Remote Sensing-Based Detection and Assessment of Vegetation Biomass and Water Content of Urban Green Spaces in Mariental, Namibia

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Abstract

Urban green spaces (UGS) improve air quality and the hydrological cycle, which, in turn, results in a cooling effect on the microclimate. However, the maintenance of UGS in terms of water demand may be costly, particularly in arid and semi-arid environments, thus, achieving a balance is imperative. Mariental is situated in an arid zone and has the highest average temperature variations among the urban areas in Namibia. This study was therefore aimed at assessing biomass and vegetation water content (VWC) of green spaces in Mariental as proxies for gauging its effort towards ameliorating the town's microclimate in a water-deficient environment. The detection and assessment were based on two indices, the Modified Soil Adjusted Vegetation Index 2 (MSAVI2) and Normalised Differenced Water Index (NDWI), derived from a dry season Sentinel-2 image, acquired in August 2018. Field validation, focusing on the types of UGS, was carried out during the same week as the image acquisition. MSAVI2 depicted UGS and other non-biomass classes better than NDWI. Approximately 1% (6.6 ha) of Mariental is occupied by UGS as estimated using MSAVI2. The NDWI and MSAVI2 recorded mean values of 0.14 (very low) and 0.61 (low), respectively. The maximum values, derived for the central business district (CBD), were categorised as very high for the moisture (0.38) and biomass (0.79) indices. The estimated green space area translates to a per capita of 5m^2, with the minimum of the global average ranging between 5m^2 and 50m^2 per capita. Assessing the water demand for existing vegetation types will complement these results for a knowledge-based decision to expand Mariental's UGS while maintaining effective water management and improving its microclimate.

Keywords: *Arid environment, microclimate, Modified Soil Adjusted Vegetation Index, Normalised Differenced Water Index, sentinel.*

Introduction

Urban green spaces (UGS) are private and public open areas in the urban

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environment covered by vegetation (Haq, 2011). These vegetated spaces have a positive impact on the microclimate of an area as they help reduce solar radiation absorption through shading and evapotranspiration (Kurn et al., 1994). The biodiversity in UGS, the positive role of UGS towards the hydrological cycle and healthy plants further improve the air quality, and, ultimately, mitigate global warming (Fam et al., 2008; Shojaei et al., 2018; Environmental Protection Agency, 2010). Conversely, the shortage of UGS in arid urban environments in particular often leads to high land surface temperature, strong winds and frequent sand or dust storms (Pearlmutter et al., 2007). Urban greeneries also contribute to social benefits in the form of recreation, social interaction, psychological and physical needs of a healthy community, while simultaneously supporting economic benefits through employment opportunities and enhanced tourism value (Cilliers, 2015; Fam et al., 2008; Mensah, 2014).

Despite these benefits, UGS is depleting at a fast rate across the world, with the situation in Africa being critical (Mensah, 2014). McDonald et al. (2010), for example, report that between 1990 and 2000, approximately 1.4 million hectares of UGS were lost to other forms of land developments in 274 metropolitan areas across the USA. In Asia, UGS in Indonesian cities decreased from 35% to less than 10% (Kirmanto et al., 2012). In Australia, minimised urban irrigation and water restrictions contributed to a decline in UGS (Fam et al., 2008). Challenges that hinder the development of UGS in Africa, include, among others, the deficiency of appropriate technology for water harvesting within the urban centres, climatic conditions such as prolonged dry seasons (Zakka et al., 2017), social-economic and political challenges, the pressure of urbanisation, and insufficient operation of urban planning regulations (Mensah, 2014).

Maintenance of UGS is challenging in arid environments where daily thermal extremes are common (Shojaei et al., 2018) and may exert a heavy toll on the water resources required for irrigation, particularly during the dry season. Deister (2013) for example estimated that UGS in arid areas with high water demand are irrigated with approximately 6 l/m2 per day, while plants with moderate water demand require approximately 4 l/m2 of water per day, and those with low water demand require roughly about 1.5 l/m2 of water per day. It is also recognised that planting mixed vegetation types, which are common in urban greeneries, have a higher water demand in sustaining plants with diverse water needs and transpiration (Deister, 2013). As a result, Hussein (2018) suggests that UGS be integrated with sustainable strategies such as wastewater and greywater usage and stormwater management. Such integration can in turn present a solution to chronic technical problems of wastewater and water crisis management in desert cities.

To harness requisite resources for the conservation and management of UGS in arid regions like Namibia, the driest country in sub-Saharan Africa, and where water is projected to get scarcer in the future (Amakali, 2017; Bosworth et al., 2018), striking a balance is imperative. Information about the temporal and spatial shift of vegetation biomass and vegetation water content (VWC) is critical for balancing the modification of the urban greeneries and water resources. VWC is also one of the vital biophysical features of vegetation health and its remote estimation can be used to monitor vegetation water stress in real-time (Zhang & Zhou, 2019), thus guiding irrigation management. This study was designed to employ remote sensing for characterising and appraising the vegetation biomass and vegetation water content (VWC) of UGS in Mariental, a medium-sized town in Southern Namibia, situated in a hot desert climate (Peel et al., 2011). A town-wide assessment of vegetation biomass and VWC in UGS contributes to improved conservation of local water resources while maximising urban greenery, which is collectively fundamental for a sustainable town (Hussein, 2018). Such information further benefits urban planners, especially those who operate in arid and semi-arid environments. By actively making provisions for appropriate UGS in urban designs, planners can help minimise urban thermal temperatures, shape urban aesthetics and influence urban biodiversity in tandem with adapted conservation measures of water resources.

