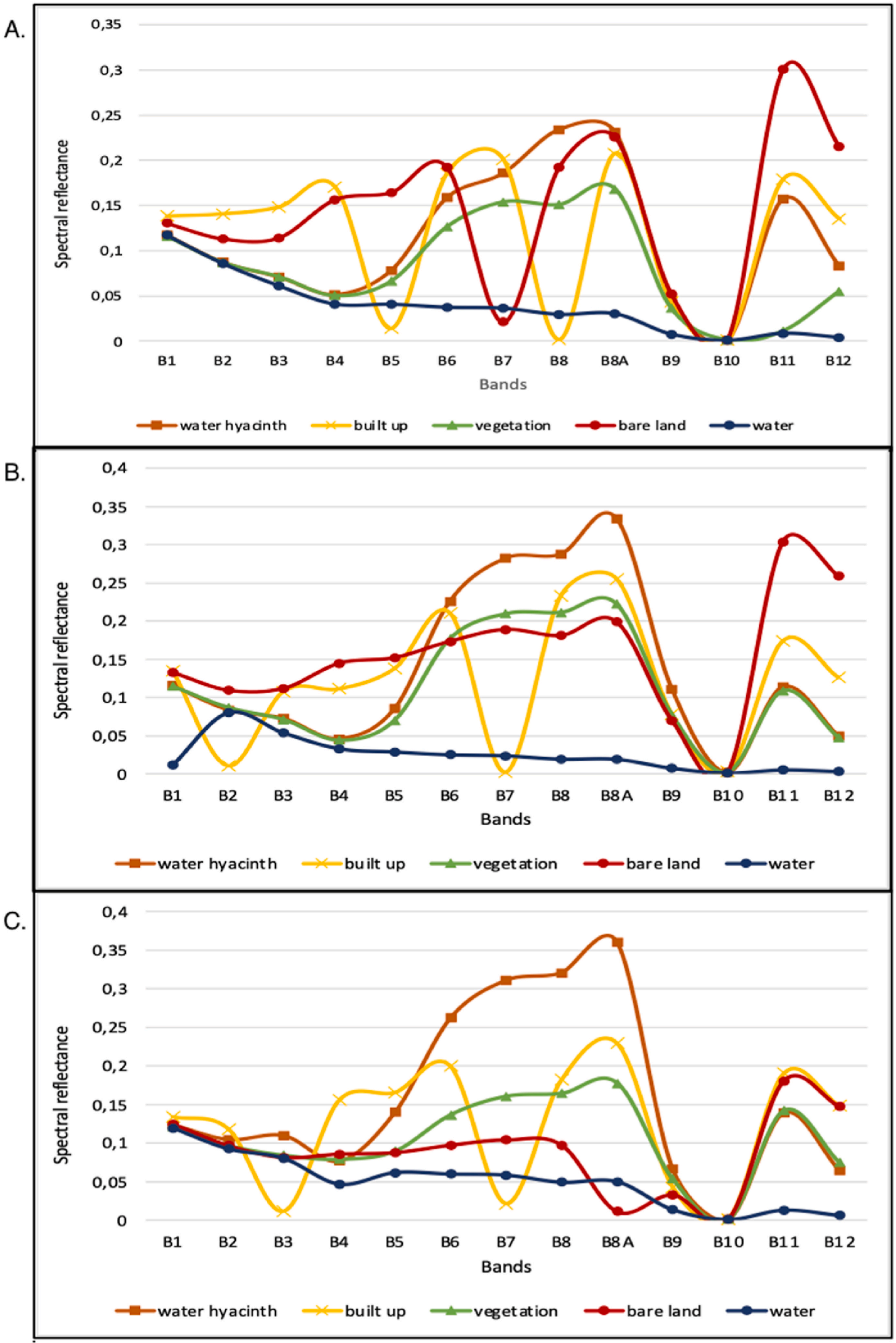

Fig. 3. Spectral reflectance curves of different land-use and land cover from Sentinel-2 data (a) 2017 November to 2018 April, (b) 2020 November to 2021 April (c) 2022 November to April 2023.

