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Assessment of Soil Moisture Status Using Mid and Thermal Infrared Bands

Case Study: Wadi Hassib, Khartoum State, Sudan

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ABSTRACT

Soil moisture is the key factor that controls plant biological processes and indicates the environmental status. Recently, the application of remote sensing techniques in soil moisture monitoring has been widely used. In this study soil moisture was monitored during pre-autumn in March, autumn in September and post-autumn in December (2002), in order to identify the signature of different types of moist soils, which can be useful to interpret images. Supervised classification technique was adopted to determine the dominant land use/land cover classes in the area so that they can be vital indicators for the area and its suitability for many life styles. Monitoring moisture statuses can be used for general evaluation of land suitability for agriculture. The assessment of moisture statuses was performed in landsat ETM+ images using band 5 (MIR) as it is known as a sensitive band for moisture status and band 6 (Thermal) as a sensitive band to temperature variation as indicator of moisture status. The study revealed that band 5 and band 6 can be used to monitor soil moisture status during the different seasons in semi-arid areas, however, band 6 is less sensitive to variations in moisture. Therefore, this study recommends the use of Band 5 for monitoring soil moisture in semi-arid regions, and does not recommend the use of band 6 alone but with some supporting bands.

Keywords: Soil Moisture, Remote Sensing, MIR and Thermal Bands

Introduction

Soil moisture is the water that held in the soil pores in liquid and vapor phases (Mweso, 2003). Soil moisture condition is a governor factor for soil fauna and crops. Water is a dominant regulator of plant growth and soil biology; it regulates important soil processes such as nitrification and hydrological. Any shortage of water occurs, even though it may be temporary, will curtail the growth of most economic crops. Therefore, the soil's ability to hold water over time against gravity is important unless rainfall or irrigation is adequate (Foth, 1976).

Various forms of water absorb strongly in the near infrared. This is due to overtones and fundamentals of the three fundamental vibration frequencies of H2O; symmetric and asymmetric O–H stretching and O–H bending. Water incorporated into the lattice of some clay minerals absorbs strongly near 1400 and 1900 nm and is obviously directly related to the mineralogy of the soil. Water adsorbed onto soil particles surfaces and water in the pore has the general effect of decreasing the albedo. This effect can be largely attributed to the change in real refractive index of the medium surrounding the soil particles from that of air to that of water, which is higher and closer to soil particles. The resulting lower contrast causes more forward scattering and the path length before reemerging is longer, increasing the chances of absorbance. The porosity and the refractive index of soil particles vary between soils, therefore, relationship between overall albedo and gravimetric or volumetric moisture cannot be found. The generation of soil spectrum requires a radiation that contains all relevant frequencies in a particular range to be directed to the soil. Different components absorb light to various degrees; resulting in vibration of individual molecular bonds, either bending or stretching. Since the energy quantum is directly related to frequency (and inversely related to wavelength), the resulting absorption spectrum produces a characteristic shape that can be used for analytical purposes. The frequencies at which light is absorbed appear as a reduced signal of reflected radiation and are displayed in % reflectance (R), which can then be transformed to apparent absorbance. The absorption of different wavelengths depends also on the chemical composition of other soil contents and environmental factors such as temperature, allowing for the detection of a range of molecules which may contain the same type of bonds. When NIR radiation interacts with a soil sample, it is the overtones and combinations of fundamental vibrations in the mid-infrared (mid-IR) region that are detected. Molecular functional groups can absorb in the mid-IR, with a range of progressively weaker orders of overtones detected in both the mid-IR and NIR regions (Stenberg et al., 2010).

This study used MIR band (1.55-1.75 μm) and thermal (10.4-12.5 μm) band in landsat ETM+ images to assess soil moisture status of different soil types at different seasons.

Soil moisture is a physical parameter which has a spatial and temporal variability, unlike other parameters as slope, relief that show mainly spatial variation. It is one of the elements that affect soil reflectance in larger wavelengths, as consequence of the high absorption of water in microwaves, near infrared, infrared and thermal wavelengths (Maffra and Centeno, 2011).

Remote sensing techniques used for soil moisture estimation are based on the collection and interpretation of satellite imaging, aerial photography beside ground data regarding soil nature, properties and state. These variations are reflected and recorded by the satellite sensors with different electromagnetic spectrum properties. Currently, a variety of remote sensing techniques for soil moisture retrieval has been evolving based on their different electromagnetic spectrum properties (Qiu, 2006).

