Use of satellite derived vegetation indices for the detection of water pipeline leakages in semiarid areas

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ABSTRACT

Remote sensing may be used for quick and cost effective detection and monitoring of water leakages, since traditional field survey methods for detection of water pipeline leakages are costly and time consuming. Vegetation indices are widely used by researchers for many applications. Among them, NDVI, RVI and SAVI are indices that can be used for pipeline leakage detection. In this study, the above vegetation indices were evaluated based on Landsat ETM+ multispectral images in a multi-temporal mode. The evaluation was performed in the semiarid environment in Cyprus, in order to detect the position of points/areas where water leakage occurs and to examine the accuracy of the vegetation indices in detecting such events. In addition, a low altitude system was used to record spectral differences before and after a leakage event. The results showed that there are leakage points that could be detected using satellite images due to the increasing and decreasing of the surrounding vegetation affected by the water leaked of the pipeline. Other characteristics such as the soil type and precipitation were also examined. Finally, the low altitude system highlighted the advantages of using such non contact techniques for monitoring water leakages.

Keywords: water leakages; vegetation indices; low altitude system; spectroradiometric measurements; Landsat ETM+.

1. INTRODUCTION

Traditional field survey methods for detection of water pipeline leakages are costly and time consuming. Conventional techniques are used to detect water pipeline leakage including acoustics, radioactive, electromagnetic, ground penetrating radar and linear polarization resistance [1-6]. Remote sensing has been used widely for several applications regarding water and vegetation studies and can be used as a tool for quick and cost effective detection of leaks [7]. A main limitation of satellite images is the spatial resolution which is required since the pipeline leakages occur in small areas along the pipeline. Therefore, the affected area must be observed using the appropriate pixel size. Vegetation indices (VIs) are the main form of satellite spectral data used for several applications. Over fifty different remote sensing VIs have been employed [8] and, following the deployment of hyperspectral sensors, the number of VIs has almost doubled. According to Agapiou et al. [9], VIs can be divided into five main categories according to their formula (equation) or the aim of use of each index: broadband indices, narrowband indices (hyperspectral), leaf pigment indices, stress indices and water stress indices. However, VIs can be simply divided according to the wavelength characteristics used (broadband and narrowband indices).

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Several researchers have examined the capabilities of remote sensing for the detection of water leakages. Pickerill and Malthus [10] analyzed two known leaks using airborne remotely sensed imagery and found that different vegetation indices and single bands were required in order to identify each leak. The spectral profile of one leak responded best to a ratio of NIR to red reflectance, while in the other, NIR to red reflectance ratio was not useful in differentiating it from its surroundings. Huang et al. [11] in the Lower Rio Grande Valley in Texas used airborne multispectral remote sensing imagery with high-resolution imaging sensors in the visible, NIR and thermal infrared wavelengths. It was concluded that airborne multispectral imaging is very promising as a tool in detection of irrigation canal leakage in distribution networks. Analysis of the processed image data from red, NIR and thermal bands is highly consistent with the observations from field reconnaissance. Images from individual bands, particularly from the thermal band, can help detect leakage from irrigation canals.

This paper presents the results from different remote sensing technologies for the detection and monitoring the water leakages. Water utility systems located in open fields in Cyprus were examined. Two case studies areas were evaluated using freely distributed Landsat ETM+ satellite images and ground spectroradiometric data. In addition, a low altitude system was deployed to observe an extensive problematic pipeline from different heights.

2. CASE STUDIES AREAS

Two different case studies were examined. The first area is the *"Lakatameia"* pipeline which is currently not in use while the second one is the *"Khirokitia - Phrenaros*", a major pipeline of Cyprus (Figure 1). For the *"Khirokitia - Phrenaros*" pipeline three major leakages have been recorded between 2007 to 2010.

