SPECTRAL DIFFERENTIATION OF SIX AQUATIC WEEDS IN LAKE CHIVERO, ZIMBABWE

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ABSTRACT

Although aquatic plants are fundamental to the functioning of aquatic ecosystem, their proliferation requires a certain level of control and management. Spectral analysis of aquatic weeds offers an opportunity for understanding the distribution and extent of specific aquatic weeds including evolution of weed invasion, propagation and colonization of affected areas. The objective of this study was to measure and differentiate aquatic weeds (*Hydrocotyle ranunculoides* (Spaghetti Weed), *Eichhornia crassipes* (Water hyacinth), *Pistia stratiotes* (Nile cabbage or Water lettuce), *Typha capensis* (Common bullrush) and *Phragmites australis* (Common reed) in Lake Chivero, Zimbabwe based on their spectral characteristics. An LI1800 portable spectroradiometer was used for collecting aquatic weed spectral data at 10-nm wavelength interval. The null hypothesis, that there was no significant difference in the mean radiance of the six aquatic weed species, was tested using ANOVA and Tukey's Honest Significant Difference test at 0.05 significance level. The study showed that most of the aquatic weeds analysed in the study possess unique spectral characteristics which provided a basis for significant ($p<0.05$) spectral separation of these macrophytes. The research further revealed that increased spectral separability of aquatic weeds is better in long wavelength region than in short wavelength region of the electromagnetic spectrum. There is need for more research on spectral separabilty of aquatic weeds, not only in Lake Chivero, but in all water bodies which are at risk of aquatic weed invasions, especially using airborne hyper spectral techniques in order to cover larger representative areas.

Key words: aquatic weeds, hyperspectral remote sensing, separability

INTRODUCTION

In many regions of the world water is not only an essential but is also a limited and fragile resource Hirji, Johnson, Maro, & Matiza (2002). Extreme climate variability and emerging climate change make the resource more vulnerable. The occurrence of aquatic weeds and their infestation in the water bodies are increasing and constitute a threat to the environment as well as the socio economic conditions of the affected countries. In addition, the proliferation of aquatic weeds has resulted in many environmental problems such as water shortages and displacement of native flora and fauna as a result of the invasive species. Other adverse problems that have emerged as result of the aquatic weeds for example in Lake Chivero include fish kills, catch decline (Chenje, Sola, & Paleczny, 1998; Moyo, 1997). There is thus need for timely intervention and aquatic weed monitoring to enable management of these weeds.

The development of techniques based on remote sensing and GIS technology enables identification, mapping and quantification of aquatic weeds (Schouten, van Leeuwen, Bakker & Twongo, 1999) and hence provide a practical and more reliable measure of the magnitude of the aquatic weeds problem. The feasibility of spectral differentiation of vegetation has been explored by a number of researchers. Spectral differences of grass (Schmidt and Skidmore, 2003), submerged aquatic vegetation (Werstak, 2004), grasslands (Psomas, Kneubuhler, Huber, Itten & Zimmermann) grass quality (Mutanga, 2004), forest (Cochrane, 2000; Matthew, Robertsa, & Clark,2005) and tropical mangrove species (Vaiphasa, Ongsomwang, Vaiphasa, & Skidmore, 2005) are some of such studies. Despite the utility of spectral differentiation in the management of prolific and invasive aquatic weeds, the technique has to date not been widely (Everitt, Yang, Summy, Glomski, & Owens, 2011). The aim of this paper therefore was to test whether aquatic weeds can be spectrally differentiated using a spectrometer, that which can be used as a basis for identification and mapping of the weeds at a large spatial scale. In this study we investigated whether we could determine and differentiate the spectral characteristics aquatic weeds (*Hydrocotyle ranunculoides* (Spaghetti Weed), *Eichhornia crassipes* (Water Hyacinth), *Pistia stratiotes* (Nile cabbage or Water lettuce), *Typha capensis* (Common bullrush) and *Phragmites australis* (Common Reed) as well as relating hyper spectral data to multispectral data in Lake Chivero, Zimbabwe.

