Assessing abundance of surface water and biomass in the Cuvelai basin, central northern Namibia using Landsat TM and AATSR data

Johanna Ngula Niipele and Patrik Klintenberg

The Desert Research Foundation of Namibia, PO Box 202 32 Windhoek, Namibia
Corresponding author: J.N. Niipele, Tel: +264-61-377500, Fax: +264-61-230172,
P.O. Box 202 32 Windhoek, Namibia

Abstract

This paper presents results of a comparative assessment of usefulness and comparability of Landsat TM and AATSR data for mapping of green vegetation and hydrological features in semi-arid environments. The study was conducted in the Namibian part of the Cuvelai basin, central northern Namibia, a basin shared between Angola and Namibia. A comparison of SAVI and NDVI based on both Landsat TM and AATSR reveals that the two platforms correspond significantly. However, the lower resolution of the AATSR imagery results in loss of detail, which might negatively influence its usefulness for monitoring initiatives requiring high levels of detail. Furthermore, values recorded by Landsat TM are systematically lower than values recorded by AATSR. The displacement is linear and can therefore be compensated for by adding a constant to the values of one of the two sensors. Surface water maps were developed. Preliminary findings indicate that both platforms provide comparable and accurate information about surface water. Results indicate that Landsat TM is the best sensor to use for surface water detection in the study area. The lower spatial resolution of AATSR leads to an underestimate of surface water, since most water bodies in the area are smaller than the spatial resolution of the satellite, leading to mixed pixel problems.

Keywords: Cuvelai river basin, surface water, ephemeral river, oshana, NDVI, SAVI

Abbreviations

AATSR	Advanced Along Track Scanning Radiometer
ESA	European Space Agency
DN	Digital Number
DRFN	Desert Research Foundation of Namibia
DWAF	Department of Water Affairs and Forestry
GCP	Ground Control Points
LANDSAT TM	Land Satellite Thematic Mapper
MERIS FR	Medium Resolution Imaging Spectrometer – Full Resolution
NDVI	Normalized Difference Vegetation Index
RWS	Rural Water Supply
SAVI	Soil-Adjusted Vegetation Index

Introduction

Satellite remote sensing aimed at monitoring the surface of the earth has been pursued since the 1970s (Barrett and Hamilton, 1986) and has become a frequently used tool for ecological applications requiring data from broad spatial areas that can not be easily collected using field based methodologies (Kerr and Ostrovsky, 2003). Information generated by remote sensing is commonly used for land cover classification and detection of natural and human induced changes within and across landscapes (Coppin *et al*., 2004; Lu *et al*., 2004). For ecological applications one of the most commonly used satellite platforms is the Landsat sensor. Landsat data have been translated into useful ecological information for more than 30 years, with both the methods and applications growing increasingly in sophistication (Cohen and Goward, 2004). However, more recent satellite platforms, such as ENVISAT delivering imagery like AATSR (Levrini and Brooker, 2000), does not have the advantage of long time series. It is therefore of interest to compare these newer products with the Landsat TM imagery to determine if these two data can complement each other, and even be used interchangeably. However, there is a significant difference in spatial resolution between Landsat TM and AATSR imagery. Landsat TM data has a spatial resolution of 30 by 30 m while AATSR imagery has a spatial resolution of 1 by 1 km. It is therefore equally important to see to what extent the AATSR sensor with its lower spatial resolution, can identify changes on the ground that are of relevance to land managers and decision makers.

Calculation of vegetation indices derived from satellite data is one of the primary sources of information for operational monitoring of green vegetation cover (Perry and Lautenschlager, 1984; Gilabert *et al*., 2002). Most of these indices are based on algebraic combinations of reflectance in the red and the near infrared spectral bands (Bannari *et al*., 1995). The most commonly used vegetation index is the normalized difference vegetation index (NDVI). However, in semi-arid and arid environments it has been shown that this index does not give a correct reflection of green biomass when green canopy cover is lower than 30% (Pech *et al*., 1986). Due to the normally sparse to very sparse ground cover in these areas, the underlying soil influences the spectral signature to such an extent that it has to be compensated for (Rondeaux *et al*., 1996; Schmidt and Karnieli, 2001; Gilabert *et al*., 2002). Therefore several indices have been developed, of which the soil adjusted vegetation index (SAVI) is one of the most well known (Huete, 1988). The extensive use of vegetation indices in monitoring of vegetation greenness makes it central to assess how new satellite platforms, e.g. AATSR, record the required spectral intervals used for calculating these indices, and to compare these results with more commonly used platforms like Landsat TM. In this study the two vegetation indices NDVI and SAVI were used for the comparison.

Objective of the study

A key objective of the Tiger project 3005 implemented by the Desert Research Foundation of Namibia (DRFN) is to test the usefulness of ESA satellite products for environmental monitoring in semi-arid environments, with an emphasis on hydrological features. For this study the following specific objectives have been identified:

1) To assess if greenness maps based on NDVI and SAVI, calculated for Landsat TM and AATSR data in a semi-arid environment, are comparable, and therefore could be used interchangeably.

2) To assess the ability of Landsat TM and AATSR to detect surface water in a semi-arid environment and to compare the results from the two platforms.

Study area

This study was conducted in the Cuvelai basin, central northern Namibia, a basin shared between Angola and Namibia (Fig. 1). The area was selected as previous research in the Namibian part of the basin had given the team comprehensive knowledge about present and past ground conditions in the area. Furthermore, numerous ground-based data sets exist, which were used for geo-referencing images and assessments of results. The Cuvelai basin has been divided into sub-basins and currently a basin management committee within the Iishana sub-basin is being formed where extensive data has been collected (Fig. 1).