Study Area

Mariental is the regional capital of the Hardap Region, one of the 14 political regions in Namibia. It is the only urban area in the country that experiences the coldest (below 2 ºC) and hottest (over 36 ºC) average temperatures, as well as the highest average number of hours of sunshine per day (Figure 1). These extreme temperature variations are attributed to its continental climate, aggravated by the interplay of its proximity (120 km) to the Tropic of Capricorn, moderate elevation (1100 masl), and infrequent cloud cover.

The town receives summer rainfall averaging 175 mm annually (Mendelsohn et al., 2002). The potential average evaporation rate in the town is estimated at 3300 mm per annum, which is about 18 times higher than the annual rainfall (Mendelsohn et al., 2002).

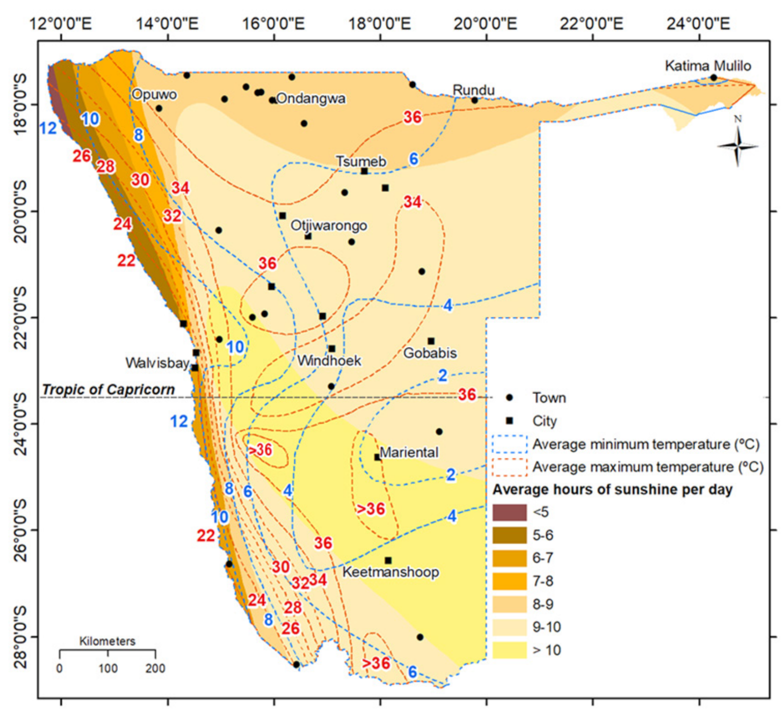

Figure 1. *Average temperatures during the coldest and hottest months and the number of hours of sunshine per day in Namibia. Note the location of Mariental where the coldest and hottest temperatures intersect, against the backdrop of the highest number of hours of sunshine per day*
(Data Source: Mendelsohn et al., 2002; cartography: this study)

The town is located in the dry Nama Karoo biome and is dominated by calcisol soils (Muche et al., 2012). The last census in 2011 placed the population of Mariental at 12,478 inhabitants (Namibia Statistics Agency, 2014). Its surface area (607 ha) is parcelled into the CBD, three suburbs and three informal settlements (Figure 2). The town obtains its water supply from the Hardap Dam, situated some 20 km to the north. The Namibia Water Corporation (NamWater), the national bulk supplier, provides water to the town in both treated and untreated states. In 2018, the cost of potable water in Mariental was N$18.41 per m3 for the first six units, after which it increased to N$18.85 per m3; untreated water was charged at a flat rate of N$2.17 per m3 (Ngovu, 2018). UGS in Mariental is predominantly irrigated with untreated water, but in some cases, treated water is used.