MATERIALS AND METHODS

Study Area

Lake Chivero is located 37km to the South West of Harare (Figure 3.1), Zimbabwe's capital city. It is located within the Manyame catchment at latitude $17^0 54^I$ and longitude $30^0 48^I$ and was dammed in 1952 Chikwenhere and Phiri, 1999). The lake is the main source of water for domestic, industrial and agricultural activities in Harare and the surrounding area. The catchment of Lake Chivero is around 2136 km^2, 13.6 km long and an average width of about 2 km, of which approximately 10% is urban development and 90% rural land (Magadza, 1997). The rural land is mainly used for agricultural crops and communal pasture.

Lake Chivero is located downstream of Harare city, which discharges partially treated and sometimes raw sewerage effluent into two of its tributaries, the Mukuvisi and Marimba Rivers. The sewage from City of Harare and Chitungwiza town

sometimes flow directly into these rivers enriching the Lake with phosphates, nitrates and heavy metals. Marimba River drains the Northern suburban area and the main industrial areas of Harare; Mukuvisi River originates in the North East and runs through the city centre of Harare and Manyame river flows to the South of Harare through Chitungwiza. From surrounding commercial farms run-off washes soil nutrients into the Manyame river system and thus contributes to the enrichment of the waters in Lake Chivero.
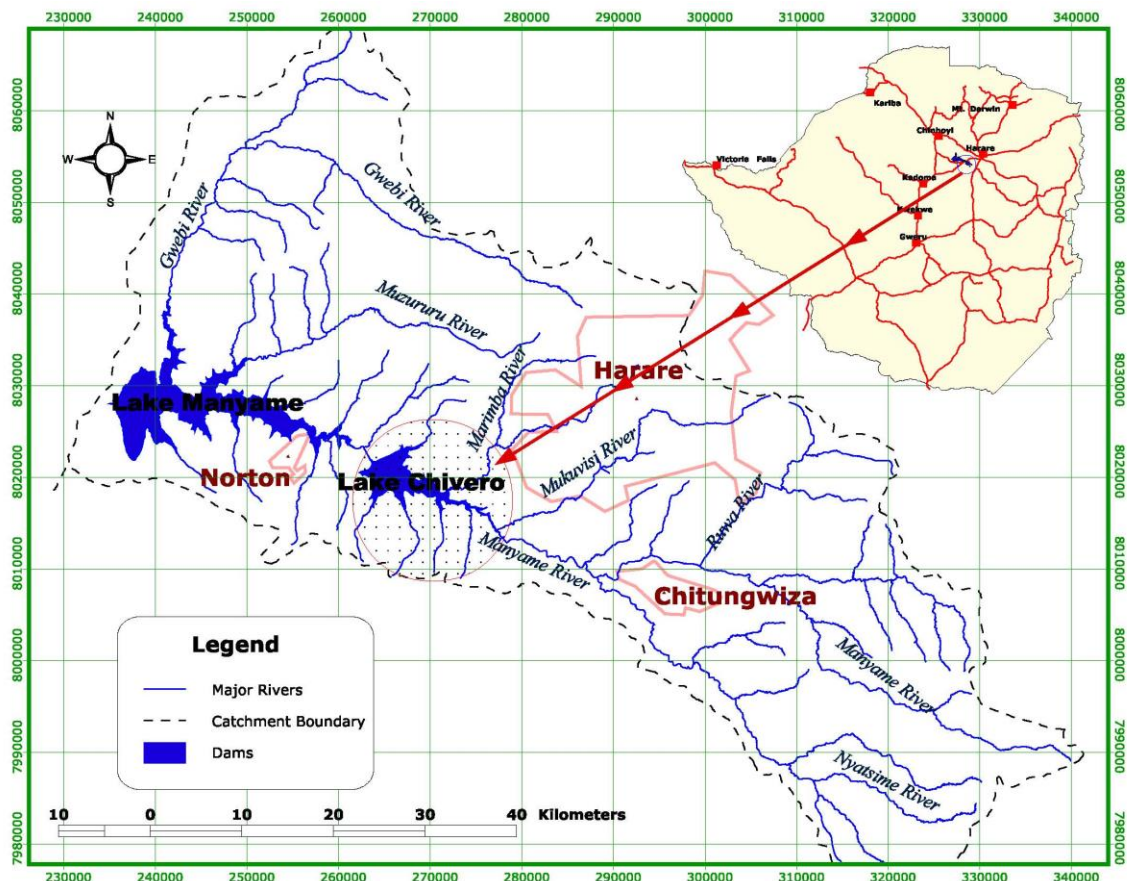