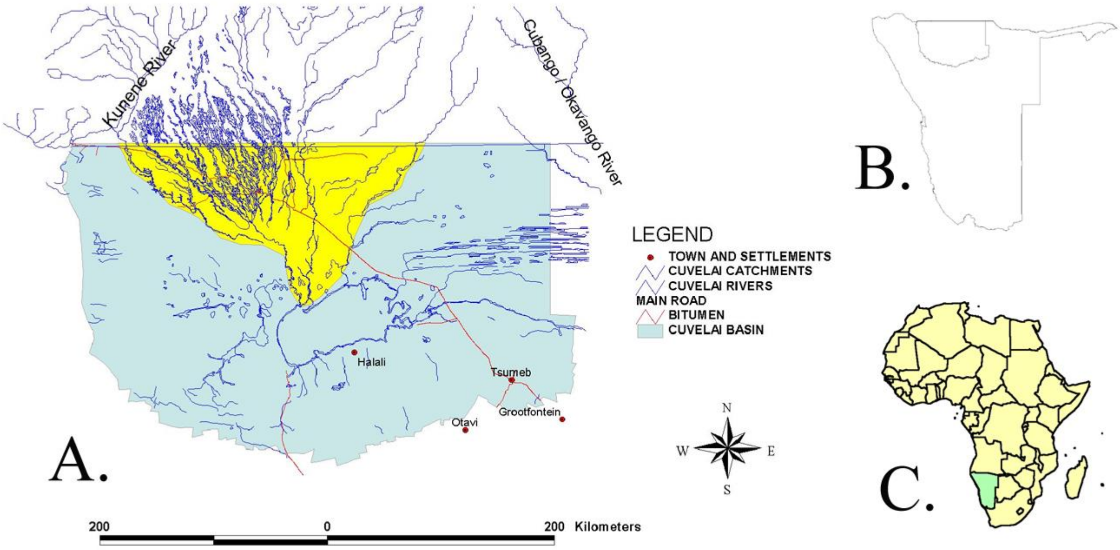

Figure 1. *Map A shows the Namibian part of the Cuvelai basin (the study area) and the Iishana sub-basin indicated in yellow. Map B: the study area in Namibia, and Map C: Namibia's location on the African continent.*

Geology

Geologically the study area belongs to the Kalahari sequence, characterised by up to 500 m thick semi- to unconsolidated sediments (Thomas and Shaw, 1991). The study area is situated in a flat landscape at approximately 1100 m above sea level. Soils consist of clayey sodic sands in the lower parts of the landscape and sodic sands on surrounding relatively higher ground (Mendelsohn *et al*., 2000). The area typically has infertile sandy topsoil, between 0 and 1m thick, underlain by a saline hardpan forming very distinct prismatic structures (Marsh and Seely, 1992).

Climate

The climate is semi-arid and the area receives average annual precipitation of approximately 300 mm in the southwest and 550 mm in the northeast (Fig. 2) (Hutchinson, 1995). Rainfall is highly variable in time and space (Mendelsohn *et al*., 2000). Monthly mean temperature ranges from 26°C in November to 16°C in July. During the coolest period, June to August, the night temperature drops to 7°C while day temperature may reach 40°C (Hutchinson, 1995). Annual potential evaporation is estimated to exceed the annual precipitation by a factor of about five (Erkkilä, 2001; Mendelsohn *et al*., 2002).

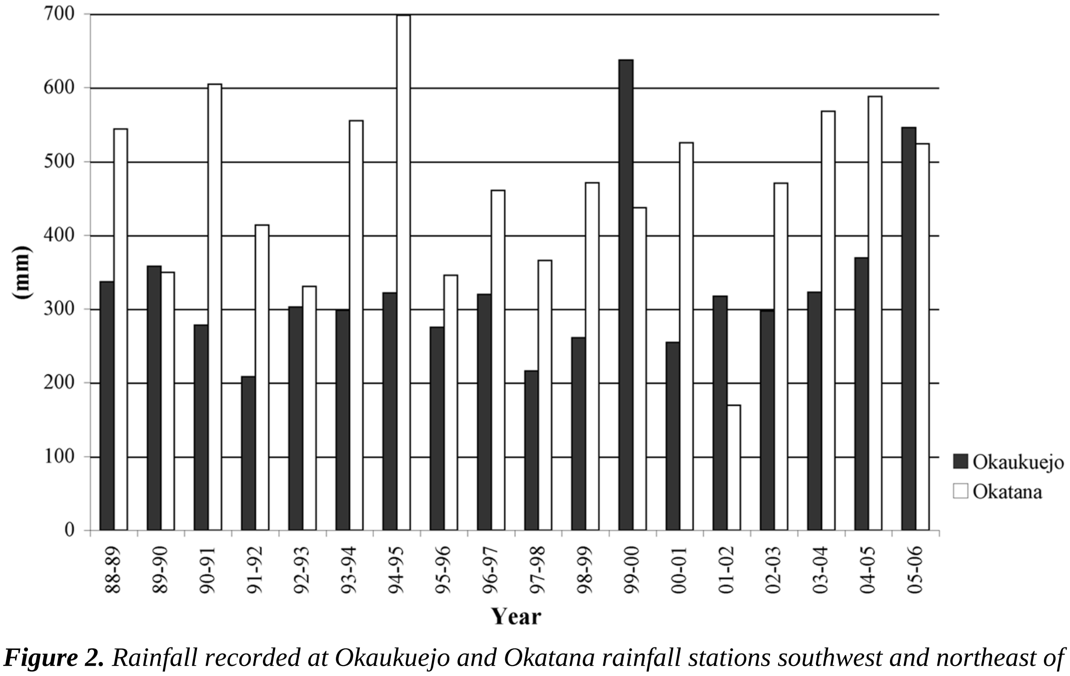

Figure 2. *Rainfall recorded at Okaukuejo and Okatana rainfall stations southwest and northeast of the study area during the time series.*

Hydrology

The basin is made-up of a network of interconnected water channels originating in the highlands of central Angola, flowing southward into Namibia and spreading across the low-lying, gently sloping areas of the Kalahari sands into the Etosha Pan at its southern reaches.