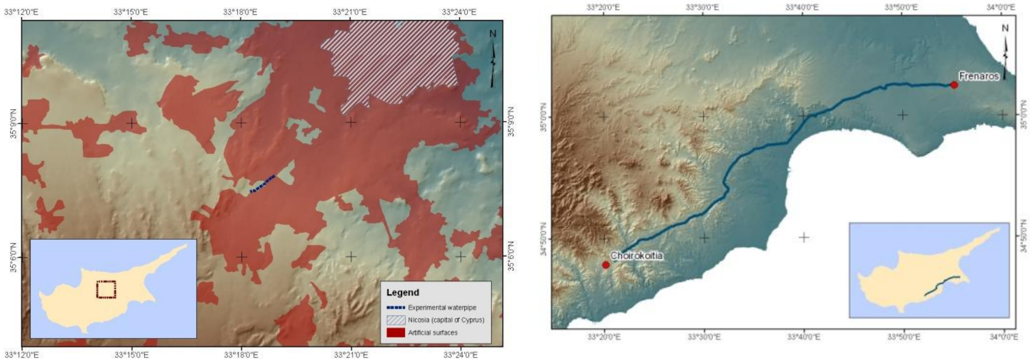

Figure 1: The "*Lakatameia*" water pipe (dash line) used as the pilot study area (left) and the "*Khirokitia - Phrenaros"* water pipe used as the case study area (right).

2.1 "*Lakatameia*" case study

A pipeline in the *Lakatameia* area (central Cyprus) was selected to be used for the pilot study (Figure 1). The pipeline, with a length of less than 5 km, has been systematically reported as problematic due to several leakages and it is therefore no longer in use by the local authorities. The pipe runs through urban and rural areas (Figure 1). A section of the pipeline with a length of over 2km and located in a rural area, has been used for the detection of leakages. Since the existing water pipe is not currently used, it was necessary to periodically filled in the pipe with water periodically in order to observe the effectiveness efficiency of such remote sensing non-contact techniques. The water pipe is made of UPVC and has 315mm diameter. It is between 1.80m and 2.00m below the ground surface and runs along the *Pediaos* River for a large part of its length. It is not currently being used due to water leakages occurring throughout almost the entire length of the pipeline. Information regarding the specific dates of events is not available from the local authorities.

2.2. *"Khirokitia - Phrenaros"* case study

The second area of interest is a major rural pipeline in Cyprus, which runs from the *Khirokitia* area to the *Phrenaros* area (Figure 1). The existing pipeline, which passes through the central and central-east part of Cyprus, has a length of over 65 km. The pipeline is located 1-3 meters below ground surface. Various geological formations, generating several soil types, including calcaric cambisols, calcaric regosols, and epipetric calcisols, exist in the area, while the higher and lower elevation of the pipeline (ground surface) is estimated to vary between 10 m and 200 m above sea level. In addition, the water pipe passes through different types of land cover, as recorded from the CORINE 2000 land use map (Figure 2). During the period 2007 to 2010, three major leakages were observed along different sections of the pipe (Figure 6). The leakages under investigation occurred during 2007, 2008 and 2010; further details for these events are presented in Table 1.

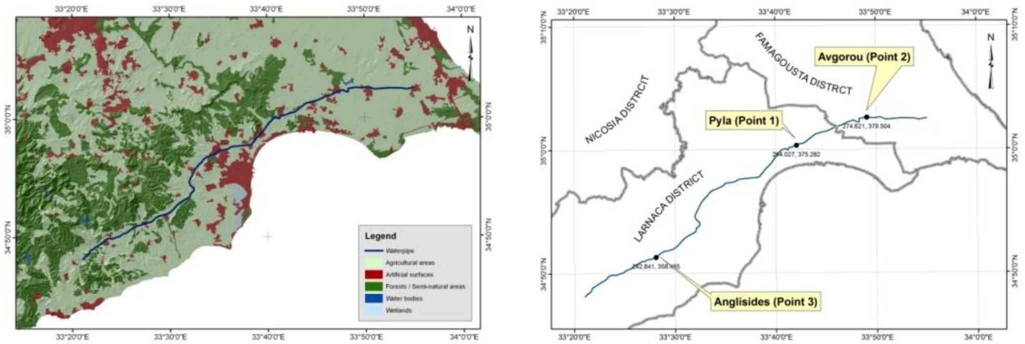

Figure 2: The CORINE 2000 land use (Level 1) in the *"Khirokitia - Phrenaros"* water pipe (left). Points 1-3 indicate the spots were water leakages have been reported (right).