Figure 1. Location of Lake Chivero within the Manyame Catchment

Lake Chivero is a warm monomictic lake with water removal time of 8.82 years (Mitchell, 1974) with a capacity of 250.4 $*10^6 m^3$, a mean depth of 9.4 m and a surface area of 2630 ha. The lake became eutrophic in early 1960s and this resulted in the appearance of seasonal cynobacteria blooms in the 1960 and the establishment of permanent bloom in 1963 (Munro, 1966). Water samples collected in 1992 from the lake revealed unacceptably high levels of nitrates and phosphates (Moyo, 1997). Nutrient enrichment on the lake led to eutrophication and subsequently the proliferation of *Eichhornia crassipes* and other macrophytes since the 1960s. Since then, water quality and water weed proliferation in Lake Chivero have been the concern and subject of study of many researchers (see Moyo, 1997; Magadza 1997, Shekede, Schimdt & Kusangaya 2008).

Sampling of aquatic weeds

For the assessment of spectral characteristics of aquatic weeds samples were taken from transects along the Lake shores. Aquatic weed samples were collected for measuring radiance in the laboratory. Four representative samples of each of the six aquatic weed were collected from the different locations. Aquatic weeds samples were then placed in cooler boxes and quickly transported to the laboratory to preserve and maintain the original leaf quality for spectral measurements.

Spectral measurements were performed under laboratory conditions (a dark room) eliminate variation that are not related to the aquatic weed structure such as atmospheric effects and changes in illumination angle (Luther and Carroll, 1999; Mutanga, 2004). Six fresh aquatic weed species, i.e *Hydrocotyle ranunculoides*, *Eichhornia crassipes Pistia stratiotes*), *Typha capensis* and *Phragmites australis* were randomly placed into six piles each representing one weed type. For each laboratory spectral measurement equal multiple layers of each weed type was placed in the black box to overfill the FOV (Field of View). Ten spectral measurements were taken for each of the six fresh aquatic weed species to capture the variability of spectra emanating from the different aquatic weed parts such as leaves and stems. An LI1800 Portable Spectroradiometer was used to measure the spectral profiles of the aquatic weeds at 10-nanometr interval. The sensor, with a field of view of 180°, was mounted on a stool and was positioned at about 0.3m above the base of the black box. A 500-Watt Tungsten lamp was used to illuminate the weed sample in the box. The method used to gather spectral data borrows from (Vaiphasa *et al.*, 2005), who used hyperspectral measurements to discriminate tropical mangrove species.

Statistical tests

Spectral data were first tested for normality using the Kolmogorov-Smirnov test. Since all aquatic weeds spectral data followed a normal distribution, one way analysis of variance (ANOVA) was used to test whether the means of radiance between spectra associated with the six aquatic weed species were significantly different at each wavelength at 0.05 confidence level. We tested whether the spectral difference between aquatic weed species is greater than the spectral difference within aquatic weed species. The Tukey's Honestly Significant Difference test was used to determine if the aquatic weeds spectral profiles significantly differed from each other. In this regard, the spectral profile associated with each aquatic weed was tested for significant differences against the spectral band associated with other aquatic weeds in the same region of the electromagnetic spectrum. The post hoc test was applied to all fifteen possible pairs of aquatic weed species (see table for aquatic weed spectral combinations) testing each individual band measured across the electromagnetic spectrum. Formally put:

$$H_0 : \mu_i = \mu_j$$

Where μ_i and μ_j are the mean radiance for aquatic weed species and, i and j represent all possible unique combinations of pairs. Success in the rejection of the null hypothesis results in the adoption of the alternative hypothesis that states that:

$$H_1 : \mu_i \neq \mu_j$$

Thus any significant differences in the spectra associated with the six aquatic weeds indicates the possibility of spectral differentiation based on hyperspectral remotely sensed data.