This drainage system is an important river system characterised by a number of shallow ephemeral watercourses covering an area of about 7,000 km² of ephemeral channels locally known as oshanas (Barnard, 1998). The oshanas provide an important source of water during the rainfall seasons (Mendelsohn *et al*., 2000). The interconnected network of oshanas act as a pathway for flooding that recharges groundwater aquifers in the basin. Groundwater recharge is one of the most important functions of floods: as water travels down the channels it infiltrates into the sandy and gravel alluvial deposits of the channel beds. The degree of recharge depends on intensity, volume and duration of a flood (Hayes *et a*l., 1998).
High salinity of groundwater in the central parts of the basin makes water a scarce resource, only available in shallow depressions and hand-dug wells for a few months after the rainfall season. The Namibian part of the Cuvelai basin covers an area between the Okavango and Kunene Rivers and is sub divided into four sub-basins; Tsumeb, Cuvelei-Iishana, Niipele-Odila and Olushandja (Fig. 3).

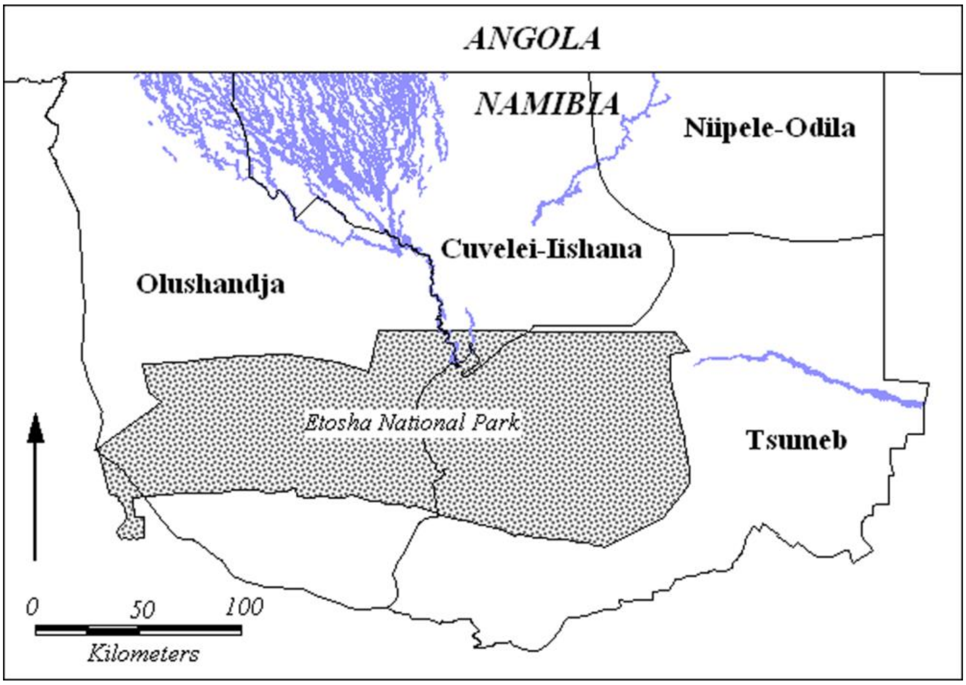

Figure 3. *The Cuvelai basin with the four sub basins indicated.*

<u>Vegetation</u>

The Cuvelai basin does not have well-defined riparian forests along its watercourses; instead the area is dominated by mopane woodlands, which stretches from south-western Angola into northern Namibia. Local conditions have an influence on the shape and sizes of mopane shrubs. In areas where the soil depth is low, mopane occurs as shrubs, while in areas with deeper soils the mopane grows taller (Barnard, 1998). In areas with deep Kalahari sands and relatively good access to groundwater, bigger trees such as *Acacia erioloba*, *Terminalia prunoides*, *Lonchocarpus nelsii* and *Spirostachys africana* are occasionally found, specifically in the southern reaches of the basin (Barnard, 1998). A number of different types of indigenous fruit trees also occur in the deeper Kalahari sands, e.g. *Hyphaene petersiana, Sclerocarya birrea, Berchemia discolor and Diospyros mespiliformis*.

The basin is also characterised by extensive grasslands. These grasslands sustain a wide variety of annual and perennial grasses as well as treesand shrubs which mainly occur in the ephemeral river channels where constant availability of groundwater allows for the presence and growth of woody vegetation.

<u>Population</u>

The Namibian part of the Cuvelai basin is home to about 800,000 people, making up half of the country's total population. The majority of the population is directly dependent upon natural resources for their livelihoods (Barnard, 1998), since subsistence farming is commonly practiced in the area. Homesteads, farms and fields are restricted to higher ground of Kalahari sand where fresh water is more abundant. Farms in this area are usually situated around clay rich pans (Verlinden *et al*., 2006). Early settlement patterns were greatly influenced by the availability of surface water as well as the deep non-saline soils of the Kalahari for crop production. However, due to population increase, more recent settlement now also occur in areas with shallower, more saline soils.