Table 1. The leakages of the "*Khirokitia - Phrenaros"* water pipeline

Point	**Position**	**Name**	**Date of pipe fixing**
Point 1	Km 43,265	*Pyla* Area	20-07-2007
Point 2	Km 55,346	*Avgorou* area	18-02-2010
Point 3	Km 12,769	*Anglisides* area	17-09-2008

3. METHODOLOGY AND RESOURCES

3.1. Methodology

In order to explore the capabilities of remote sensing for the detection of water leakages, two different methodologies were followed. For the *"Lakatameia"* water pipe, ground spectroradiometric measurements were taken using a handheld spectroradiometer. A leakage event was created by filling small sections of the pipeline with water so that ground spectral signatures could be taken before and after the leakage. Spectroradiometric data were also recorded from different heights using a low altitude system. In this way, spectral signatures were able to simulate satellite data. For the *"Khirokitia - Phrenaros"* water pipe, three major leakages have been recorded (see Table 1). Several Landsat ETM+ images, before and after the water pipe was repaired, were evaluated. Both geometric and radiometric calibrations of the satellite images were performed, followed by a multi-temporal analysis of all datasets based on vegetation indices.

3.2. Resources

In this section, the resources and processing used for each case study are presented. The resources are grouped into two main categories: (a) spectroradiometric ground data used for the "*Lakatameia"* pipeline and (b) medium resolution satellite data used for the *"Khirokitia - Phrenaros"* pipeline.

3.2.1 Spectroradiometric data – *Lakatameia site*

Spectroradiometric hyperspectral measurements were carried out using the GER 1500 field spectroradiometer (Figure 3, left). The GER 1500 spectroradiometer records electromagnetic radiation between 350 nm to 1050 nm (visible and NIR part of the spectrum) A calibrated spectralon panel, with ≈100% reflectance, was also used simultaneously to measure the incoming solar radiation. The spectralon panel measurement was used as a reference, while the measurement over the crops was used for the target measurement. To avoid any errors due to changes in the prevailing atmospheric conditions

[12] the measurements over the panel and the target were taken within minutes of each other. The coordinates of the measurements were mapped using a Global Navigation Satellite System (GNSS) (Figure 3, right).

Figure 3. The GER 1500 spectroradiometer used for the collection of ground measurements (left) and the GNSS used for mapping the pipeline (right).

In addition, spectroradiometric measurements were taken from a low altitude system (Figure 4). The spectroradiometer was attached to the air balloon and raised over the pilot study area. Measurements were taken at several heights in the pilot study area and also in the surrounding area in order to compare their spectral signature profiles. As the airborne system was raised, the pixel size on the ground increased. Hyperspectral measurements recorded from the GER 1500 instrument needed to be recalculated according to the characteristics of a specific multispectral satellite sensor. The authors modified these data to mimic Landsat 7 ETM+ satellite imagery based on Relative Spectral Response (RSR) filters since such data are freely distributed by the USGS.