One of the used methods is microwave RS, which depends on the relationship between soil moisture and dielectric characteristics of the target and radar backscatters. Radar waves may not be able to penetrate soil if it is moist. The intermolecular forces of water and soil molecules that affect backscatters are strongly affected by soil texture. Many experiments were conducted to determine the relation between soil texture and moisture, and revealed various empirical models referred to as dielectric mixing models (van der Velde, 2010). Hossain and Easson (2009) have found that in semi-arid environment the vegetation can influence the estimation of soil moisture using the linear relationship between radar backscatter and soil moisture reported in other earlier researches. Newton et al. (1982) had tested the depth to which soil moisture can be directly measured using microwave radiometers at1.4, 4.9, and 10.7 GHz at both vertical and horizontal polarization at off nadir angles from 0 to 500, and found that passive microwave measurements at frequencies down to 1.4 GHz can only measure soil moisture directly to very shallow soil, due to the fact that the dependence of soil moisture on the transmission coefficient across the air-soil interface predominates over the dependence on the total energy originating within the soil volume. They also found that the combination of low incident angle and measurement frequency in the C-band range does not minimize the effect of surface roughness for passive microwave measurements, due to the fact that this combination of frequency and incident angle has been described as the optimum combination for minimizing the effect of surface roughness on the response of radar-backscatter measurements to soil moisture. MIR band (1.55-1.75 μm) is very sensitive to moisture, and therefore used to monitor vegetation, soil moisture and differentiate between clouds and snow. Thermal IR (3 to 5 μm) and (8 to 14 μm) are the principal atmospheric windows in the thermal region. Imagery at these wavelengths is acquired through the use of optical-mechanical scanners. TIR band (10.4-12.5 μm) is used to measure surface temperature, and because of the relationship between temperature and moisture content this band can be helpful to discriminate soil condition (Levin, 1999).

Hummel et al. (2001) conducted a research to document the ability of a previously developed near infrared (NIR) reflectance sensor to predict soil organic matter and soil moisture contents of surface and subsurface soils at three soil cores for eight depths of the US Cornbelt area. They found low standard deviations of the soil moisture levels across soil cores, and attributed that to the relatively uniform clay content and reduced organic matter content in the B horizon of these soils. The prediction of soil moisture showed a tendency to under-predict at the higher moisture levels, and was unaffected by the removal of the A-horizon data from the dataset. The ability of the NIR sensor was hampered by introduced layer of water on the surface of some of the saturated samples during the reflectance data collection. While at lower moisture content the sample surface presented to the sensor than within the remainder of the sample and more likely for the saturated samples, because of moisture movement due to gravity. They concluded that the technology may be applicable for the estimation of soil organic matter and soil moisture in subsurface soils.

A study by Given (2010) was conducted to determine the ability of the NIR Scanalyser to obtain accurate soil moisture content to monitor water changes in the root zone. The study concluded that NIR Scanalyser can be used to obtain accurate estimations of soil moisture content in a homogenous soil column, and the relationship between mean pixel value and gravimetric moisture content of soil is significant. Finn et al. (2011) researched the relationship between SWIR data and soil moisture and identified possible wavelengths for determining soil moisture for a given soil type and vegetation distribution. They found a significant statistical correlation for the hyperspectral data at the 2 inches model, and they best modeled the soil moisture at that depth in 1300 to 1670 nm wavelengths range. While at 8 inches and 12 inches the models were not able to estimate soil moisture to the same degree.

The differences between the thermal properties of soil and water include heat capacity, thermal conductivity and thermal inertia. Therefore, a little change of the soil-water portion gives a large change in the thermal properties and this is the base of using thermal infrared technique that is mainly based on earth's surface emissivity which depends on the surface temperature and the soil surface emissivity. The advantages of using the thermal infrared technique can be summarized in wide coverage of large areas, the ability of using multi spatial, spectral and temporal resolutions. But this technique has also many factors that impede the recorded thermal energy, and they are: atmospheric effects; which are a large impediment that may attenuation the signal or change it by the clouds or bushfires or others else, and these errors can be solved by applying a complex series of noise removal mechanisms before the utilization of the thermal data. Also the vegetation cover; which prevents the thermal spectrum to pass through (depending on the canopy density); if the canopy is dense it obscures more than about 10 to 20% of the soil surface, therefore the thermal image would have wrong recorded temperature of the soil's surface and the thermal properties of the vegetation cover will be measured instead of the soil's, so that it is preferred to choose regions with low density of the vegetation cover when using thermal infrared technique in remote sensing. Another impediment is added to the mentioned above which is the surface penetration depth (Qiu, 2006).