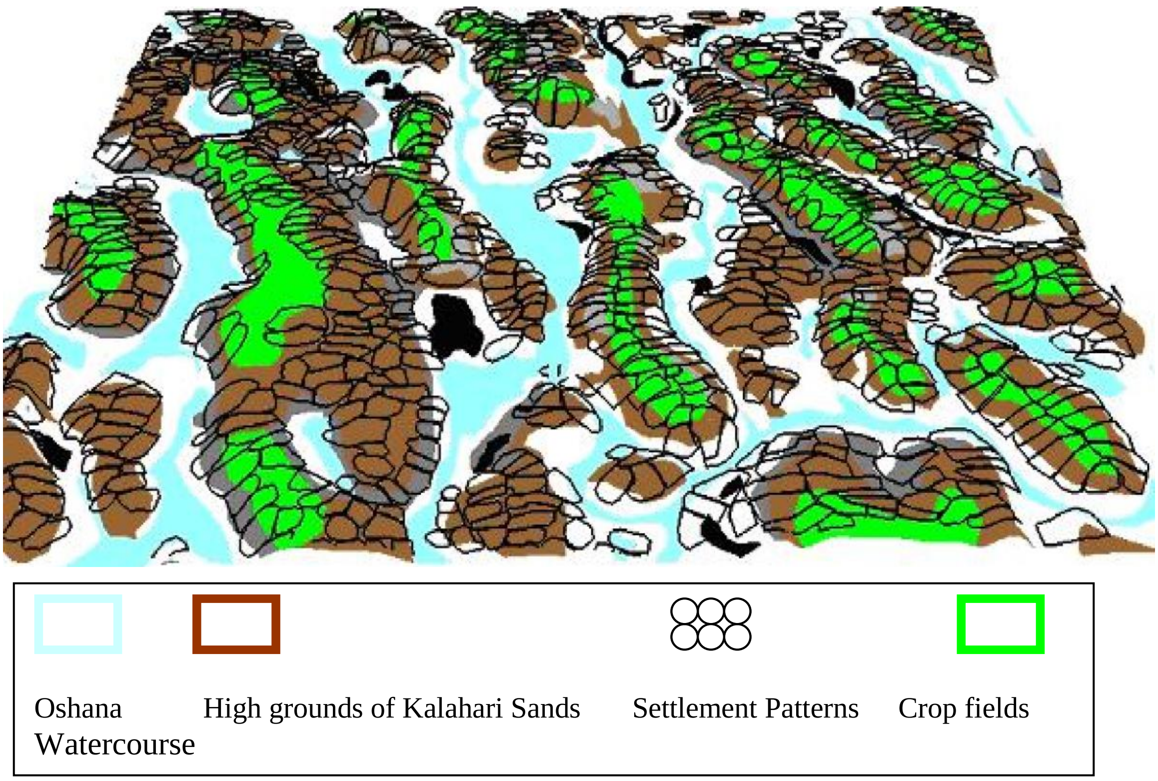

Figure 4. *Is a three-dimensional view of the influence of elevation on traditional farm establishment and settlement patterns in central northern Namibia (Verlinden et al., 2006).*

Water Supply

In the past most people and livestock in central northern Namibia relied on surface water accumulated from rainfall, collected in earth dams and in shallow hand dug wells as their main water source (Quan *et al*., 1994; Klintenberg and Christiansson, 2005). In areas where the salinity of the groundwater is low enough for cattle, hand dug wells were constructed. This traditional water supply system is still in use in rural areas of central northern Namibia (Klintenberg and Christiansson, 2005). However, in response to increasing population and generally saline groundwater, a bulk water supply system was developed in the 1960s and 70s, providing water from the Kunene River on the Angolan border to central northern Namibia through the Etaka canal (Fig. 1) (Quan *et al*., 1994; Mendelsohn *et al*., 2000; Niemann, 2002). This was followed by development of a pipeline system providing purified water to settlements and water points for cattle to areas where previously, lack of fresh water prevented extensive grazing (Quan *et al*., 1994; Niemann, 2002).

Methodology

Scenes used for the analysis

The Landsat TM5 scene (Path 179, Row 073) that was used was recorded on 2005-04-12. The spatial resolution of the Landsat imagery is 30 by 30 m. The scene covers the area in the far southern Angola and northern Namibia between the Okavango and Kunene River reaching as far as the Otavi, Tsumeb and Grootfontein hills. The AATSR scene that was used was recorded on 2005-04-24. The spatial resolution of the AATSR imagery is 1 by 1 km. The extent of this scene is much larger than the extent of the Landsat TM scene. To simplify the comparison of the two data sets a subset was created covering the same area as the Landsat TM scene. Table 1 presents the band configuration of the two sensors.

Importing AATSR data into ER Mapper

For the purpose of the comparison of Landsat TM and AATSR imagery the investigated area was defined by the extent of the Landsat TM scene, after which a subset of the AATSR scene was created. The AATSR data was opened and viewed in BEAMVISAT, in which a subset of the image was created and saved in DIM format. The seven spectral nadir bands from the subset scene were imported into ER Mapper in IMG format. Each band was saved as a raster dataset. The spectral bands were saved accordingly: band 1: 0.55 µm, band 2: 0.67 µm, band3: 0.87 µm, band 4: 1.6 µm, band 5: 3.7 µm, band 6: 1.1 µm and band 7: 1.2 µm (Table 1). These bands were then combined and saved into one dataset.

Geo-referencing

Landsat and AATSR images were geo-referenced with ER Mapper using a linear polynomial function. Due to the low spatial resolution of the AATSR imagery which made it difficult to use known points for geo-referencing, the sub-scene was first roughly geo-referenced against a geo-referenced Landsat TM image. Thereafter the AATSR image was further geo-referenced using ground control points of known physical objects.

Resampling of the Landsat TM scene

For the comparison of Landsat TM and AATSR imagery the Landsat TM scene was resampled to the resolution of AATSR data (1 by 1 km) using the IDRISI software (IDRISI, 1999).

Calculation of vegetation indices

For the detection of green biomass, NDVI and SAVI vegetation indices were calculated (Formulas 1 and 2).

Formula 1 *(NDVI): (NIR-R)/NIR+R)*

Formula 2 *(SAVI): [(NIR-R)/NIR+R+L)]*(1+L) (L=0.5)*

For the calculation of SAVI an L-factor of 0.5 was used as suggested by Huete (1988) for areas with intermediate vegetation cover.

The resulting NDVI and SAVI images, calculated using both Landsat TM and AATSR, were transformed from a range of -1 to 1 (real data) to byte binary format with pixel values ranging from 0 to 255 by applying the formula (X+1)*127.5, where X is any pixel value in the SAVI image. The NDVI and SAVI images were then analysed in Idrisi.
Using Idrisi, 1450 pixels were sampled from each NDVI and SAVI image using random stratified sampling. To enable direct comparison of the results the same pixels were sampled in all images. The resulting values were assessed to compare how the two satellite platforms record vegetation greenness using NDVI and SAVI.

Surface water detection

Surface water was identified by applying a water detection formula defined by ERMapper (ER Mapper, 2005) (Formula 3) using spectral bands between 1.55-1.75 µm (infrared) and 0.52-0.60 µm (red) for Landsat TM and the spectral band 1.60 µm (infrared) and 0.55 µm (red) for AATSR (Table 1). This formula was applied to both Landsat TM and AATSR in order to test the ability of the two datasets to detect surface water.

Formula 3*: IR/R, values <1 = water*

Surface water maps were created in which water was classified as 1 and everything else classified as 0.