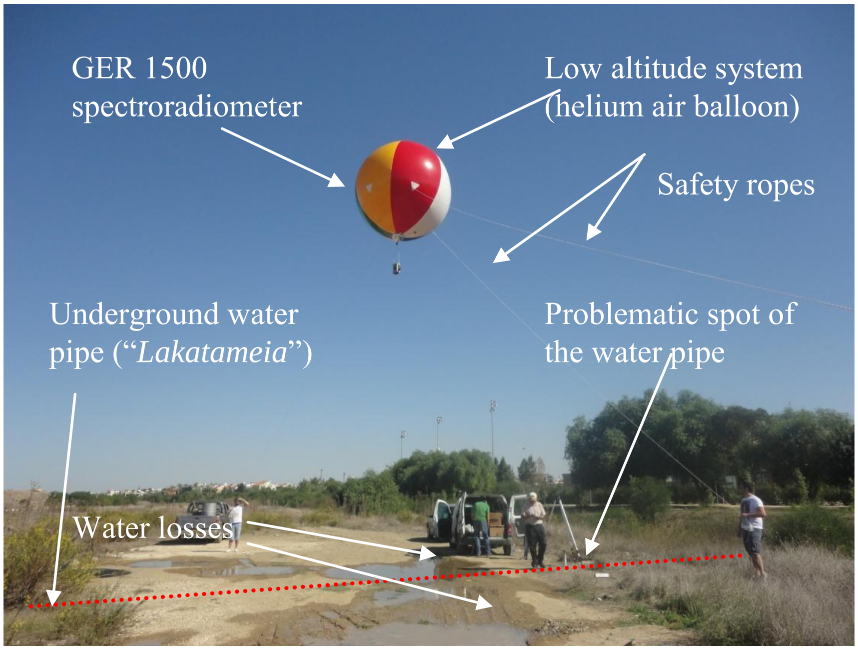

Figure 4: The low altitude system deployed over the leakage in the "Lakatameia" waterpipe.

3.2.2 Medium resolution Satellite data "*Khirokitia – Phrenaros*" site

Twelve medium resolution Landsat 7 ETM+ satellite images were used, dated before and after the local authorities repaired the leaks on the "*Khirokitia - Phrenaros*" pipeline (Figure 5; Table 2). ERDAS Imagine software was used for the pre- and post-processing of satellite imagery. Pre-processing included geometric and atmospheric correction of the satellite imagery. Geometric correction of the satellite images was conducted using ground control points (GCPs).The Darkest Pixel (DP) atmospheric correction method was used, which is the most widely applied method that provides reasonable correction [13-14]. After the necessary pre-processing steps, several vegetation indices were evaluated.

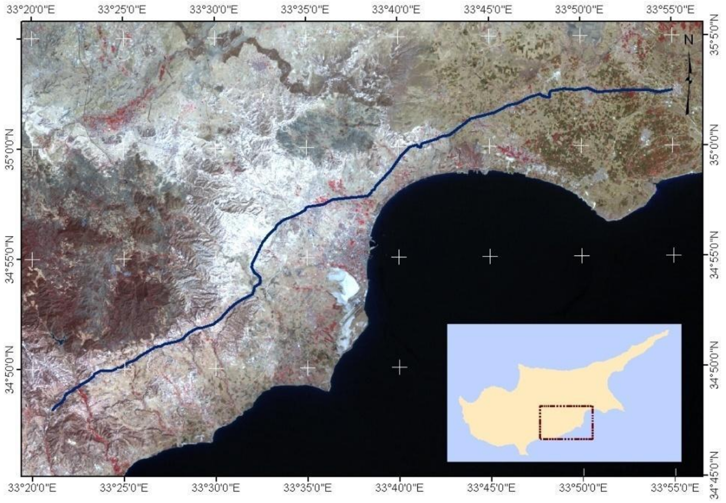

Figure 5: Landsat 7 ETM+ satellite image (28/07/2008) over the *"Khirokitia - Phrenaros"* water pipe.

Table 2. Satellite images used for this study

no	Satellite	Overpass	no	Satellite	Overpass
1	Landsat ETM+	07/05/2007	7	Landsat ETM+	14/09/2008
2	Landsat ETM+	23/05/2007	8	Landsat ETM+	30/09/2008
3	Landsat ETM+	27/08/2007	9	Landsat ETM+	16/10/2008
4	Landsat ETM+	28/07/2008	10	Landsat ETM+	22/12/2009
5	Landsat ETM+	13/08/2008	11	Landsat ETM+	07/01/2010
6	Landsat ETM+	29/08/2008	12	Landsat ETM+	13/04/2010