Lesaignoux et al. (2010) analyzed the impact of surface soil moisture on the spectral reflectance in the domain of 0.4 – 15 µm. They tested bare soils at different moisture contents. They classified the soils according to their spectral reflectance and analyzed the impact of moisture on the reflectances. In the visual domain they classified the soils into three types according to their spectral behavior. In the near and shortwave infrared domain the absorption peaks (1.4, 1.9 and 2.2 µm) where commonly present in all samples, thus they considered that there is only one type of spectra behavior for all the samples in NSWIR domain. In midwave infrared domain, they considered two types of spectra: bell-shaped and spectra with two lobes. Since in LWIR domain, most minerals have typical maximum of reflectance which is known as Reststrahlen band, the soils were classified for three types: spectra with strong and weak Reststrahlen bands of quartz plus spectra with weak secondary Reststrahlen bands of carbonates and spectra with strong secondary Reststrahlen bands of carbonates. They found that the impact of soil moisture on spectral reflectance is decreasing the reflectance in the visible domain when moisture is increased for all soil types, while the reflectance decreases and hydroxyl (OH-) absorption peaks depth at 1.4 µm and 1.9 µm, increase and widen with the increase of moisture in NSWIR domain. In thermal domain (3 – 15 µm), they found a decrease in reflectance with moisture increase as the solar domain and they were not able to detect absorption peaks at moisture content upper 20 %. In MWIR, carbonates and silicates (quartz) absorption peaks were found lower when moisture increases. Since the Spectra level deviation was higher in MWIR than in LWIR domain, it was difficult to study the impact of soil moisture content in LWIR domain. They concluded that the increase in the soil moisture content leads to reduction of reflectance level in optical domain with growth of depth and spreading absorption peaks of hydroxyl, a reduction in the depth absorption peaks of minerals in NSWIR and MWIR beside a decrease of Reststrahlen bands of quartz and carbonates in LWIR. Remote sensing methods used to estimate variables like soil moisture are valid, and a satisfactory correlation between RS moisture estimations and ground measurements were found (Gidey, 2009).

The Study Area

The study area is Wadi Hassib, which lies in the southern east of Khartoum State, Sudan. Wadi Hassib area is 24 km south of the south west of Khartoum North within (Figure 1).