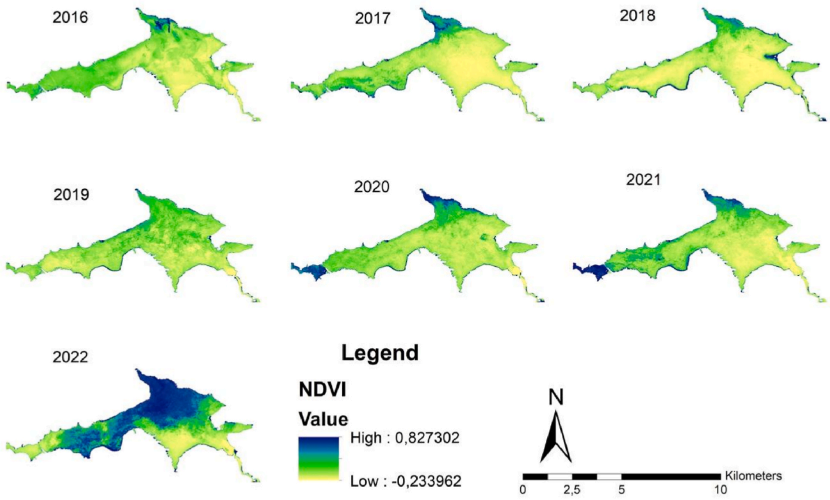

Fig. 4. Normalised difference vegetation index (NDVI) for Hartbeespoort Dam water hyacinth detection.

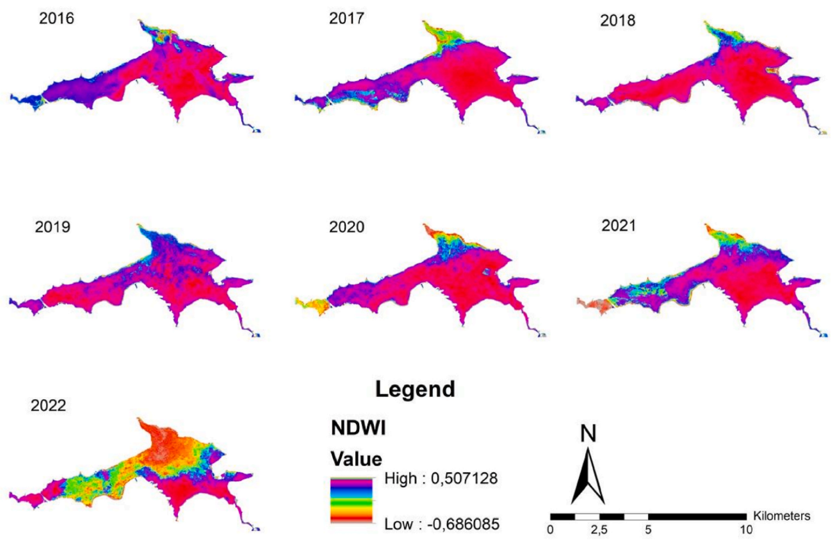

Fig. 5. Normalised difference water index (NDWI) for Hartbeespoort Dam water hyacinth detection.

biological control in the Hartbeespoort Dam was implemented in 2018 in the month of October by the Centre for Biological Control (BCB). There was a gradual decrease in the water hyacinth area coverage after the implementation of this agent however in 2022 there was a visible sharp increase in the water hyacinth area coverage this is clearly demonstrated on Fig. 8.

5. Discussion

This study intended to map water hyacinth (*Eichhornia crassipes*) in the Hartbeespoort Dam, using machine learning algorithms on google earth engine cloud computing platform pre and post the implementation of biological control agent (*Megamelus scutellaris*) to manage the spread and proliferation of water hyacinth in this system. Using remotely sensed datasets the findings underscored the relevance of GEE cloud-computing platform and a combination of Sentinel-2 data in monitoring the effectiveness of biological control in managing the spread and proliferation of water hyacinth in the Hartbeespoort Dam. The classification results showed that RF and SVM classification methods produced a higher overall accuracy compared to the NB and CART. This was expected because RF model has been considered to be less sensitive to noise, hyperparameters and sample size compared to other classifiers, as such RF is more capable of handling high-dimensional data, missing data, outliers, and unbalanced classes, therefore causing the classifier to outperform the others. This has been observed in numerous studies mapping water hyacinth across different countries, such as Rwanda (Mukarugwiro et al., 2019), Ethiopia (Bayable et al., 2023) and Portugal (Pádua et al., 2022) amongst other studies.