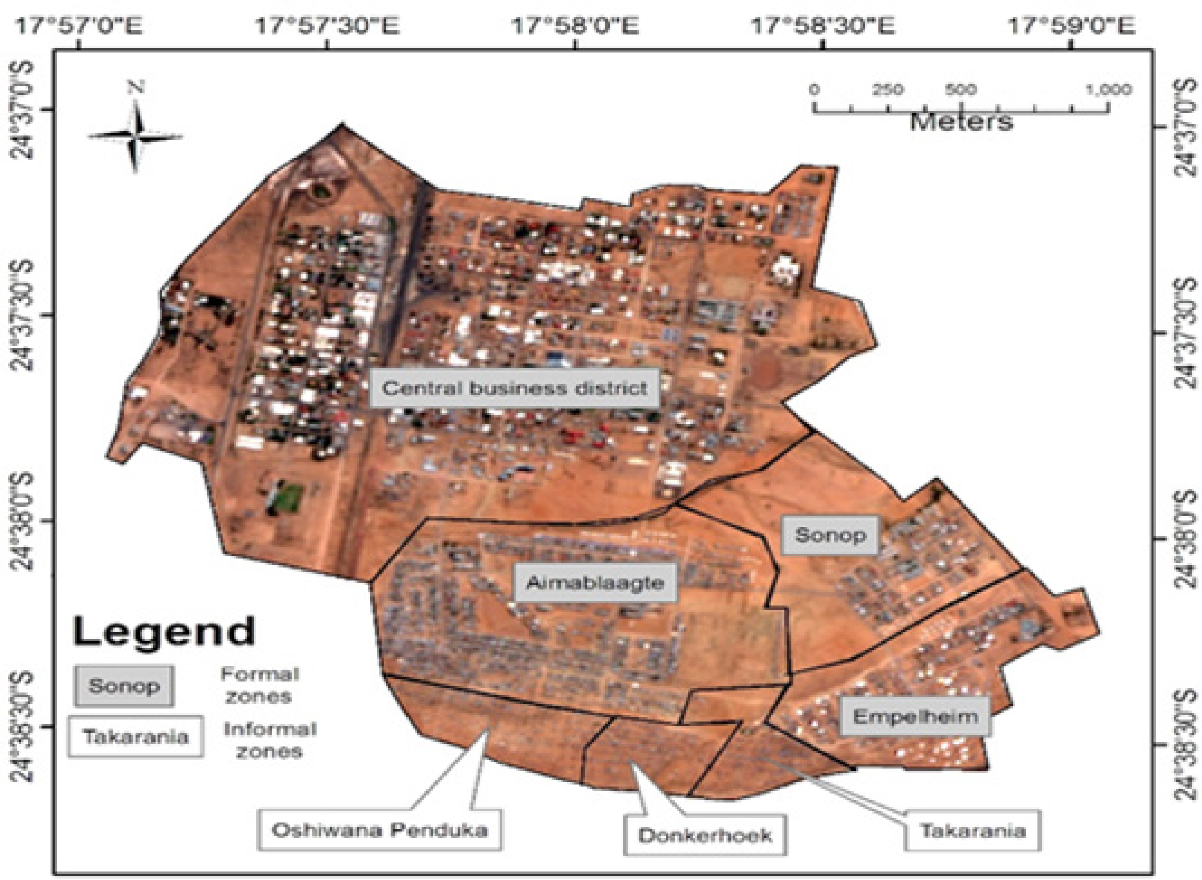

Figure 2. *The layout and zones of Mariental*
(Source: This study)

Methodology

Sentinel 2 image covering Mariental acquired on 7 August 2018 (ID: L1C_T33JYN_ A016320_20180807T084755) was downloaded from the United States Geological Survey (USGS) website. Preliminary indices of biomass and vegetation moisture content (discussed below) were derived from that image to facilitate and guide field verifications. Field data were then collected between 20 and 24 August 2018. To address the two weeks' time gap between the pre-fieldwork image and field visit, another image (ID L1C_T33JYN_A007626_20180822T085344) coinciding with the fieldwork period was later obtained from USGS to facilitate the final assessment of the study area. The timing of fieldwork and acquisition of a dry season image were beneficial for capturing the vegetation condition with diminished influence from direct rainfall and therefore accentuating areas under irrigation. Both images had a cloud cover of 0%.