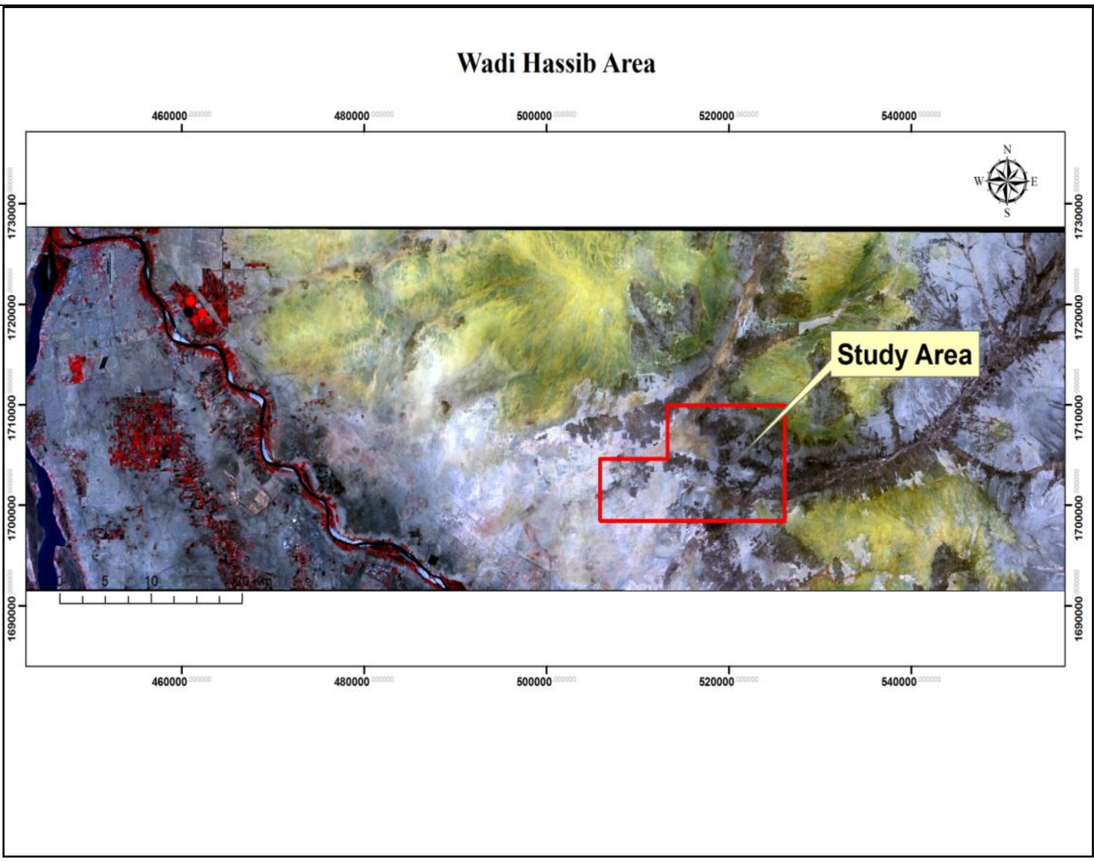

Figure 1: The location of the study area in Khartoum state

The area contains older alluvium, raised terraces, younger gravel and sand plains of the quaternary age. The area is recharged from two main sources: direct percolation of rainwater and seepage through the beds of the gullies and valleys and the seepage from the Blue Nile.

The study area is within the arid zone at mean annual temperature of 29.9ºC. The summer season extend from April to June while the winter season extends from Dec to Feb. The relative humidity fluctummuates during the day (GMT) and during the year (seasons). The average annual rainfall is about 121 mm falling mainly in July and August with fewer amounts in September. The rainfall is erratic in quantity, intensity and distribution.

The main dominant land forms are valleys (Wadis) which are seasonal wadis occupying low lying areas; Elevated areas (locally known as Gala'a) which are resulted from in-situ weathering followed by deflation of the fine materials leaving behind gravels, boulders and rock fragments of different sizes and chemical composition; plain sandy sheets which are the weathering products of the Nubian sandstone; slightly sloping areas which occupy slightly sloping areas; therefore they are subject to erosion either by wind or water leaving very little time for horizon differentiation and slightly concave areas which are the soils that have received materials from their surroundings; therefore, they have the chance to form pedogenic horizons in form of cambic horizon. The soils of the study area were classified according to the Soil Taxonomy (Keys to Soil Taxonomy, 2010) into Typic Torrifluvents, Typic Torriorhtents and Typic Haplcambids.

Materials and Methods

Three imageries of landsat ETM+ were freely downloaded from Global Land Cover Facility of (GLC) to monitor soil moisture status for three periods (March, September and December), and these months represent summer, autumn and winter respectively. Band 5 (1.55- 1.75 µm) and band 6_VCID_2 (10.40- 12.50 µm) were used. Band 5 is a shortwave infrared, while band 6 is thermal one.

Visual interpretation was used to assess spatial and temporal variations in moisture status at different soil types. Reference features were used as reference for different moisture levels namely: River Nile as saturated water object, Gezira Scheme for moistened vegetation and Gala'a areas for dry areas.

Results and Discussion

Moisture Status Monitoring Using Band 5

In March, although it is summer and dry months with low moisture content, spatial variation in moisture content was witnessed (Figure 2). A low reflectance, high absorption of energy, at the gullies/valleys areas was recorded. This could be a good indicator of high moisture content at these areas despite the low rate of rainfall. This reservation of water could be attributed to the dominancy of silt and clay particles in these valleys. These particles have high water holding capacity. This result shows that NIR region has high sensitivity for moisture condition. Gala'a (high lands) at the sides of the valley had a high reflectance as indicator for low moisture content as a result for low rate of rainfall and the dominancy of gravels and sand particles which have low water holding capacity. This agreed with Given's (2010) who recorded a high reflectance of sand when a NIR scanalyser camera was used. In Aljazeera scheme high NIR reflectance was associated with cultivated ones, while fallow wet land had showed a low reflectance this could be attributed to high moisture holding capacity of heavy clay soil.