Table 1. *Band configuration of Landsat TM and AATSR.*

	Landsat 5 TM			AATSR		
Band	**Resolution (m)**	**Wavelength**		**Resolution (m)**	**Wavelength**	
1	30	0.45-0.52	B	1000	0.55	G
2	30	0.52-0.60	G	1000	0.67	R
3	30	0.63-0.69	R	1000	0.87	NIR
4	30	0.76-0.90	NIR	1000	1.60	IR
5	30	1.55-1.75	IR	1000	3.70	
6	120	10.40-12.50		1000	11.00	
7	30	2.08-2.35		1000	12.00	

Results

The comparison of NDVI and SAVI values based on Landsat TM and AATSR are presented in Figure 5 to Figure 7. In Figure 5 it can be seen that AATSR systematically records higher values for NDVI compared to Landsat TM. After adding trend lines to the data it was revealed that this is a linear displacement, which was compensated for by adding a constant to the Landsat TM data (Fig. 7 and Fig. 8). The constant was defined by the distance between the trend line of AATSR and the trend line of Landsat TM. The resulting SAVI and NDVI values were compared for each sensor, revealing that SAVI values are higher than NDVI values (i.e. more greenness) for both sensors (Fig. 8 and 9)

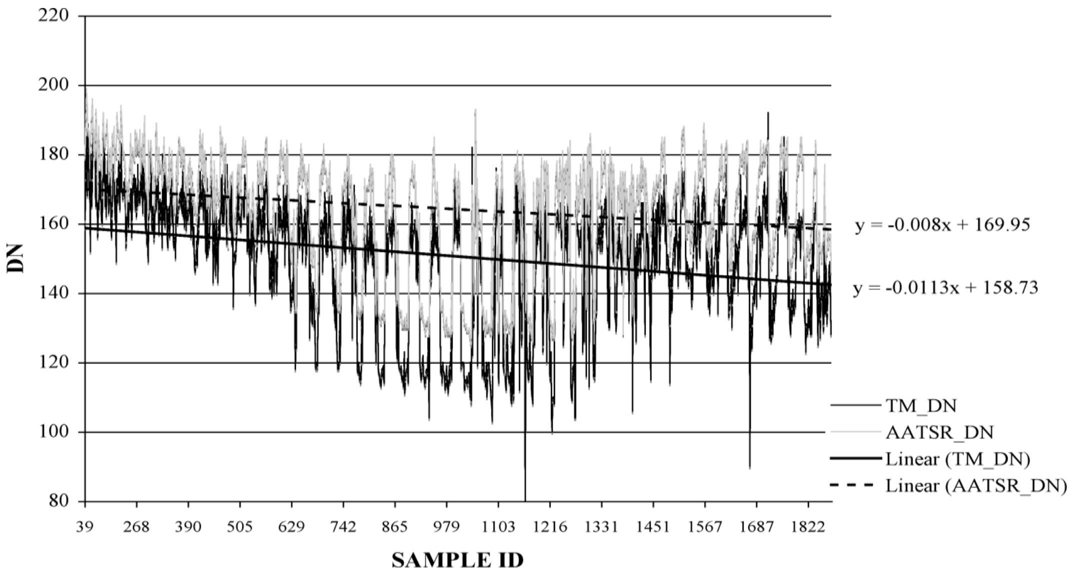

Figure 5. *Comparison of NDVI recorded by Landsat TM and AATSR.*

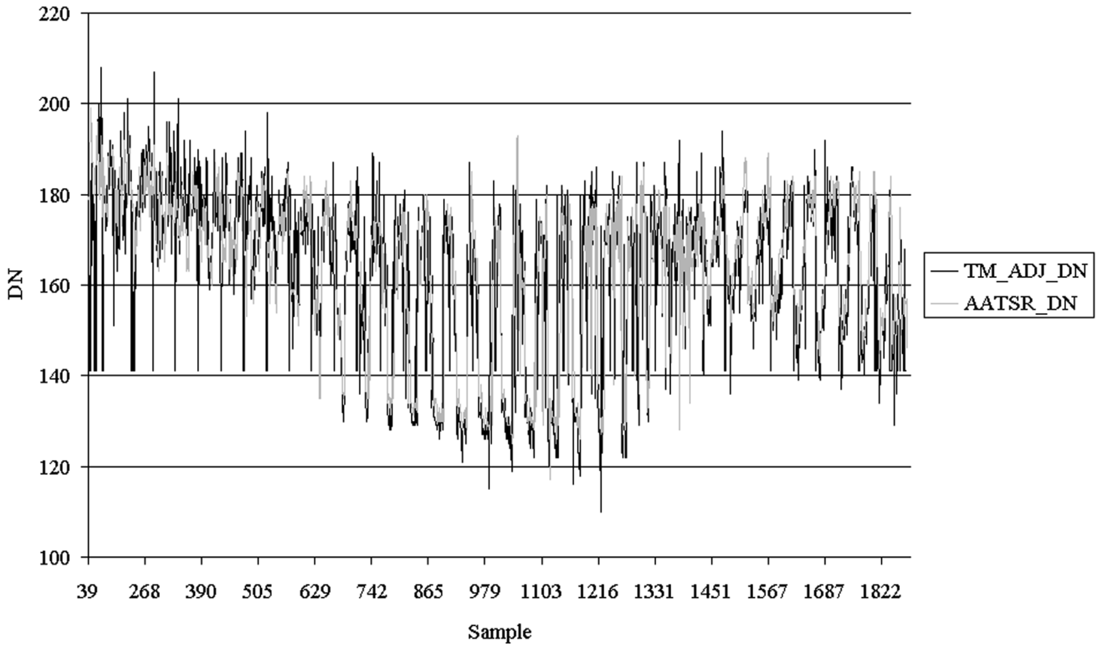

Figure 6. *Comparison of NDVI recorded by Landsat TM and AATSR. Note that a constant factor has been added to the Landsat TM data to compensate for the systematic lower values given by the Landsat TM sensor compared to values given by AATSR.*