The results further showed a steady decline in the areal coverage of water hyacinth in the dam where the changes moved from 15% in 2018 to 9% in 2019 and from 7% in 2020 to 6% in 2021. The biological control was implemented in order to reduce the invasion of water hyacinth to a level where it is no longer problematic and the dam can be accessible for use (Venter et al., 2013; Thamaga

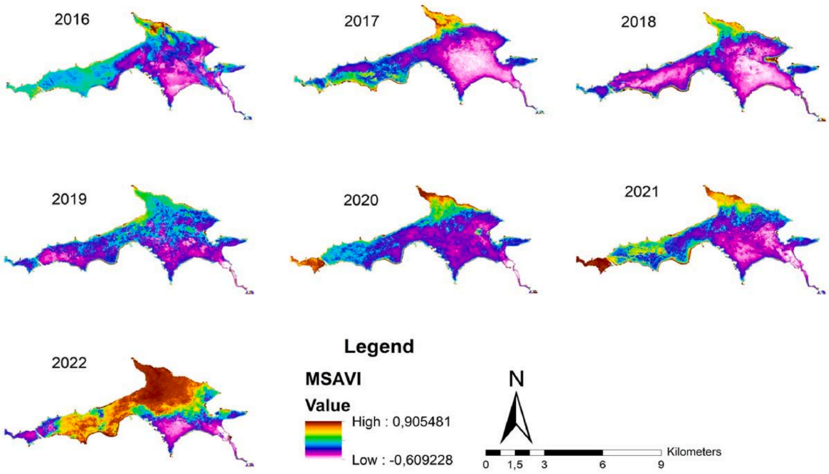

Fig. 6. Modified Soil Adjusted Vegetation Index 2 (MSAVI-2) for Hartbeespoort Dam water hyacinth detection.

Table 1
Overall accuracy using RF, CART, SVM and NB.

Overall Accuracy	2016	2017	2018	2019	2020	2021	2022
RF	96,59	96,67	97,22	98,7	97,3	97,14	93,42
CART	95,33	94,06	94,81	96,1	94,9	96,67	90,38
SVM	97,56	97,03	97,25	97,4	95,92	97,4	93,88
NB	91,46	92,08	90,91	88,31	90,82	88,31	87,76

The producer and user accuracy of the RF classifications range from 89% to 100% and 79%–100% respectively. Water hyacinth classification producer accuracy was 100%for most of the years. However, the user accuracy had variations in 2016 and 2018 which produced 96%–92%. Vegetation class had the lowest accuracy values ranging from 86% to 100% for the producer accuracy. For the user accuracy the Bare land class has the lowest accuracy ranging 76%–100%.

Table 2
Producer and user accuracy classifying water hyacinth using Random forest.

Producers Accuracy:	2016	2017	2018	2019	2020	2021	2022
Water	100%	100%	91%	100%	100%	100%	100%
Bare land	95%	94%	100%	93%	100%	100%	85%
Vegetation	89%	91%	100%	86%	89%	95%	88%
Water Hyacinth	100%	100%	100%	100%	100%	100%	100%
Built up	100%	100%	94%	96%	100%	93%	92%
User Accuracy:	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Water	100%	100%	100%	100%	100%	100%	100%
bare land	100%	89%	93%	76%	83%	92%	79%
Vegetation	94%	100%	100%	100%	100%	100%	94%
Water Hyacinth	96%	100%	92%	100%	100%	100%	100%
Built up	93%	94%	100%	96%	100%	93%	92%

and Dube, 2019a,b). The introduction of the (*Megamelus scutellaris*) proved to have reduced the proliferation and spread of this alien invasive within the Hartbeespoort Dam. This was expected because water hyacinth plant hopper is known to feed on the water hyacinth and therefore decreasing the flower and plant size, reproduction of vegetation and seed production thus preventing its spread and growth (Del Fosse, 1978; Coetzee et al., 2005; Damtie et al., 2021a,b; Venter et al., 2013). A similar finding was reported in a study by Sanders et al. (2014), where biological agent *Megamelus scutellaris* was released to control the spread of water hyacinth in the Gulf Coast state Louisiana. The findings indicated a decline 33% of water hyacinth coverage within the area, therefore corroborating our study.