3.2.3 Soil data

The soil types of the area around the three points under investigation were classified according to the FAO/UNESCO soil classification system [15-16]. For Point 1 and 3, soils are characterized as Cambisols or Regosols. Their parent material is medium and fine-textured derived from a wide range of rocks, mostly in colluvial or alluvial deposits. Cambisols are soils that have a cambic B-horizon and no diagnostic horizon other than an ochric or an umbric A horizon, a calcic or a gypsic horizon. Soils classified as Cambisols occupy extensive areas. Calcaric Cambisols in (irrigated) alluvial plains in the dry zone are intensively used for production of food and oil crops. Calcaric Cambisols in undulating or hilly (mainly colluvial) terrain are planted with a variety of annual and perennial crops or are used as grazing land. Regosols are soils from unconsolidated material, having no diagnostic horizons other than an ochric A horizon. Regosols are divided into calcaric and eutric sub-orders. For Point 2, soils are characterised as Calcisols or Luvisols. Luvisols are soils that have an argillic B-horizon and they are subdivided into Vertic, Calcic and Chromic. Calcisols include soils in which there is substantial secondary accumulation of lime. Calcisols are common above highly calcareous parent materials and widespread in arid and semi-arid environments.

3.2.4 Meteorological data

Meteorological data were provided from the Meteorological Service of Cyprus. Precipitation data for the years 2007-2010 at the five main meteorological stations in Cyprus (Pafos, Prodromos-Nicosia, Limassol, Athalassa and Larnaca) were examined. During the study period, the highest precipitation amounts were recorded during December, January and February at all meteorological stations. Examination of the precipitation by date and month showed that significant rainfall was recorded on 25th, 26th and 27th February 2010, a few days after the fixing of the leaking pipe (18th February 2010) near Larnaca station, which is the closest station to Point 2.This supports the hypothesis that in the case of Point 2, the main factor which increase the vegetation index value can be related with leakage. Regarding Point 3 (*Anglisides* area), precipitation data did not affect the pipe leakage since significant precipitation was not recorded either before or after the pipeline repair (17-09-2008).

4. RESULTS

4.1 *“Lakatameia”* pipeline

The results of this study show that water leakages can be monitored using remote sensing techniques. As shown in Figure 6, the spectral signatures of dry and wet soil, taken from different heights from the low altitude system, is easily recognized in the visible range of the spectrum (400 -700 nm) and in the very near infrared range (750-900nm). Indeed, wet soil tends to give up to 20-25% lower reflectance values compared to the dry soil, with the difference being maximized in the very near infrared range of the spectrum. Similar findings can also be observed for other areas, too. Dry grass tends to give approximately 5% reflectance in the green part of the spectrum (520-600nm) and 25% in the very near infrared (750-900nm) in contrast to 12% and 35% respectively for the wet grass. In addition, it was found that reflectance initially increased as the system was raised above ground level (until 10 meters) while a small decrease of the reflectance was observed afterwards (16 meters) which can be associated with the larger area covered from the spectroradiometer. However, it should be noted that these differences (~5%) are similar to the relative uncertainties of calibration of satellite sensors (within 5%) [17].

The above results are well supported in the literature. Several researches [18-21] have found that moisture affects the reflectance value of soil. There is a notable decrease in reflectance with increasing moisture in the ground. However, the rate of decrease in relative reflectance becomes more moderate with increasing ground moisture, since at very high moisture contents the soil is already quite dark (as it manifests in spectral signature) and further moisture added to the soil has less of an effect on the reflectance [20]. Moisture dominates the spectral reflectance of soils in the 340-2500 nm wavelengths [22]. Moisture affects the reflection of shortwave radiation from ground surfaces in the visible and near-infrared - VNIR (400-1100nm) and shortwave infrared - SWIR (1100-2500nm) regions of the spectrum. It is notable that although precipitation affects the reflectance value for each surface type, it does not change the typical spectral signature between wet and dry conditions [23].