In September, the moist areas appear darker than the previous one (Figure 3). A low reflectance at the gullies/valleys areas in the image appeared as an indicator for high moisture content due to rainfall and the high water holding capacity of the clay. This finding agreed with Lesaignoux et al. (2010), they found that the increase of moisture content results in decrease of spectral reflectance. Gala'a (high lands) had a high reflectance, because of the presence of the gravels and sand in addition to low moisture content despite rainfall (sandy soils do not hold water for long time).

Lesaignoux et al. (2010) had noted loss of absorption peaks of the hydroxyl (OH-) at 2.2 μm, which was attributed to other minerals that compose the soil such as quartz. These minerals contribute to the high reflectance. Vegetation dominated around water bodies like Nile, wet lands of the valley and agricultural areas in Wadi Hassib and Aljazeera scheme. Vegetation obviously appeared as red color feature in false composite image of bands 4, 3, and 2 (RGB). The natural vegetation and pastures growth was due to good rainfall at that time.

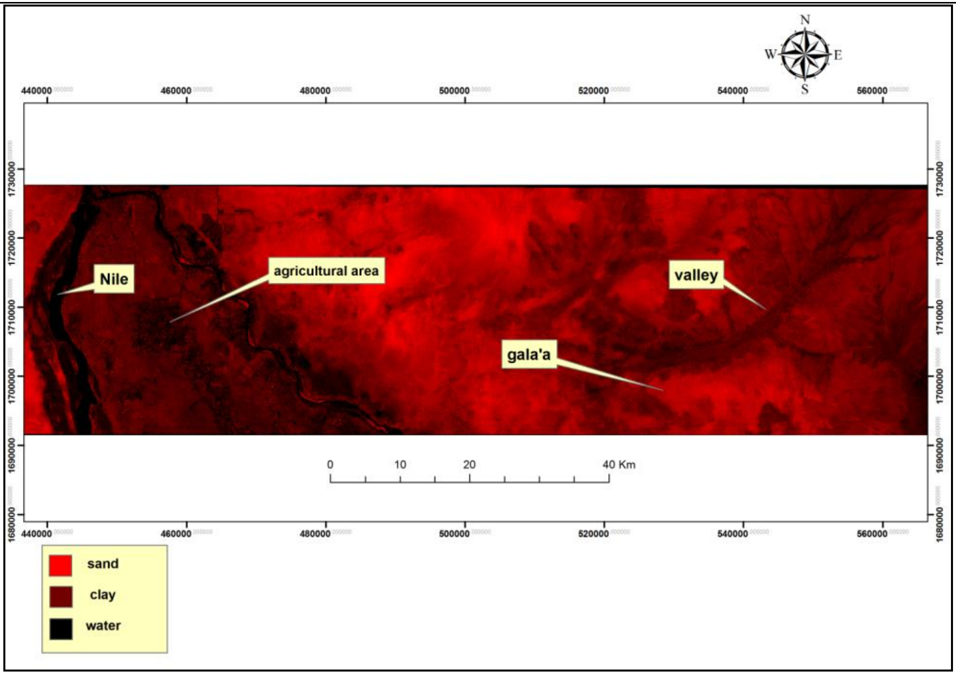

Figure 2: Moisture status in March, moist areas appear darker than dry/sandy areas