Table 1: The fifteen possible pairs of aquatic weed species

	Phragmites australis	*Pistia stratiotes*	*Hydrocotyle ranunculoides*	*Typha capensis*	***Eichhornia crassipes***
Phragmites australis					
Pistia stratiotes	1				
Hydrocotyle ranunculoides	2	6			
Eichhornia crassipes	3	7	10		
Typha capensis	4	8	11	13	
Persicaria senegalensis	5	9	12	14	15

Resampling of laboratory spectral data

Raw library spectra were used in the initial analysis of the efficacy of using hyperspectral remotely sensed data to differentiate aquatic weed species. However, hyperspectral remote sensing data is expensive to acquire for large areas. As a result, we resampled hyperspectral data to mimic the response of Landsat TM in order to test whether the aquatic weeds could be differentiated using relatively low spectral resolution multispectral data. The rationale behind this approach was to establish a functional relationship that would enable combining of laboratory data with LANDSAT data since it is the sensor that has readily available images for determination of weed coverage and abundance changes. The aquatic weeds spectra were resampled to laboratory spectra to match the response of Landsat TM bands assuming the critical sampling and a Gaussian model with a FWHM (Full Width at Half Maximum) equal to the band spacing in ENVI (ENvironment for Visualising Images Research Systems Inc., 2005). The spectral range of the laboratory spectrometer only covered the first four of the Landsat TM bands. ANOVA test, was used for test whether the resampled spectral data for the 6 aquatic weeds were significantly different ($p < 0.05$). Further, Tukey HSD test was performed to test whether indeed there was a significant difference between the spectral associated with the six aquatic weeds.

RESULTS AND DISCUSSION

Visual differentiation

A visual examination of the spectral radiance curves of the six aquatic weeds allows for some spectral differences to be discerned between the aquatic weeds (Fig 2). The different aquatic weeds have a seemingly unique spectral signature although there are some overlaps between weed types. For instance there seems to be modest differences in the radiance curves of *Persicaria senegalensis* and *Hydrocotyle ranunculoides* in the 400-700nm and at about 750 to 1100 nm bands. However within the 750-800nm regions the two aquatic weeds exhibit spectral differences (Figure 2).
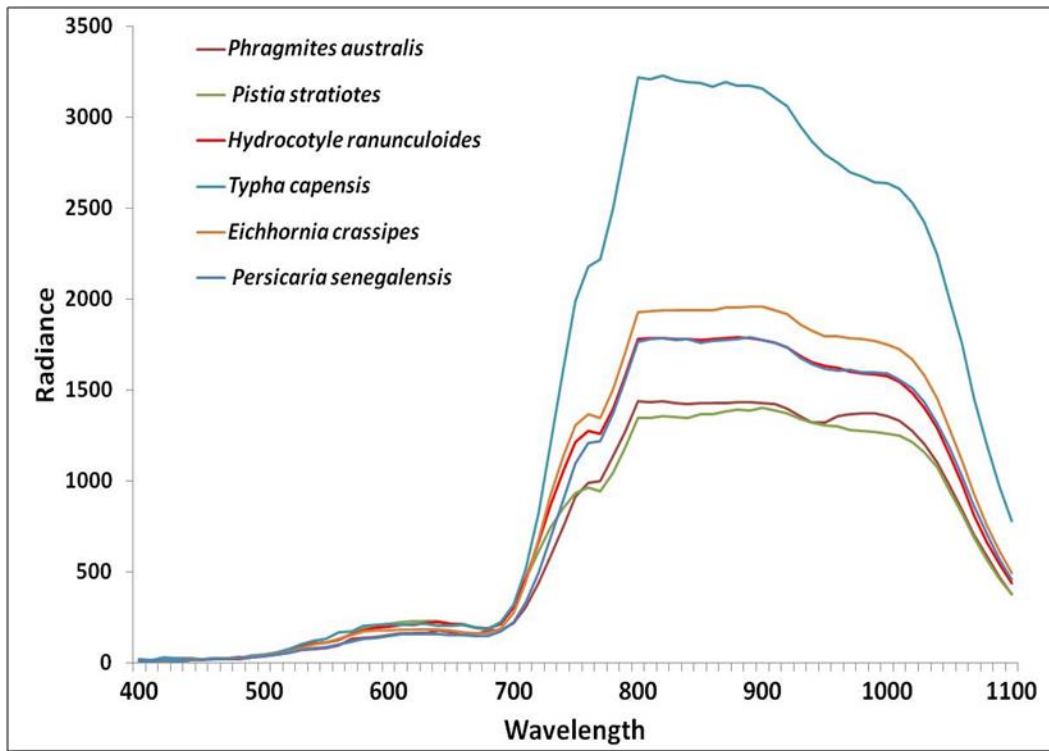