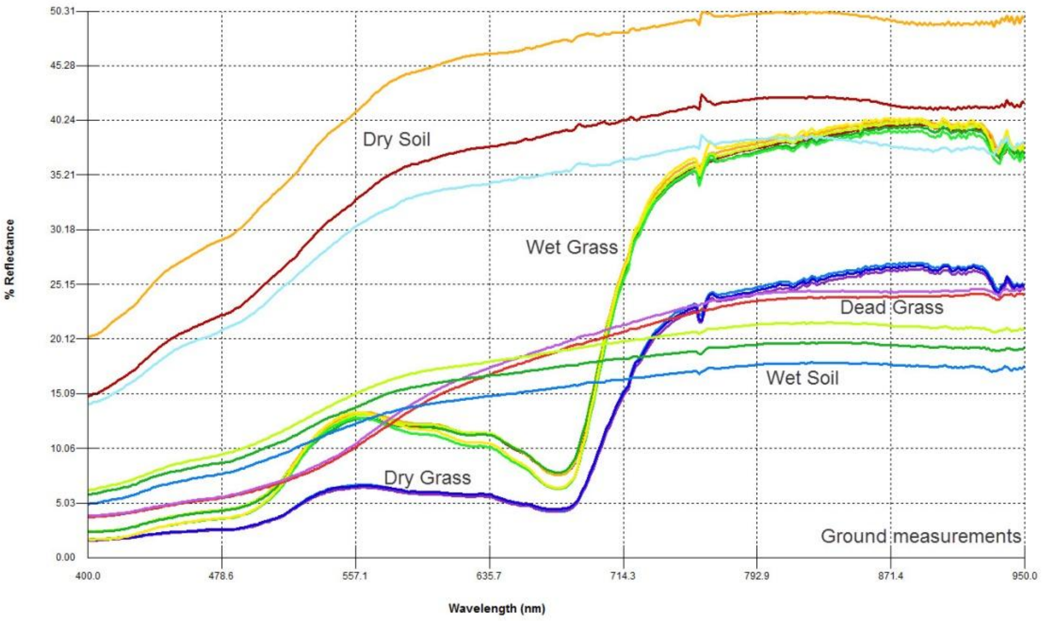

Figure 6: Ground spectral signatures of different targets in the *“Lakatameia”* pipeline

The results indicate that the detection of a leakage event is possible using remote sensing techniques. The very near infrared range of the spectrum can be used on areas with bare soil or with vegetation. The findings from this pipeline were therefore evaluated using the case studies of water leakage from the *“Khirokitia - Phrenaros”* pipeline.

4.2. *"Khirokitia - Phrenaros"* pipeline

Based on the findings of the *"Lakatameia"* water pipe, satellite images were used for the detection of known water leakages using archive satellite images. To examine the capabilities of satellite remote sensing images for the detection of water leakages, several algorithms and analyses were carried out. At first, reflectance values of all datasets were calculated based on the metadata file. Following this, several vegetation indices were also calculated.

For Point 1 in the *Pyla* area, leakage detection was difficult using medium resolution images. Monitoring of the pipeline using the red and the NIR part of the spectrum for Point 1 did not reveal any significant changes of reflectance due to the water leakage. Similarly, vegetation indices did not show any differences for Point 3 (*Anglisides* area). However, for Point 2, the Landsat satellite image dated January 7, 2010 tended to give higher vegetation index values, prior to the water leakage being repaired on February 18, 2010. However, the above findings seems to be similar for other areas of the water pipe as well. The above results have shown the limitations of using medium resolution satellite images for the detection of water leakages, especially when these are rare and small.