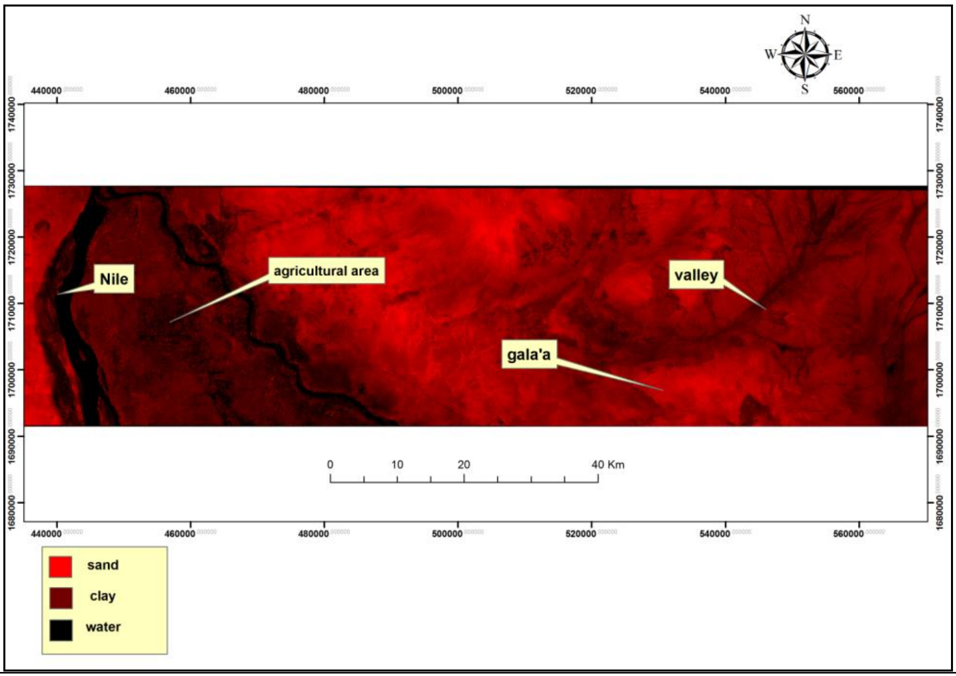

Figure 3: Moisture status in September, moist areas appear darker than dry/sandy areas

December:

In the December, the spatial variation of moisture status was similar to that of March (Figure 4). The areas of the gullies/valleys pattern showed low reflectance despite the stop of rainfall, which can be attributed to the dominancy of silt and clay particles which have dark color beside high water holding capacity.

Gala'a (high lands) at the sides of the valley showed high reflectance, indicating for low moisture content as a result of gravels and sand dominancy in those parts.

There was no appearance for vegetation in Wadi Hassib area; because of the stop of rainfall since the cultivation type is rain-fed.

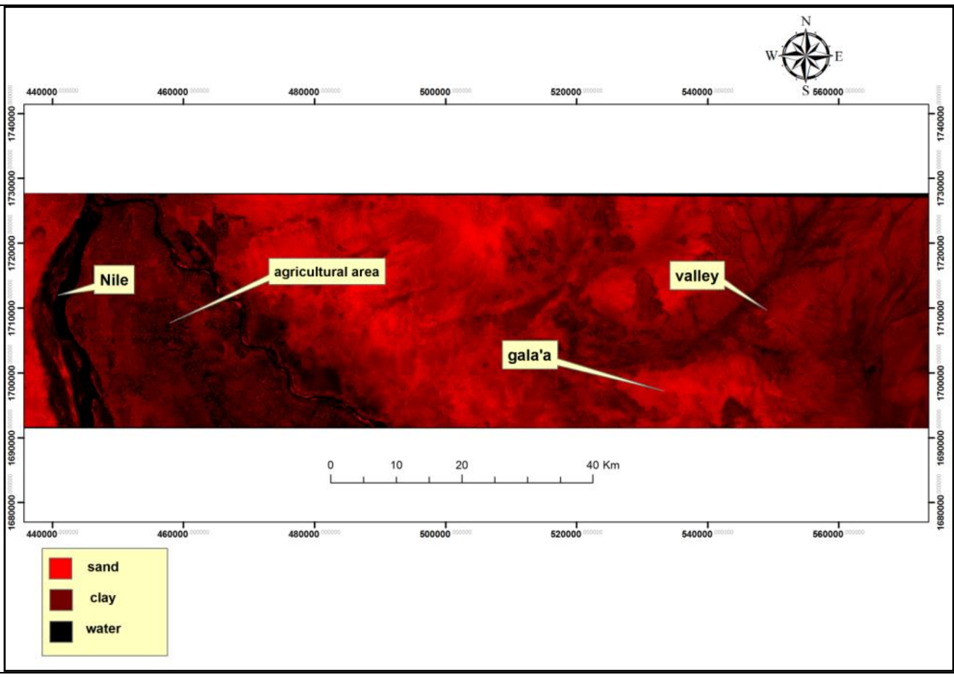

Figure 4: Moisture status in December, moist areas appear darker than dry/sandy areas

The Reflection Ranges of the Different Moisture Statuses

Table (1) showed different reflectance ranges for the different soil types during the three periods in band 5. High values were recorded for the gala'a sand at minimum and maximum levels (104 and 154). Clay of the valleys recorded intermediate minimum and maximum ranges (87 and 123). Water recorded the lowest values range of minimum and maximum (51 and 54).