Figure 2: Mean radiance spectra for six aquatic weeds in the 400-1200nm spectrum

An examination of the spectral profiles of the aquatic weeds in the visible region (400-700nm) may lead one to conclude that the weeds cannot be spectrally differentiated. However, by zooming in on this region, the seemingly inseparable weed pairs were found to be visually distinct and appear to show much variation in the feature space as shown in Figure 3. The existence of crossovers in the spectral profiles of the six aquatic weeds may however make spectral differentiation difficult in the affected spectral bands.
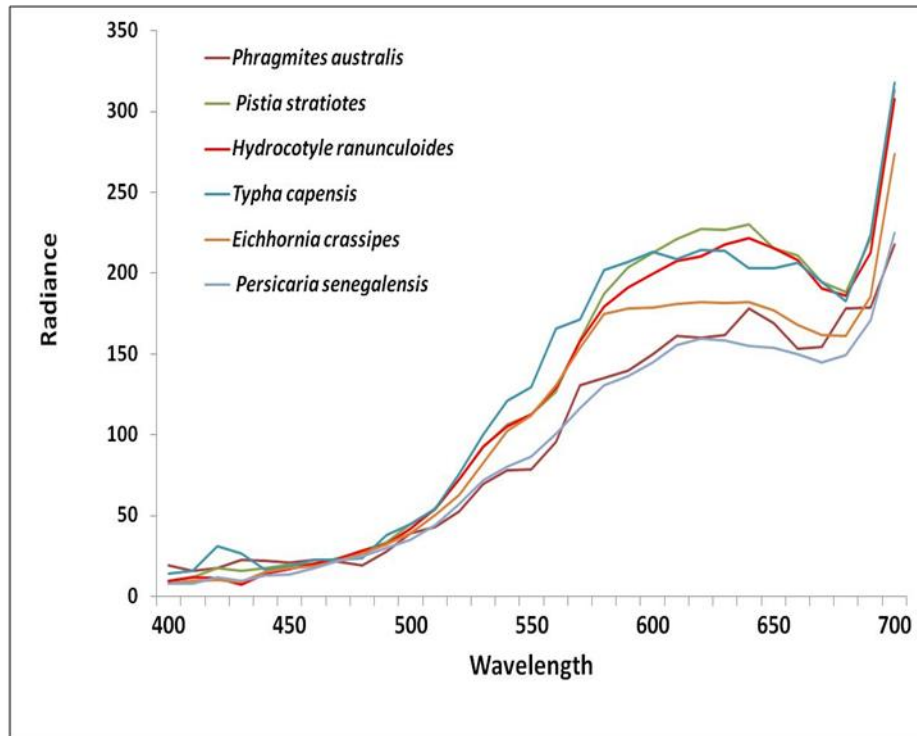
Figure 3: Mean light radiance spectra in the 400 to 700 nm spectral range of 6 aquatic weed species

With regards to spectral profiles of the six aquatic weeds, *Typha capensis* generally had higher spectral radiance in the visible region (from 400nm to 600nm and between 690nm-750nm) and a marked increase in radiance in Near Infrared (750nm to 900 nm) region than the other aquatic weed species. *Persicaria senegalensis* had the minimum spectral radiance in the visible region among the 6 species considered but increases sharply in the Near Infrared. *Hydrocotyle ranunculoides* and *Persicaria senegalensis* generally had similar spectral profiles across all wavelengths though the similarity is high in the Near Infrared Region.

Spectral separability of the 6 aquatic weeds across the electromagnetic spectrum

Results of the One Way Analysis of Variance on aquatic weed spectral pairs in the blue region (450-500 nm) indicate that there is a significant ($p<0.05$) difference in the spectra of the six aquatic weeds across all spectral bands. However, Tukey's Honestly significant difference test results on aquatic weeds spectral pairs in the blue region indicate that most aquatic weeds pairs have spectral profiles which are significantly different ($p<0.05$) from each other except the pair of *Hydrocotyle ranunculoides* and *Eichhornia crassipes* in the 450 and 470nm wavelengths (see Table 2). As could be inferred from the visual inspection of the aquatic weed spectra (figure 2), there are more inseparable aquatic weed spectral pairs in the green band than those in the Blue . Specifically, the spectral pair of *Phragmites australis* and *Typha capensis (at 530nm)*, *Phragmites australis* and *Persicaria senegalensis (at 550nm)*, *Hydrocotyle ranunculoides* and *Eichhornia crassipes (570nm)*, *Pistia stratiotes* and *Hydrocotyle ranunculoides (at 580nm)* cannot be significantly separated ($p>0.05$) based on their spectral radiance in the bands indicated in brackets. However, results of the posthoc analysis indicate that all the aquatic weed pairs

have unique spectral radiance in the green band except at the bands mentioned above. Further, the aquatic weed pairs are separable in 5 bands in the Green compared to 7 bands in the blue region of the electromagnetic spectrum.