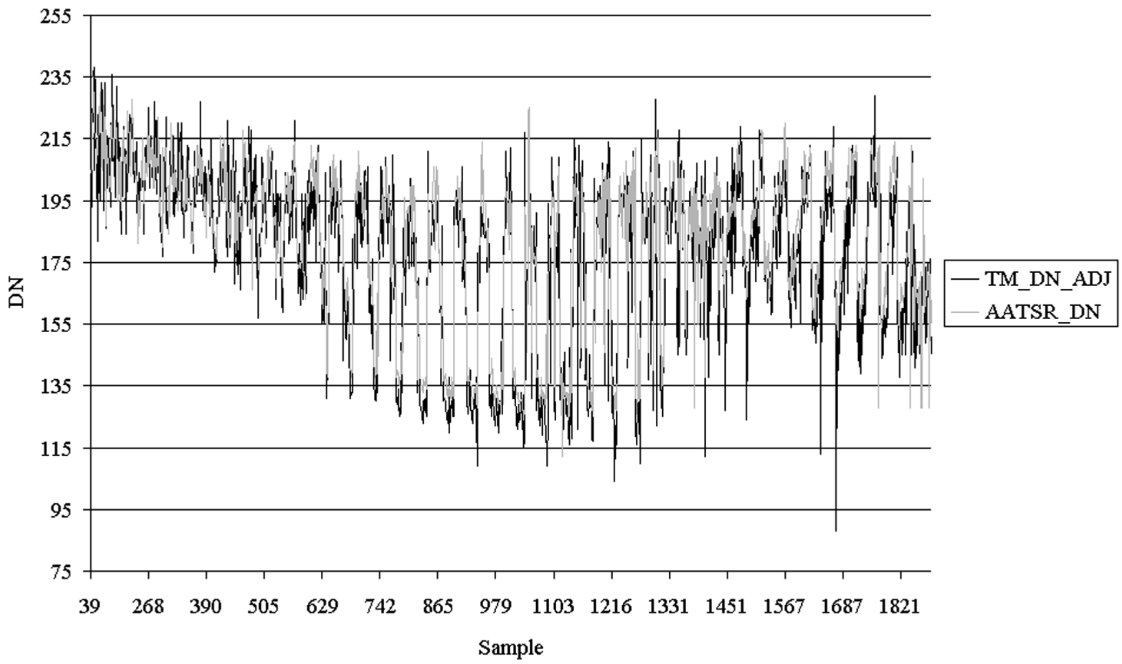

Figure 7. *Comparison of SAVI recorded by Landsat TM and AATSR. Note that a constant factor has been added to the Landsat TM data to compensate for the systematic lower values given by the Landsat TM sensor compared to values given by AATSR.*