Table 4.1 the reflection ranges of the soils of Wadi Hassib using band 5

Month	Soil Type	Minimum Reflection	Maximum Reflection
March	Clay	97	149
	Clay of the Valley	87	123
	Northern gala'a sand	104	154
	Southern gala'a sand	99	161
September	Clay	95	143
	Valley clay	87	117
	Northern gala'a sand	104	147
	Southern gala'a sand	104	155
December	Clay	80	118
	Valley clay	68	98
	Northern gala'a sand	80	126
	Southern gala'a sand	81	133
Water		51	54

The clay showed a low range of reflectance during the three months, as a result for its dark color in addition to the high water holding capacity. Clay particles are small, and so, have a large surface area which absorbs the energy, and conversely reflects low energy.

The clay of the valley showed the lowest reflectance between all soil types, and this can be explained by the presence of much water amount in the valley due to its topography and hydrology (the water path).

Gala'a showed the highest reflectance range, which explained by the light color of the sand in addition to its low water holding capacity.

Moisture Status Monitoring Using Band 6_ VCID_2

Thermal images interpretation is affected by the acquisition time of the image. These images were taken during day time. Therefore, they showed different features with different grades of the gray color, the cooler the feature the darker it is. Figures (5, 6 & 7) indicated that cool features were water bodies (Nile and its tributaries), vegetation (natural and cultivated) and wet soils, due to the reverse relation between temperature and water.

The Nile tributaries had the darker grade at all images. However, sandy soils were brighter than the water but darker than the clay in March and September, despite the low moisture content in these parts (Figure 5 & 6). Clayey and wet soils had the brightest gray color in March and September, but darker in December despite the high moisture content in September (Figures 6 & 7). The low reflectance of sandy soils compared to clayey and wet ones during the dry seasons (March and December) could be attributed to quartz, the main component of the sand, which has strong reststrahlen band between 8 and 10 μm depending on the amount of silica, and a weak reststrahlen band between 12.2 and 13 μm. All these obtained results indicate that the thermal band is not as accurate as the mid infrared band in identifying different moisture statuses. Lesaignoux et al. (2010) study mentioned that it is difficult to study the impact of soil moisture content in LWIR domain.

All clayey parts appeared brighter than the others, while high lands that were mainly sand and gravels were dark. Cultivated parts of Aljazeera scheme were also dark since vegetation is a cool feature during the day due to the moisture resulted from accumulated water vapor from evapo-transpiration.

The clayey parts and the valley had the brightest grade despite their high moisture content, but they were darker in March. Sand and high lands were dark, and this could be attributed to the increase of their moisture content in that month due to good rainfall.

The clayey parts and the valley were darker than the sand and high lands in this image. And this referred to the higher moisture content in clay than that in sand. The water (Nile and its tributaries) had always the darkest grade at all images.