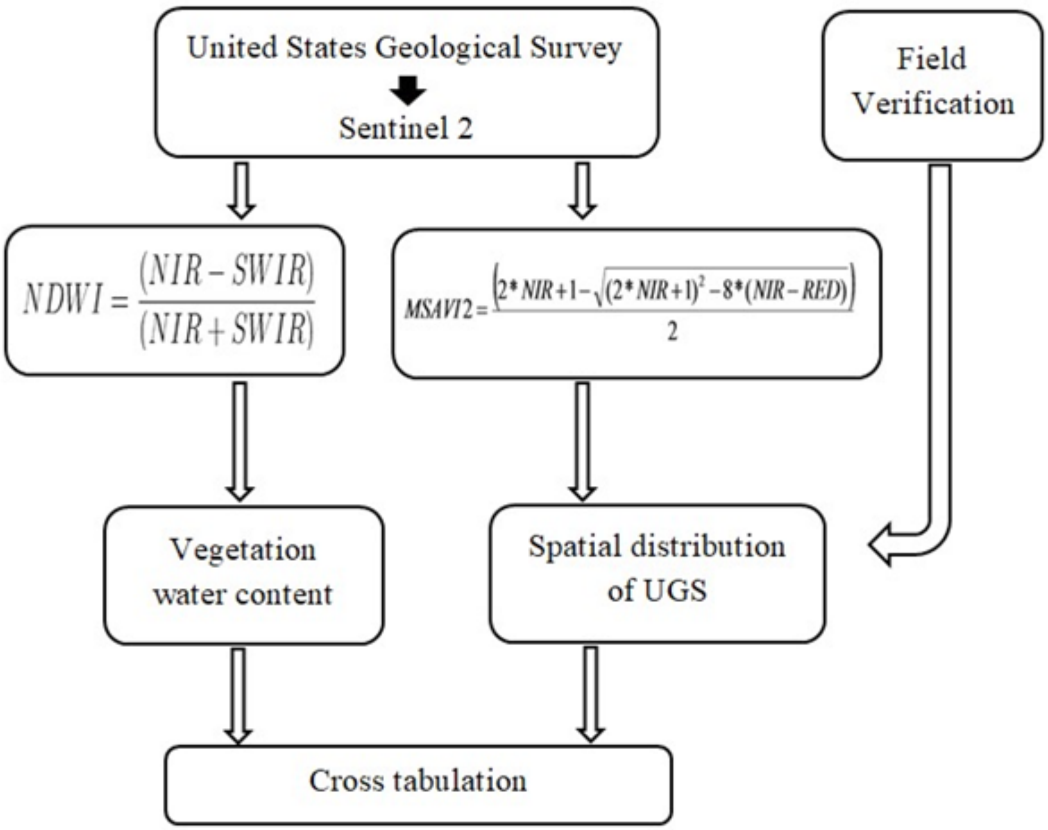

Figure 3. *The methodological approach with content for the MSAVI2 and NDVI equations* (Source: This study)

Using ArcGIS 10.3 (Esri, CA), the study employed the Modified Soil Adjusted Vegetation Index 2 (MSAVI2; Figure 3; Equation 1) and the Normalised Differenced Water Index (NDWI; Equation 2). Both indices are commonly used for extracting information such as vegetation health and VWC from digital remotely sensed data (Jensen, 2014).

The MSAVI2 addresses some of the limitations of the Normalised Differenced Vegetation Index (NDVI) when applied to areas with a high degree of exposed soil surface

(Qi et al., 1994). This index is best known for reducing the effect of soil brightness, which is notorious for affecting results from areas with low vegetation cover; it also permits improved vegetation vigour assessment (Dunno & Weber, 2001). The MSAVI2 also increases the dynamic range of the vegetation signal, which makes it less difficult to ascertain a threshold value for vegetation (Qi et al., 1994). Dunno and Weber (2001) found that MSAVI2 values approaching 1.0 are associated with vegetation cover and/or vigour and those approaching 0.0 are areas of low vigour or low vegetation cover.

$$MSAVI2 = \frac{\left(2 * NIR + 1 - \sqrt{(2 * NIR + 1)^2 - 8 * (NIR - RED)}\right)}{2}$$

Equation 1 *where NIR is the near-infrared and RED is the red spectral band* (Source: Qi et al., 1994)

The NDWI is a measure of liquid water molecules in vegetation interacting with the incoming solar radiation (Gao, 1996). This index was mainly introduced for the application of remote sensing of vegetation liquid water content from space using the near-infrared and the shortwave (SWIR) bands (Gao, 1996). The SWIR reflectance reveals changes in the spongy mesophyll structure and the water content in the vegetation, while the NIR reflectance is affected by the leaf dry matter and the leaf internal structure. The combination of the NIR and the SWIR bands removes the variations induced by the leaf's internal structure and the leaf's dry matter content (Gao, 1996). The NDWI values of areas of dead grass or no grass are negative, while the positive values are depicting water content for areas of living vegetation (Gao, 1996). This remote sensing algorithm is known for accurately estimating vegetation water content (Colombo et al., 2012).

$$NDWI = \frac{(NIR - SWIR)}{(NIR + SWIR)}$$

Equation 2 *where NIR is the near-infrared and SWIR is the shortwave spectral bands* (Source: Gao, 1996)

Thresholds and classes of the MSAVI2 and NDWI assigned in this study are indicated in Table 1. The respective total area sizes of derived classes were obtained through the reclassifying, conversion, Structured Query Language and the clip tools in ArcGIS. For the NDWI, band 11 (SWIR) was resampled to 10 m resolution, to harmonise it with the resolution of band 8 (NIR), the other input band.

Table 1. *Assigned thresholds values and classified classes for the two employed indices, MSAVI2 and NDWI*

MSAVI2 (Index value)	Assigned class name / Biomass	NDWI (Index value)	Assigned class name / Vegetation water content
-1.42 - 0.09	Built-up area	-0.31 - -0.04	Bare soil
0.10 - 0.54	Bare soil	-0.03 - 0.08	Built-up area
0.55 - 0.59	Very low	0.09 - 0.16	Very low
0.60 - 0.64	Low	0.15 - 0.20	Low
0.65 - 0.69	Moderate	0.21 - 0.26	Moderate
0.70 - 0.74	High	0.27 - 0.32	High
0.75 - 0.79	Very high	0.33 - 0.38	Very high

(Source: This study)

For field verifications, only vegetated areas with an area size equal to or larger than 600 m2 were eligible for sampling. The minimum threshold area of 600 m2 was set by taking cognisance of the coarsest (20 m, original) spatial resolution of the employed bands, and the GPS accuracy. That means that the sampling area on the ground should be covered by at least one pixel at 20 m resolution. Random stratification was used to obtain 30 field verification sites from each classified biomass and VWC class.

Field verifications entailed the identification of land cover, type of UGS, areal estimation of UGS (m2), average plant canopy to gap ratio and plants' height (m). Accessing some privately owned UGS proved to be a challenge, especially when the owners were not available; this limiting factor resulted in 39 ground verification sites.