Table 2: Summarised results of ANOVA and Tukey's multiple comparison of 6 aquatic weed species based on the radiance spectra between the 400 and 1100nm bands. *Phragmites australis (Pa), Pistia stratiotes (Ps), Hydrocotyle ranunculoides (Hr), Typha capensis (Ts), Eichhornia crassipes* (*Ec*) and *Persicaria senegalensis* (*Sp*). Aquatic weeds with the same letter (s) do not have a significantly different spectral radiance at p=0.05.

Bandwidth Range	F statistic range	1	2	3	4	5	6
400-450	3264.51-116866.92	a	b	c	d	e	a
460-500	6002.58-16323.82	a	b	c	d	e	f
510-550	1535.28-5346.21	a	b	c	a	d	a
560-600	1047.58-3186.67	a	b	b	a	a	c
610-650	642.35-3186.67	a	c	c	ab	b	a
660-700	270.10-4275.98	d	bcf	c	bd	aef	de
710-750	1515.56-5631.12	a	a	b	c	d	e
760-800	5267.56-5966.11	a	b	c	d	e	c
810-850	5035.04-5936.07	a	a	b	c	d	c
860-900	4976.3-5667.68	a	a	b	c	e	b
910-950	4165.55-4891.81	a	a	b	c	d	b
960-1000	3512.92-4040.06	a	b	c	d	e	c
1010-1050	3795.39-4487.89	ae	a	be	c	d	e
1060-1100	3443.58-6037.28	ab	b	ac	e	d	dc

Similar to the green band the, red region (630-690nm) possesses twelve aquatic weed combinations that are spectrally inseparable (p>0.05) with band 670 and 680nm having at least 3 inseparable aquatic weed pairs. In fact, at the 670nm band the pairs of *Pistia stratiotes and Hydrocotyle ranunculoides, Typha capensis , Eichhornia crassipes* as well as that of *Typha capensis and Eichhornia* crassipes are not significantly (p>0.05) different. Similar patterns are observed at the 680nm band.

Although there is greater spectral separability of aquatic weeds ($p<0.05$) at the red edge (700-800nm), the pair of 3 and 6 are insperable at the 700nm,760nm,770nm, and 790nm) while that of *Phragmites australis* and *Pistia stratiotes* cannot be spectrally differentiated at the 740 and 750nm bands. However, the rest of the spectral pairs are separable at this region. The Near Infrared Region (800-1100nm) does not suffer much from spectral overlaps compared with shorter wavelength regions. As a result the two wavelength regions have better spectral differentiation of aquatic weeds ($p<0.05$) compared with the green and the red bands. Only *Hydrocotyle ranunculoides* and *Persicaria senegalensis* as well as *Phragmites australis and Pistia stratiotes* are the only pairs that are spectrally inseparable ($p>0.05$) across the Near Infrared region. Specifically, *Hydrocotyle ranunculoides* and *Persicaria senegalensis'spectral* profiles are not significantly different ($p>0.05$) between 840nm and 920, 940-990nm and at the 1010-1020nm bands.

In summary, most weed types can be spectrally discriminated from each other in most parts of the electromagnetic spectrum. Most of the spectral overlap between aquatic weed species occurs in the visible spectrum especially in the red region. In the red region, aquatic weed combinations cannot be spectrally distinguished ($p>0.05$) in 13% of the bands. This is followed by 6.8% in the Near Infrared and 6.6% in the green portion of the electromagnetic spectrum (see table 3). However the percentage of inseparable aquatic weed combinations is very low compared to the number of possible cases that are significantly different ($p<0.05$).

Table 3. Number of significantly different spectral bands (Tukey's HSD test, $p<0.05$) for all possible pairs of vegetation per spectral band measured.