Although the results showed a continued decline in the spatial coverage of water hyacinth, a spike was observed for 2022. This was however expected because the Hartbeespoort Dam receives an inflow of water from the Crocodile River which has been confirmed in a recent study by Germishuys and Diamond (2022) that the water had elevated faecal coliforms and *Escherichia coli* values. As a result of this, when there is a large inflow rate of water from the Crocodile River into the dam this would cause significant increase in dissolved nitrogen entering the dam. This would cause eutrophication in the dam and therefore increasing the eutrophic state of the dam thus causing the growth water hyacinth. This was also observed in a study by Yu et al. (2019), which assessed the relationship between the eutrophication, elevated nutrients, and growth of water hyacinth in China. The results in this study revealed positive correlation between eutrophication levels, nutrient concentration, and water hyacinth growth in China, therefore corroborat-

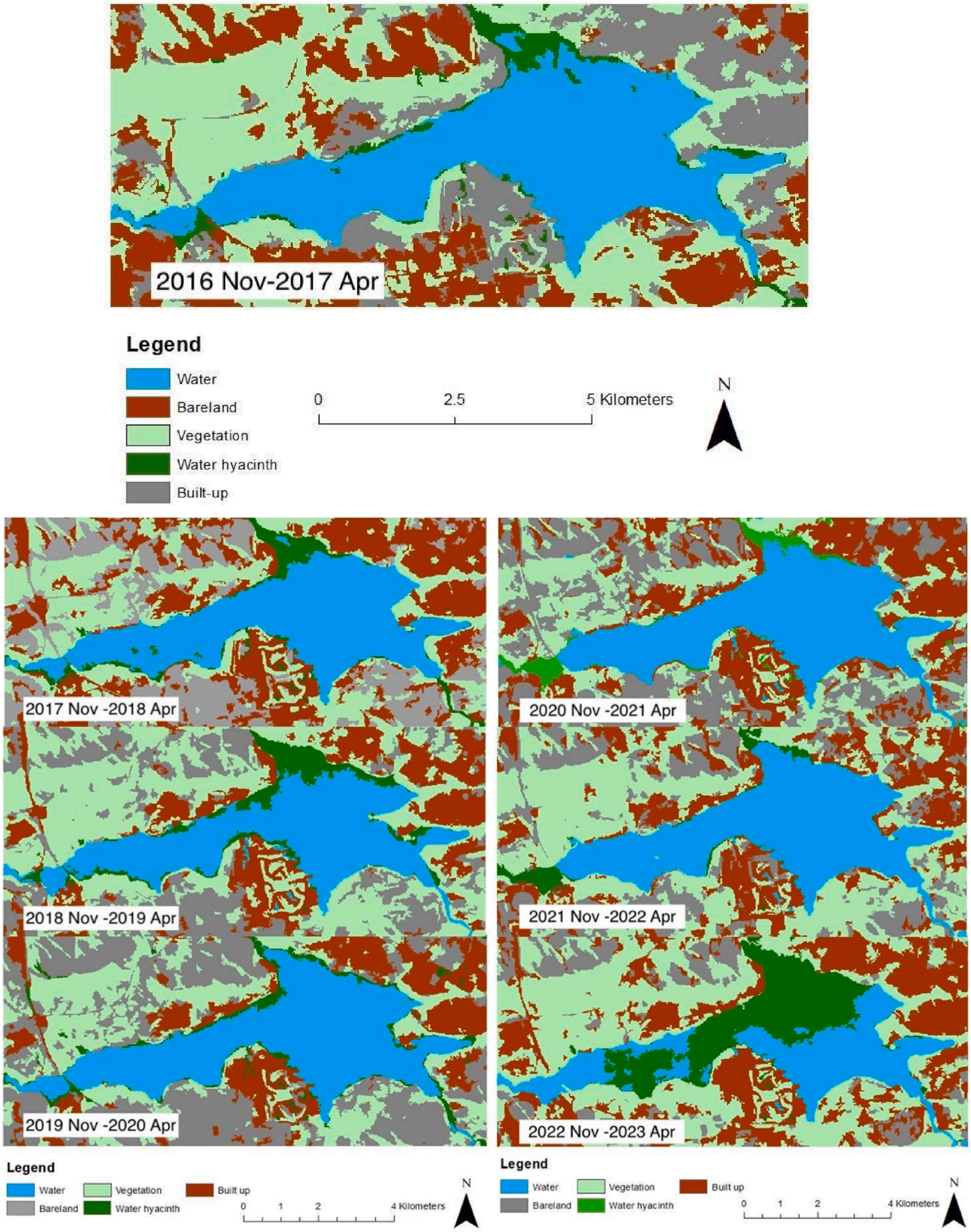

Fig. 7. Spatial distribution of water hyacinth in 2017 November to 2023 April.

ing our study. Spectral separability results show that water hyacinth was most separable from other classes in the Near-Infrared, Red edge regions of the electromagnetic spectrum. This was expected because of the high chlorophyll pigmentation in this alien invasive which causes it to reflect more light in the regions than the other classes especially during its healthy fully grown stage which corresponds to the dates of the used remotely sensed image. As such, its strongest reflectance around the time and stage made it more discernible from the other land cover classes. This has been also observed in a study by Mouta et al. (2023) which analysed the spectral reflectance of water hyacinth in Carvado River northern Portugal using Sentinel-2 data. The findings by Mouta et al. (2023) showed that water hyacinth reflected more light in the Near-Infrared and Red edge regions of the electromagnetic spectrum, therefore corroborating our findings.