The extent of agreement between vegetation biomass and vegetation water content levels was assessed through a matrix table of the classified MSAVI2 and the NDWI images, which was created through cross-tabulation. UGS area sizes were used to estimate the amount of water needed to irrigate UGS using Deister's (2013) estimate as well as the water cost of these UGS using the 2018 water tariffs for Mariental.

Results

Based on the biomass index, approximately 1% (6.6 ha) of Mariental's land is covered by UGS; built-up areas occupy 9% and 90% is bare soil. The UGS had a mean biomass index of 0.61 (low). The maximum biomass index of 0.79 (very high) was obtained in the CBD (Figure 4).

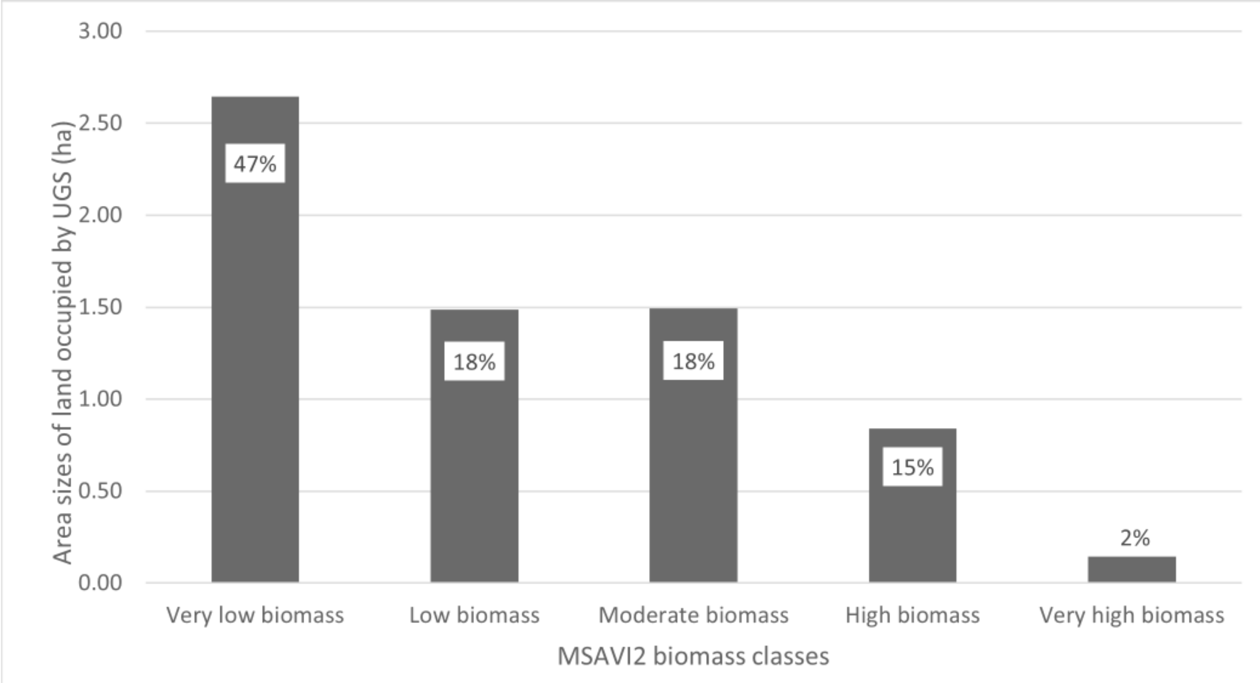

Figure 4. Area sizes of UGS per biomass class
(Source: This study)

The water content index revealed an average value of 0.14 (very low) and a maximum of 0.38 (very high). Similar to the biomass index, the maximum value of the water content was derived from the CBD.

The area covered by greenery is inclusive of the native vegetation in their natural setting, as well as those in cemeteries. The very low, low and moderate biomass classes make up over 80% of the UGS (Figure 4) and are predominantly located in the CBD (over 95%), followed by a distant Sonop suburb with approximately 3%. The high and very high biomass classes are only located in the CBD (Figure 5).