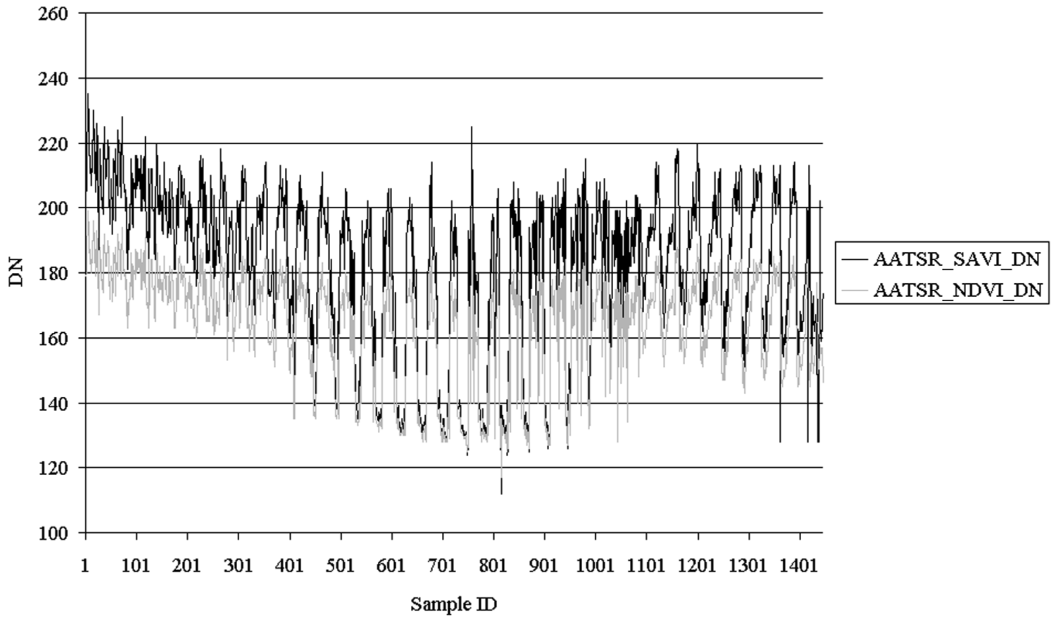

Figure 8. *Comparison of SAVI and NDVI recorded by AATSR.*

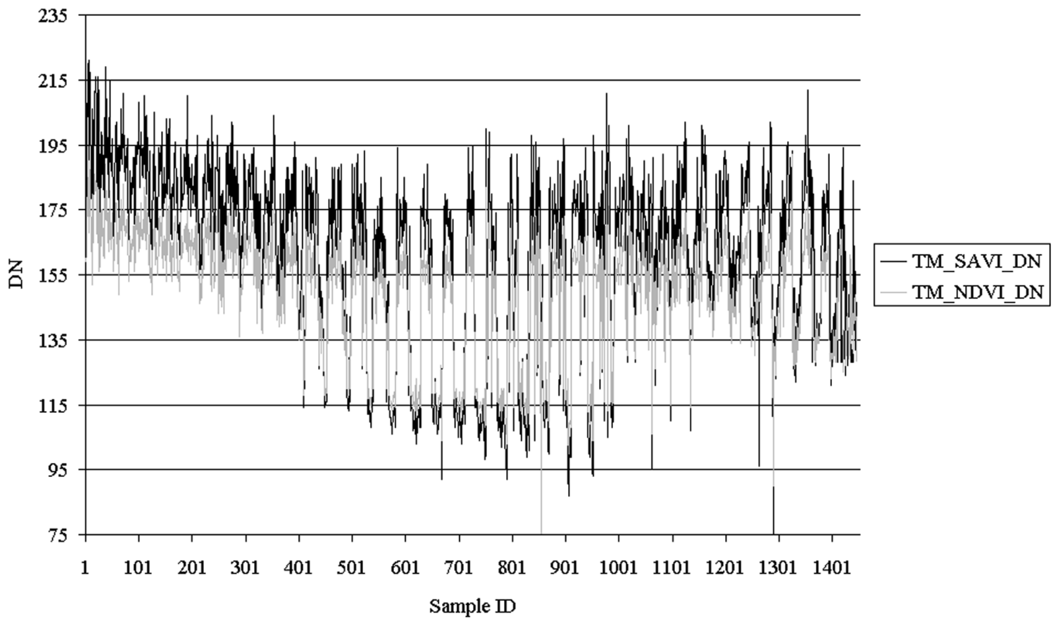

Figure 9. *Comparison of SAVI and NDVI recorded by Landsat TM.*

Figure 10 shows the surface water maps produced by applying the standard water formula to both Landsat TM and AATSR data. Landsat TM with a spatial resolution of 30 by 30 m classified 6.2% of the area as surface water, while the AATSR sensor classified 2.2% of the area to be surface water. After re-sampling the Landsat TM scene to 1 by 1 km (the spatial resolution of AATSR data) 3.2% of the area was classified as surface water.

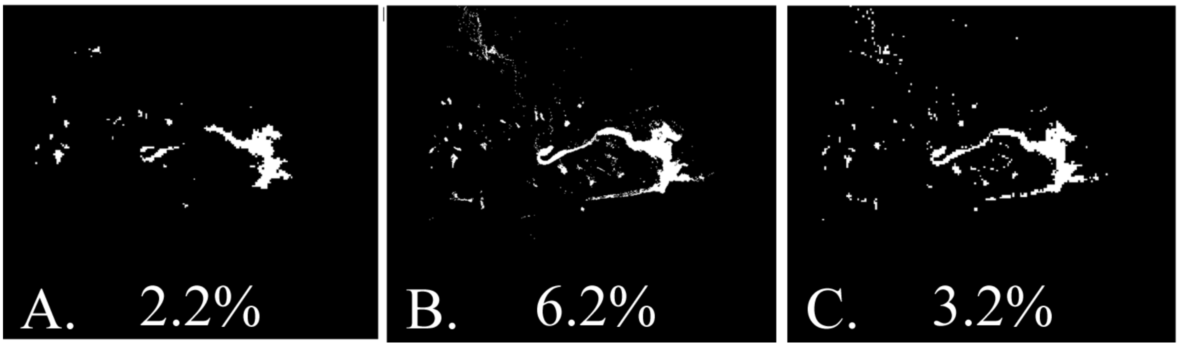

Figure 10. *Images of surface water derived from AATSR and Landsat TM imagery by using the standard water formula in ERMapper. Figure A: AATSR, Figure B: Landsat TM, and Figure C: Landsat TM resampled to spatial resolution 1*1 km.*

Discussion

Detection of green biomass

The comparison of NDVI and SAVI calculated based on Landsat TM and AATSR data reveals that Landsat TM systematically records lower values compared to the AATSR sensor. The reason for this is not known but it could be an effect of differences in radiometric calibration between the two sensors. It can also be caused by differences in the width of the spectrum being recorded for each band by the two sensors. However, as results indicate that this is a linear shift, it can be calibrated for by adding a constant to the NDVI and SAVI values recorded by one of the sensors. Regardless of this linear difference in the data, results show that the two data sets are highly correlated (NDVI 0.9 and SAVI 0.9), which indicates that results from the AATSR sensor are reliable and can be used to map greenness of vegetation. Furthermore, after compensating for the difference between the two data sets, re-sampling of Landsat TM data to the same spatial resolution as AATSR data allows development of time series based on data from both sensors. However, the question still remains if the spatial resolution of 1 km is fine enough for detection of environmental changes over time. This all depends on the physical extents of features being monitored. If these are smaller than the pixel size of the AATSR sensor, then this might limit the usefulness of this data.

SAVI showed higher values compared to NDVI for both sensors. Several authors have shown that NDVI is negatively affected by spectral signature of the underlying soil surface when vegetation cover is sparse, which is a common situation in semi-arid environments (Pech *et al.*, 1986; Rondeaux *et al.*, 1996; Schmidt and Karnieli, 2001; Gilabert *et al.*, 2002). Therefore, the fact that SAVI values are higher compared to NDVI is most likely an effect of the compensation for the influence of the soil surface, reducing the spectral backscattering in areas with a low vegetation cover, providing a more accurate account of abundance of green vegetation.

Results presented here do not provide any guidance towards which of the two indices is the best to use. This can only be done after a simultaneous field based assessment of actual abundance of green biomass at the time when the satellite images are recorded. However, based on findings from other studies it can be assumed that SAVI is the index to use in areas with sparse vegetation cover, as is the situation in the study area. The results here show that NDVI and SAVI based on Landsat TM imagery can be compared to the same indices based on AATSR imagery. However, further investigations of the systematically lower values recorded by Landsat TM has to be done in order to determine if the same constant is applicable for different scenes. If the factor differs over time, then that will add a complication to the use of the two data sets in the same time series.

Detection of surface water

The comparison of the two sensors' ability to detect surface water presented in Figure 10 shows that Landsat TM with a spatial resolution of 30 by 30 m detected 6.2% of the area as water, while the AATSR sensor with its coarser resolution only classified 2.2% of the area as being covered with water. After resampling the Landsat TM scene to 1 by 1 km pixels, 3.2% of the area was classified as surface water. This illustrates the problem with the courser spatial resolution of the AATSR sensor. In the area where this investigation was carried out many of the water bodies are too small to cover one single pixel. This leads to mixed pixels, i.e. the single DN value recorded for a pixel is the product of spectral signatures from more than one class, which leads to a lower accuracy of the classification. Therefore, given the small extent of most water bodies in the study area, Landsat TM in its original spatial resolution was found to be the best platform for detection of surface water. However, in areas with larger uniform areas, larger than 1 by 1 km it can be assumed that the two platforms will perform equally well.