Spectral Region	Total number of aquatic weed combinations	Number of significantly different aquatic weed combinations ($p<0.05$)	Number of inseparable spectra combinations ($p>0.05$)
Blue (450-520)	120	118	2
Green (530-600)	120	112	8
Red (630-690)	105	93	12
Red edge (700-800nm)	165	156	9
Near Infra red (810-1100)	450	419	31

Resampled spectra

The spectra of the six aquatic weeds were resampled as mentioned above. The resampling procedure resulted in the reduction of number of spectral bands by resampling the 10 nm bands of the laboratory spectrometer to the wider bands of the Landsat TM sensor. The resulting band centres lie at 479, 561, 661 and 835 nm and represent the Blue, Green, Red and the Near Infrared bands of Landsat Thematic Mapper respectively. Figure 3 shows the resampled spectra associated with the six aquatic weeds considered in the study. It can be observed that *Typha capensis* still maintains the maximum radiance across all band centres while *Pistia stratiotes* has the least spectral radiance profile.
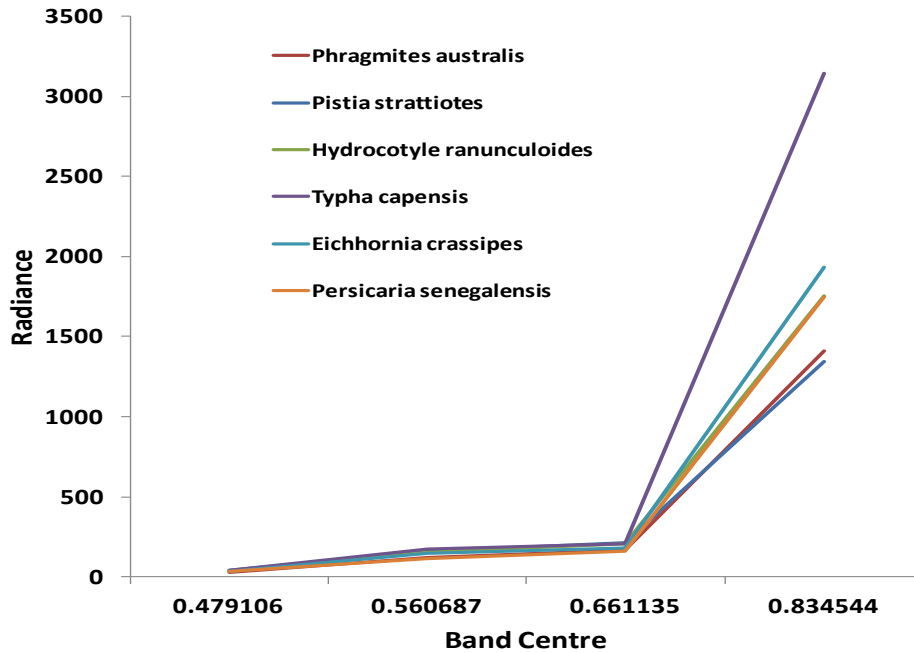

Figure 3. Resampled aquatic weed spectra

The results of the ANOVA analysis show that, in general, all the radiance spectra associated with each weed type were significantly different ($p<0.05$) in every spectral band (see Table 4).

Table 4: Summary of ANOVA results

Band Centre	F-statistic	P value
0.479	587.46	0.000
0.561	1171.10	0.000
0.661	855.51	0.000
0.835	5565.75	0.000

Results of the post hoc analysis indicate that while most weed combinations are spectrally separable across the bands the pair of *Pistia strattiotes* and *Typha capensis, Hydrocotyle ranunculoides and Typha capensis* as well as the pair of *Hydrocotyle ranunculoides* and *Persicaria senegalensis* are spectrally inseparable (p>0.05) at band centres *0.479,* 0.661 and 0.835 respectively. Similar to hyperspectral results, there are more instances when aquatic weed pairs are separable (57 times) across the bands than cases were 3 cannot be significantly separated based on their spectral profiles.

DISCUSSION

A visual examination of aquatic weed spectra in across the electromagnetic spectra (400-1100nm) showed that the six aquatic weeds are seemingly inseparable though analysis at close range revealed several overlaps among the spectra. Specifically, there are more spectral overlaps in the aquatic weed spectra in the shorter wavelength, especially in the red, than in the longer wavelength. Studies have shown that the red regions is a band of maximum chlorophyll absorption (Schmidt and Skidmore 2003, Mutanga et al 2003) and as chlorophyll concentration reaches high levels for all weed species, the spectral curves in the red spectrum tend to overlap. This may in part explain the prevalence of more aquatic weed spectral pairs that were statistically insignificant in the red region more than any other region in the visible portion of the electromagnetic spectrum.