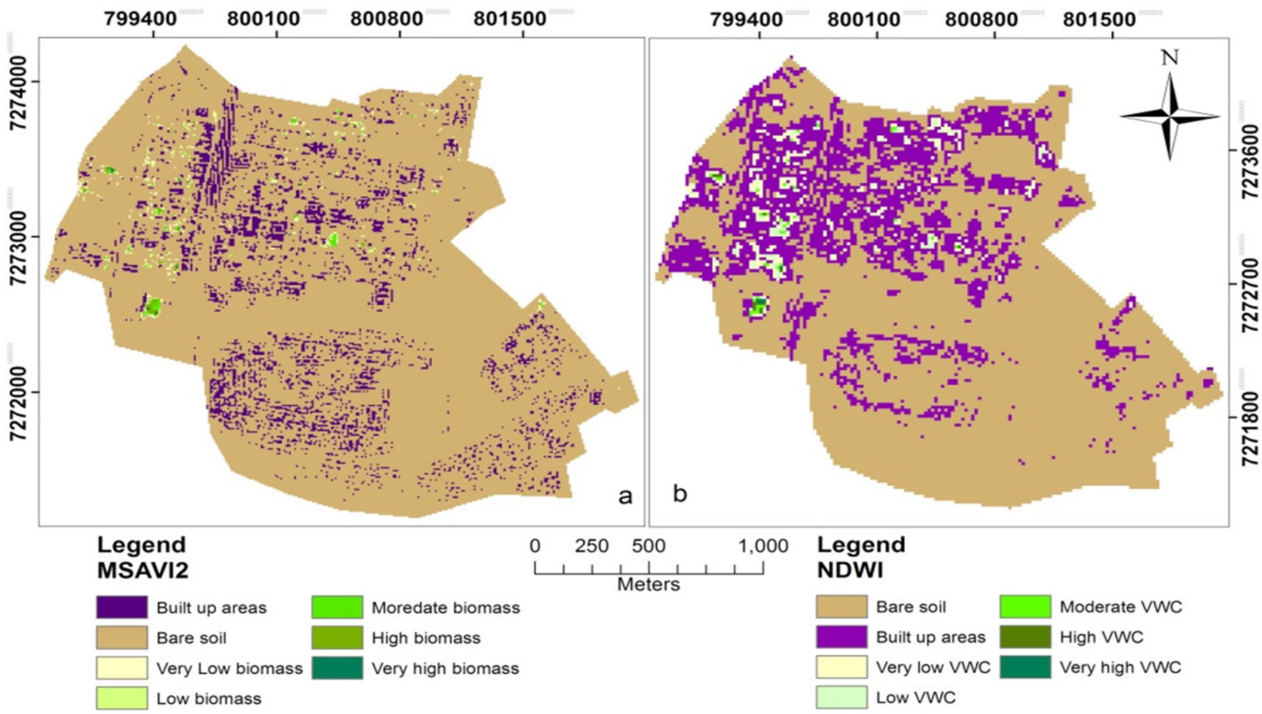

Figure 5. *Distribution of UGS in Mariental: a) Vegetation biomass and b) Vegetation water content*
(Source: This study)

Table 2. *Matrix table of Mariental's MSAVI2 and the NDWI indices (%; n = 370). The grey-shaded fields indicate pixels (totalling 64%) falling under identical bins between the MSAVI2 and NDWI indices*

	MSAVI2							
NDWI	**Bare soil**	**Built-up areas**	**Very low biomass**	**Low biomass**	**Moderate biomass**	**High biomass**	**Very high biomass**	**Total**
Bare soil	61.442	5.992	0.005	0	0	0	0	**67.44**
Built-up areas	17.273	2.756	0.02	0.008	0	0	0	**20.06**
Very low VWC	9.204	1.863	0.435	0.188	0.092	0.021	0.003	**11.81**
Low VWC	0.13	0.012	0.061	0.053	0.063	0.012	0	**0.33**
Moderate VWC	0.079	0.003	0.031	0.025	0.061	0.046	0.005	**0.25**
High VWC	0.002	0	0.002	0.003	0.021	0.043	0.015	**0.07**
Very high VWC	0	0	0	0.002	0.013	0.015	0.003	**0.03**
Total	**88.129**	**10.625**	**0.553**	**0.278**	**0.250**	**0.137**	**0.026**	**100**

(Source: This study)

Major variations between the MSAVI2 and NDWI (Table 2) occur in areas with very low biomass, built-up area and bare soil. The first two were overestimated by over 80% in the NDWI, while the same index underestimated bare soil by over 20% when compared with MSAVI2. A closer look revealed that cemeteries and native vegetation were the main contributors to such variations between these two indices. Spatially, NDWI overestimated built-up areas in the CBD, whilst they were underestimated in neighbourhoods where building structures are relatively small, such as in the informal settlements.

Using the derived 1% of the UGS estimates for water demand of UGS in the study area at present averages approximately 1000 m3 daily, assuming all plants have a low water requirement. The water demand nearly triples to 2,600 m3 and quadruples to 4,000 m3 for watering plants with moderate and high water demand, respectively (Figure 6). This water volume of 4,000 m3 is roughly 0.32 litres per capita per day for the 2011 population in Mariental.