Conclusion

The comparison of SAVI and NDVI calculated for both Landsat and AATSR reveals that the two platforms correspond significantly. However, the lower resolution of the AATSR imagery results in loss of detail, which might negatively influence its usefulness when high levels of detail are required.

The comparison of the two sensors' ability to detect surface water indicates that both platforms can be used for this purpose in semi-arid environments. However, the lower spatial resolution of the AATSR sensor seems to lead to an under-estimate of surface water in the study area, an effect of the small size of most water bodies in the area, leading to mixed pixel problems. Nevertheless, it can be assumed that in areas where water bodies are larger than the pixel size of the AATSR sensor, the results will be more accurate.

Acknowledgements

The authors would like to thank Dr. Alex Verlinden for his advice and training in Remote Sensing applications. We also extend our thanks to ESA for providing us with the AATSR imagery used for this study and the training and workshops that enabled us to implement the project and to increase our knowledge in the application of ESA spatial data and software programmes.

References

Bannari, A., Morin, D., Bonn, F., Huete, A.R., 1995. A review of vegetation indices. *Remote Sensing Reviews*, 13: 95-120.

Barnard, P. (Editor), 1998. Biological diversity in Namibia: Namibian National Biodiversity Task Force. Directorate of Environmental affairs, Windhoek.

Barrett, E.C., Hamilton, M.G., 1986. Potentials and problems of satellite remote sensing with special reference to arid and semiarid regions. *Climate Change*, 9: 167-186.

Cohen, W.B., Goward, S.N., 2004. Landsat's role in ecological applications of remote sensing. *Bioscience*, 54(6): 535-545.

Coppin, P., Jonckheere, I., Nackaerts, K., Muys, B., Lambin, E.F., 2004. Digital change detection methods in ecosystem monitoring: a review. *International journal of remote sensing*, 25(9): 1565-1596.

ER Mapper, 2005. ER Mapper version 7. Earth Resource Mapping Ltd.

Erkkilä, A., 2001. Living on the land: change in forest cover in north-central Namibia 1943-1996. PhD Thesis, University of Joensuu, Joensuu, Finland, 118 pp.

Gilabert, M.A., Gonzalez-Piqueras, J., Garcia-Haro, F.J., Melia, J., 2002. A generalized soil-adjusted vegetation index. *Remote sensing and environment*, 82: 303-310.

Hayes, P., Silvester, J., Wallace, M., Martmann, W., 1998. Namibia under South African rule: Mobility and Containment 1915-46. James Currey, Oxford, 330 pp.

Huete, A.R., 1988. A soil adjusted vegetation index (SAVI). *Remote sensing and environment*, 25: 295-309.

Hutchinson, P., 1995. The climatology of Namibia and its relevance to the drought situation. In: Moorsom, R., Franz, J., Mupotola, M., (Editors), Coping with aridity: Drought impacts and preparedness in Namibia. Brandes & Apsel Verlag / Nepru, Frankfurt, 17-38.

IDRISI, 1999. IDRISI 32. Clark Labs, Clark University, Worcester, MA, USA.

Kerr, J.T., Ostrovsky, M., 2003. From space to species: ecological applications for remote sensing. *Trends in Ecology and Evolution*, 18(6): 299-305.

Klintenberg, P., Christiansson, C., 2005. Improved access to water: an enemy in disguise?, Drainage basin management -Hard and soft solutions in regional development. Stockholm International Water Institute, Stockholm. 267-268.

Levrini, G. and Brooker, G., 2000. The ENVISAT data products. Geoscience and Remote Sensing Symposium, vol.3: 1198-1201.

Lu, D., Mausel, P., Brondizio, E., Moran, E., 2004. Change detection techniques. *International journal of remote sensing*, 25(12): 2365-2407.

Marsh, A., Seely, M.K. (Editors), 1992. Oshanas, sustaining people, environment and development in central Owambo, Namibia, Windhoek, Namibia, 52 pp.

Mendelsohn, J., el Obeid, S., Roberts, C., 2000. A profile of north-central Namibia. Environmental Profiles Project. Gamsberg Macmillan Publishers, Windhoek, Namibia, 79 pp.

Mendelsohn, J., Jarvis, A., Roberts, C., Robertson, T., 2002. Atlas of Namibia: A portrait of the land and its people. David Philip Publishers, Cape Town, 200 pp.

Niemann, S., 2002. Indigenous water resources management and water utilisation in northern Namibia (former Owamboland) - Can tradition help to overcome current problems? *Die Erde*, 133: 183-199.

Pech, R.P., Davis, A.W., Lamacraft, R.R., Graetz, R.D., 1986. Calibration of Landsat data for sparsely vegetated semi-arid rangelands. *International Journal of Remote Sensing*, 7(1729-1750).

Perry, C.R., Lautenschlager, L.F., 1984. Functional equivalence of spectral vegetation indices. *Remote sensing and environment*, 14: 169-182.

Quan, J., Barton, D., Conroy, C., 1994. The economic impact of desertification in northern communal areas: Uukwaluudhi, Directorate of Environmental Affairs, Ministry of Environment and Tourism, Windhoek, 35 pp.

Rondeaux, G., Steven, M., Baret, F., 1996. Optimization of soil-adjusted vegetation indices. *Remote sensing and environment*, 55: 95-107.

Schmidt, H., Karnieli, A., 2001. Sensitivity of vegetation indices to substrate brightness in hyper-arid environments: the Makhtesh Ramon Crater (Israel) case study. *International journal of remote sensing*, 22(17): 3503-3520.

Thomas, D.S.G., Shaw, P.A., 1991. The Kalahari environment. Cambridge University Press, Cambridge, 284 pp.

Verlinden, A., Seely, M.K., Hillyer, A.E.M., 2006. Settlement, trees and termites in Central North Namibia: A case of indigenous resource management. *Journal of Arid Environments*, 66: 307-335.