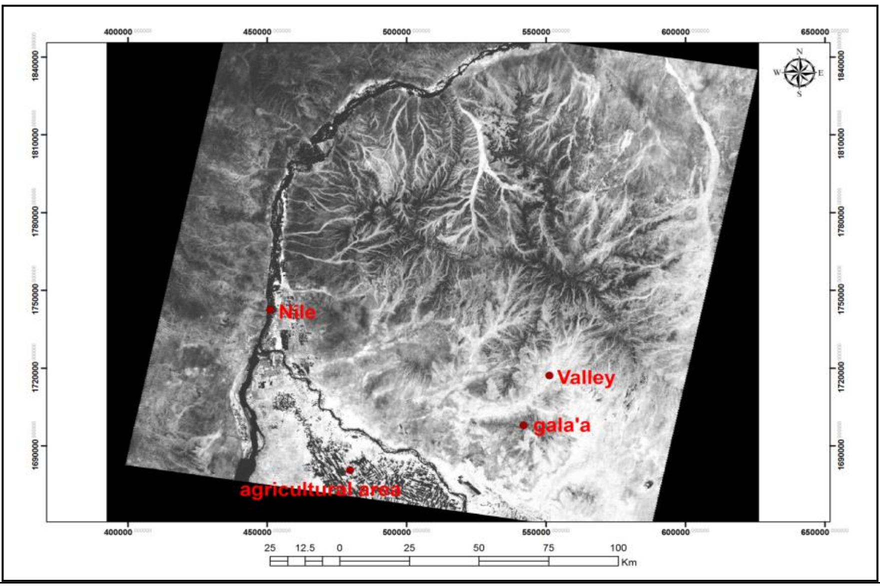

Figure 5: Thermal band image of March

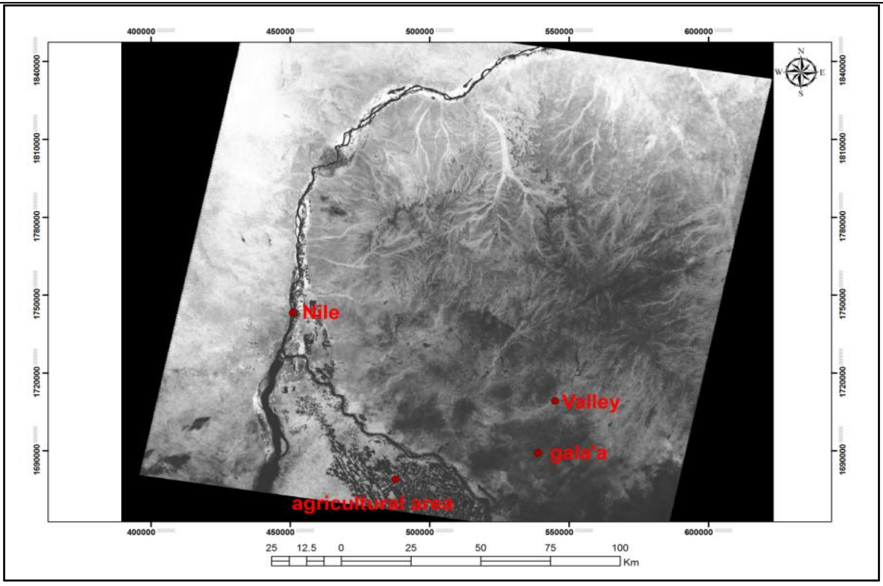

Figure 6: Thermal band image of September

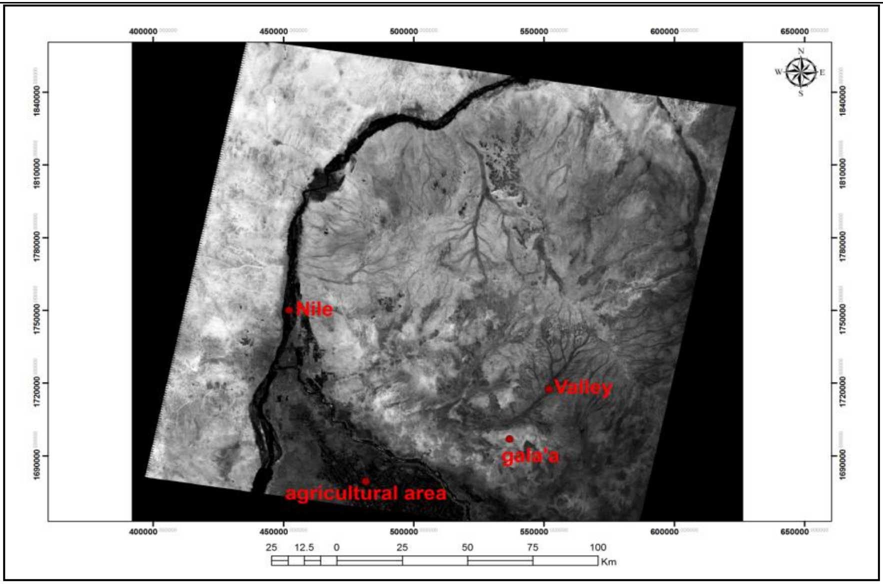

Figure 7: Thermal band image of December

Conclusion

This study was limited on using MIR and Thermal bands to monitor soil moisture status during three months that represent dry, wet and pre-wet seasons; namely; March, September and December; respectively for the year 2002.

Wadi Hassib is an arid area, so the moisture content is often low. The study revealed that the use of band 5 sensor can detect moist areas even at low moisture contents, on the other hand, band 6_VCID_2 sensor show moist areas at high moisture contents, however, it gives inaccurate results in the cases of low moisture contents in the arid areas.

Recommendations

- Based on the findings of this study the following recommendations are suggested:
- Band 5 can be used to state soil moisture in different contents while band 6 must be used with some cautions due to its limited accuracy in semi-arid areas.
- For sake of accuracy improvement, high spatial and spectral resolution satellite images should be used to monitor soil moisture in arid areas.
- In depth studies of related reflectance to soil moisture content is recommended.

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