Results from this study have demonstrated that the six aquatic weeds (i.e *Phragmites australis, Pistia stratiotes, Hydrocotyle ranunculoides, Typha capensis , Eichhornia crassipes* and *Persicaria senegalensis*) possess unique spectral profiles in selected bands and thus can be distinguished from each other based on their spectral radiance. Specifically, multiple comparison results showed that the blue, the green, the red-edge and the Near Infrared bands are the optimal bands for distinguishing aquatic weeds. This is evidenced by the large number of separable aquatic weed spectral combination compared with the inseparable ones (see Table 6). These results are consistent with those of Everitt *et al* (2011) who found out that although wetland vegetation could be differentiated in selected parts of the electromagnetic spectrum it was mainly in the NIR band that the greatest and noticeable differences were detected. Similarly, Ullah *et al*. (2000,) characterised spectral signatures of 3 emergent macrophytes and noted that the best separation among the species occurred at several bands in the NIR region with the optimal bands being bands882 and 885 nm. Though not specifically focusing on aquatic weeds, Becker et al. (2005) tested whether hyperspectral reflectance measurements could be used for identifying dominant botanical and

substrate classes of Great Lakes coastal wetlands. They reported that 8 spectral regions, 2 in the green (515 and 560 nm), 2 in the Red edge (686 and 732 nm), and four in the NIR (812, 824, 836, and 940 nm) were optimal for discriminating three selected emergent aquatic macrophytes. All these results suggest that though different aquatic weeds have specific bands of optimal separation, the NIR band seems to be optimal for separation of a number of aquatic weeds and plants (Becker *et al.*, 2005; Everitt *et al.*, 2011; Schmidt *et al.*, 2001; Ullar *et al.*, 200). These results offer have the potential to improve satellite based aquatic weed monitoring and management especially considering the adverse impacts of the aquatic weeds to aquatic ecosystems, economy as well as wellbeing of societies dependent on the aquatic resources.

In this study the response of Landsat TM (a relatively low resolution multispectral scanner) was mimicked, by degrading hyperspectral data to match the spectral response of Landsat TM in ENVI and tested whether aquatic weed species are separablebased on the resampled sprectra. Multi-comparison results have shown that *Pistia strattiotes* and *Typha capensis, Hydrocotyle ranunculoides and Typha capensis* as well as the pair of *Hydrocotyle ranunculoides* and *Persicaria senegalensis* are spectrally inseparable ($p>0.05$) at band centres *0.479,* 0.661 and 0.835 respectively. The results confirm that selected aquatic weeds can be separated directly from Landsat TM spectral measurement. However, the crossovers that exist between the spectra of aforementioned aquatic weeds call for more refined spatial and radiometric resolutions which enables the harnessing of hyperspectral data with satellite based remote sensed data for aquatic weed separation. The separability of aquatic weed species essentially provides a utility avenue of using remote sensing for weed monitoring and therefore water resources management.

CONCLUSION

The objectives of this study were to test whether aquatic weeds can be spectrally differentiated based on hyperspectral remotely sensed data as well as multispectral data generated from resampling hyperspectral data. This study has shown that aquatic weeds analysed in the study possess unique spectral radiance that was used to statistically discriminate among these aquatic macrophytes. This suggests that each aquatic weed can be spectrally differentiated and offers the possibility of carrying out targeted aquatic weed monitoring and management. This study has also proved that increased spectral separability of aquatic weeds is better in the long wavelengths especially the NIR than short wavelengths of the electromagnetic spectrum. Further, the study has employed a resampling method of mimicking Landsat TM's spectral response based on hyperspectral data to determine whether the six aquatic weeds could be discriminated using low resolution data. To this end, we have shown that the resampled spectra can be used to discriminate aquatic weeds. There is however to need to collect additional data of aquatic weeds over different seasons in order to build long and robust spectral profiles that can then be related to low resolution satellite data. This approach may provide a cheap and inexpensive way of detecting, mapping and managing aquatic weeds.

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