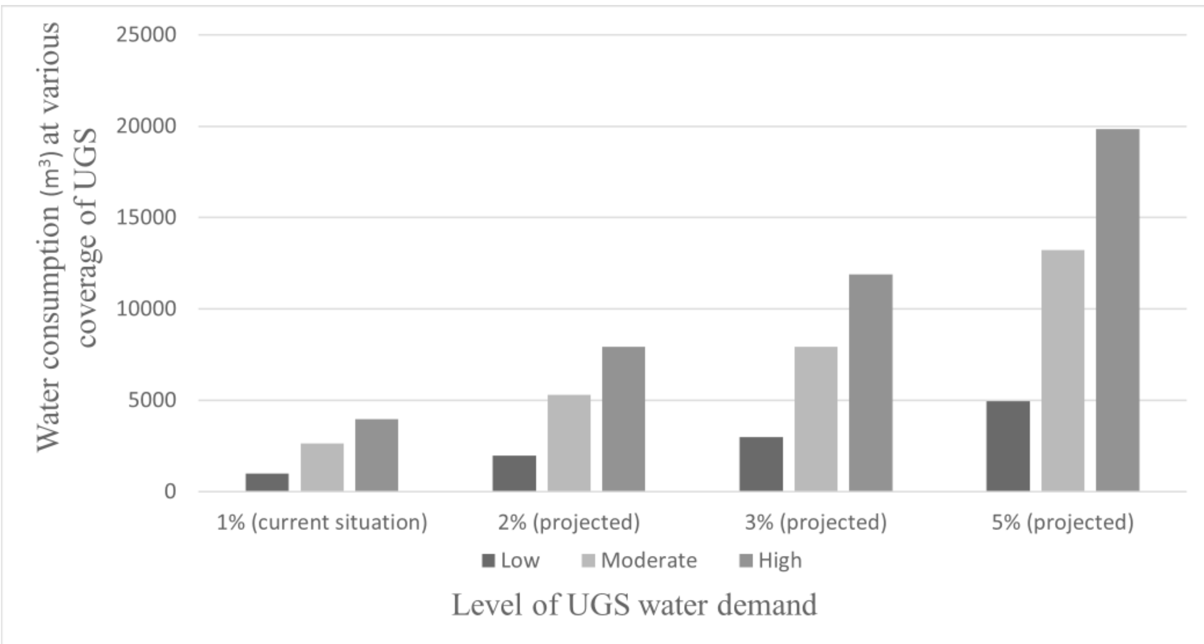

Figure 6. *Estimated daily water consumption levels for irrigating current and expanded UGS Under varying vegetation water requirements*
(Source: This study)

Tripling the proportion of UGS in the study area from the current 1% to 3% and endowed with low water demand vegetation would require approximately 75% of the current estimates of high water demand levels. The cost involved for keeping current UGS under irrigation with treated water is estimated to be a daily amount of around N$2,000 and N$16,000 for low and high water demand vegetation, respectively (Figure 7). The exact amount would be lower after taking into consideration the native vegetation in a natural setting.

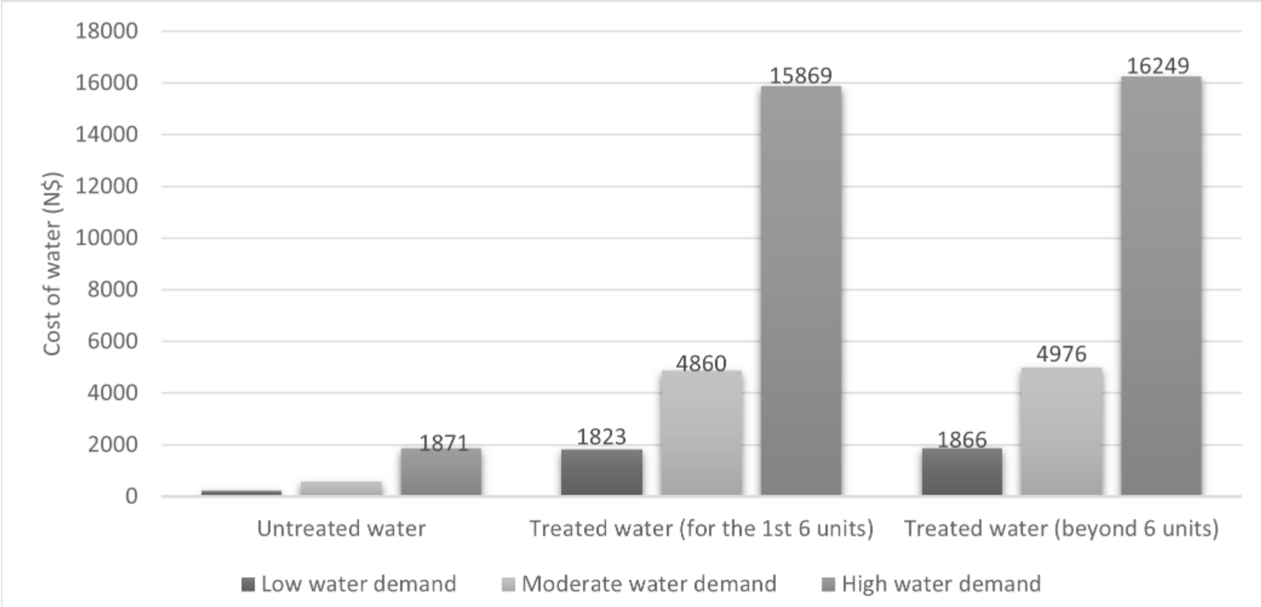

Figure 7. *Estimated daily water costs (N$) for different types of plants' water demand and the water quality based on the 2018 rates*
(Source: This study)

Discussion

The main objective of this study was to employ remote sensing technologies and appraise the vegetation biomass and water content of UGS in Mariental as a surrogate for determining the extent to which the town invests its effort towards ameliorating the microclimate. The derived 1% green space coverage in the town translates to 5 m2 of green space per capita as per the 2011 population census (Namibia Statistics Agency, 2014). KheirKhah and Kazemi (2015) reported that the global standard for green spaces per capita ranges between 5 m^2 and 50 m^2. Because of the population increase during the intervening period, the derived figure per capita at Mariental may have marginally fallen short of this global standard of green space per capita at present.