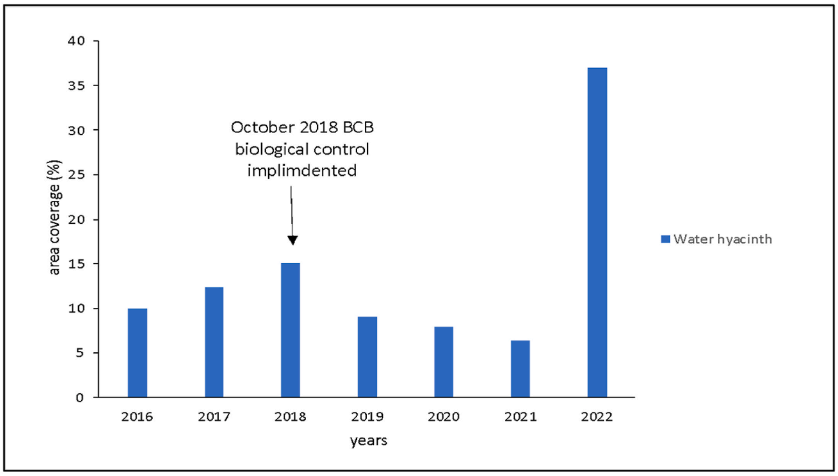

Fig. 8. Area coverage of water hyacinth in Hartbeespoort Dam between 2016 and 2022.

Overall, the study provides insights on the robustness of remote sensing data coupled with cloud computing approaches and Machine Learning techniques in understanding the effectiveness of the biological control in managing spread and proliferation of alien invasive, in particular water hyacinth. Such findings are critical in environmental and ecosystems protection services since it provides information on whether the successfulness of strategies managing the spread and proliferation of alien invasives, therefore allowing for the determination of whether there is a need for new strategies and efforts to manage these species. Moreover, this study aligns with 2030 Sustainable Development Goals (SDG 6) emphasizing on the importance of implementing effective control strategies for invasive species to ensure the sustainability of freshwater ecosystems and the availability of clean water resources. Although the study underscores the relevance of cloud computing platforms coupled with freely accessible remotely sensed data in assessing the effectiveness of biological controls in managing the growth and spread of water hyacinth, the unavailability of cloud free images for a certain time of the year limits the time series monitoring of the changes in the extent of this alien invasive. Moreover, the unavailability ground control points for other times limited the robustness of the monitoring of the changes in the extent of water hyacinth in this study.

6. Conclusion

This study focused on assessing the effectiveness of biological control in managing spread and proliferation of water hyacinth in the Hartbeespoort Dam using GEE cloud computing platform coupled with freely assessable multi-year Sentinel-2 data and machine learning techniques. The analysis revealed that water hyacinth varied spatially and temporally pre- and post-biological control, where a continued decline was observed post-biological control until 2022 were a spike in the growth was observed. This was attributed to the increase in *E. coli* within the water resulting from inflows from Crocodile River which favoured the growth of water hyacinth in the Hartbeespoort Dam. Moreover, the results showed that RF and SVM were the most appropriate algorithms for monitoring the effectiveness of biological control in managing the spread and proliferation of water hyacinth, where these algorithms outperformed NB and CART. Spectral separability results indicated that water hyacinth is more discernible from other land cover classes from the NIR and Red edge bands where it was noted this alien invasive had the strongest reflectance. Based on these findings it can be concluded that remote sensing data coupled with cloud computing platform and machine learning techniques offer unique opportunities address challenges associated with the monitoring of the effectiveness of biological controls in managing water hyacinth spread and growth, however challenges such as cloud cover on the images during certain times of the year limits the use of remote sensing approaches.

CRediT authorship contribution statement

Pawu Mqingwana: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Cletah Shoko:** Writing – review & editing, Writing – original draft, Validation, Supervision, Formal analysis, Data curation, Conceptualization. **Siyamthanda Gxokwe:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Timothy Dube:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflicts of interest related to this research.

Data availability

Data will be made available on request.

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