At a town-wide level, the estimated water demand of 0.32 litres per capita per day for maintaining the current UGS with high water demand suggests that the town placed a higher premium on water conservation than the UGS. Gleick (1996) estimates that domestic water use in an urban area with gardens ranges between 150 and 400 litres per person per day. Windhoek, for example, has a daily average water consumption of 160 litres per person (Uhlendahl et al., 2010). Houses without gardens in a similar setting have an average domestic water use ranging between 60 and 100 litres per person per day (Gleick, 1996). Although the daily average water consumption rate of Mariental is unknown, the gap of 50 litres of daily water consumption per capita between houses with and without gardens is indicative of the minimum water allocation for maintaining a small garden. From that perspective, daily water demand of less than half a litre per capita for maintaining UGS in Mariental effectively tips the balance in favour of water conservation. In other arid and semi-arid environments, water demand for maintaining UGS is reported to account for up to 50% of the municipal water supply during the summer months (Beard, 1973, cited in Christians & Engelke, 1994). Subsequently, these figures illustrate that the calculated amount of water for sustaining current UGS in Mariental is frugal.

The proportion of more than 90% of UGS being situated in the CBD shows an imbalance in the spatial distribution of green spaces in the study area. This high percentage of greenery in the CBD suggests the social, environmental and economic value that is assigned to this zone, as documented elsewhere (Cilliers, 2015). It may also reflect the age of occupation of the CBD as vegetation planted over time grows in height and extent. As Dimoudi and Nikolopoulu (2003) reported, the reduction of ambient temperature is proportional to the green area; in other words, the larger the green area the more lowering of ambient temperature. In that light, the CBD is expected to fare better in terms of ambient temperature than the rest of the town.

Further, a vegetation water index of up to 0.38 was detected in the CBD. Benabdelouahab et al. (2016) retrieved similar values for flood-irrigated wheat water contents in a semi-arid area in Morocco. These vegetation water content values reflect the presence of high water requirement plants and regular irrigation at Mariental. Values for the vegetation biomass of up to 0.79 in the CBD also supports the existence of lush green vegetation in some areas in the town.

There was a good correlation between the two indices for UGS. However, the NDWI underestimated the built-up areas, particularly in the informal settlements, and overestimated the built-up areas in the CBD. This was attributed to the original 20 m spatial resolution of the SWIR band that was factored into generating the NDWI. Smaller building structures that predominate in informal settlements can therefore be easily underestimated at a 20 m pixel size. Similarly, smaller UGS next to large building structures in the CBD could also be underestimated by a 20 m spatial resolution band. In contrast, both the Red and NIR bands used for the MSAVI2 have a 10 m spatial resolution, which may have enhanced its performance in depicting UGS and the non-biomass classes.

Collectively, the overall spatial distribution and related imbalance of green spaces in the study area suggest that the ability of the current UGS at Mariental to effectively contribute to the improvement of its microclimate is modest at best. There is thus a need to expand and intensify UGS in the study area.

With careful planning, the town is well-positioned to address this demand. One such strategy is to introduce water-efficiency plants and harness with prudence the available water resources from the nearby Hardap Dam. The pervasive calcisols soil in the study area is another advantage. This soil type is known to be fertile under a sound irrigation regime (IUSS Working Group WRB, 2015) and it has adequate water storage capacity (Zhang et al., 2011). An example of an arid area that expanded its UGS is Urumqi city in China, which utilised greening policies during three stages from 1992 to 2019 (Shi et al., 2020). During these stages, the total land occupied by UGS increased six-fold, from

24 km^2 to 152 km^2 (Shi et al., 2020). Green spaces are considered a viable adaptation strategy to climate change (Mees & Driessen, 2011); their expansion in Mariental will thus also contribute to the sustainable development of the town.

Conclusion

Vegetation biomass and VWC of UGS in Mariental were effectively detected and assessed using remotely sensed data. Values of high vegetation biomass and VWC indices were mainly located in the CBD. The estimated green space per capita of 5 m2 for Mariental is barely within the global standard. The unique climatic conditions of Mariental, being the urban area with the highest temperature variations in Namibia, warrant the amelioration of its microclimate. An effective, natural approach for improving microclimate is through UGS. Efforts directed at expanding the green space per capita may therefore consider the promotion of, and investment in plants with low water demand. Coupled with the availability of untreated water from the Hardap Dam and the relatively productive soil in the study area, green spaces with low water demand vegetation can be increased sustainably to generate climatic, environmental and socio-economic benefits associated with urban green spaces. Further studies may focus on assessing the water demand of current plant species in this area and help direct the planning effort.

Acknowledgements

We would like to extend our gratitude to the Mariental residents who allowed us access to gather in-situ data from their properties. The 2019 student assistants at the Department of Geography, History and Environmental Studies, UNAM, assisted MD with availing the GIS laboratory. Ben van der Waal and two anonymous reviewers made suggestions that helped improve the manuscript.

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