In an effort to explore further the information extracted using satellite data the three pilot areas were examined separately. Three vegetation indices, the Normalized Difference Vegetation Index (NDVI); the Soil Adjusted Vegetation Index (SAVI) and the Ratio Vegetation Index (RVI) were calculated based on the formulas 1-3.

$$\mathrm{NDVI} = (p_{NIR} - pr_{ed}) / (p_{NIR} + p_{red}) \qquad (1)$$

$$\mathrm{SAVI} = (1+0.5)\,(p_{NIR} - p_{rb})/(\,p_{NIR} + p_{red} + 0.5) \qquad (2)$$

$$\mathrm{RVI} = p_{red} / p_{NIR} \qquad (3)$$

Where:
p_{NIR} is the reflectance at the near infrared part of the spectrum
p_{red} is the reflectance at the red part of the spectrum

Figure 7 (left) presents the NDVI evolution during the examined 12 dates of satellite overpasses (see Table 2). Figure 7 (right) presents the SAVI evolution during the examined 12 dates of satellite overpasses.

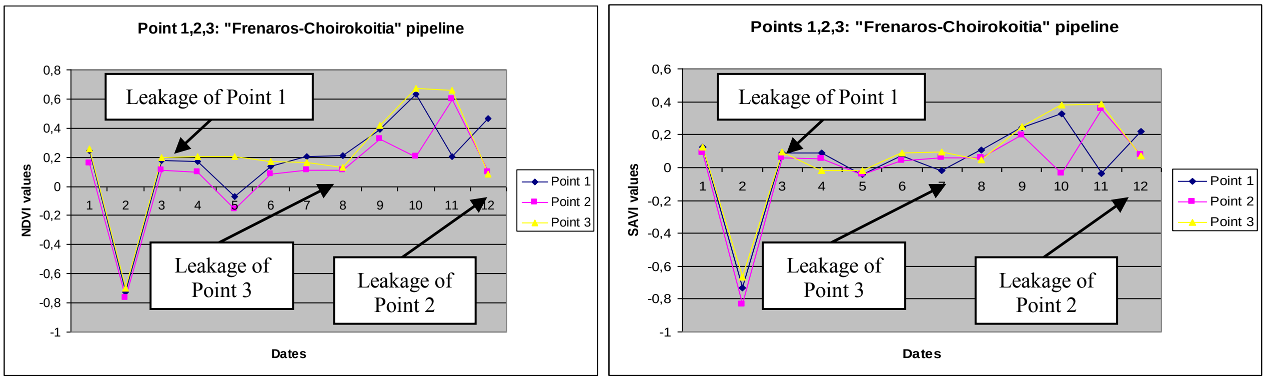

Figure 7. NDVI (left) and SAVI (right) development during the examined 12 dates (Landsat images) in Points 1, 2 and 3

Based on the results of Figure 7, the NDVI values present the following pattern: during May 2007 (no 1 at X-axis, Figure 7), in all 3 points of the known water leakage, NDVI decreases significantly with values close to -0.8, when almost in all cases NDVI is above zero with similar values. After September 2008 (no 8 at X-axis, Figure 7), the NDVI values increase until April 2010 7 (no 12 at X-axis, Figure 7) when they decline again. Such results indicate that the vegetation of the area around the study points reflects soil moisture resulting from rainfall as it can differentiate according to the season. Detailed examination of each point related to the pipeline repair indicates that for Point 1, there is a significant change of NDVI value before and after the repair date of the pipeline. In Point 2, the NDVI value decreased significantly (from 0, 60 to 0, 09) following the repair of the pipeline. However, in Point 3 there is no significant change of the NDVI value before and after the repair date of the pipeline. Although there is a slight decrease in NDVI values immediately following the repair, there is a significant increase within 2 weeks: Point 3: NDVI values are 0,16; 0,13 and 0,42 for dates 7 -9 respectively.

The results indicate that only at Point 2 is there a significant decline of NDVI values due to the absence of soil moisture around the pipe. Another factor that could affect the above situation is that the lack of rainfall during the period between the two measurements, of 7 January 2010 and 13 April 2010 respectively, may have resulted in moisture evaporation. The same conclusion is reached with SAVI data (Figure 7). The value of SAVI in Point 2 was 0,35 in January 2010 and declined to 0,07 just after the pipeline repair. Figure 8 presents RVI data which were calculated using equation (7). The RVI index indicates the effect of soil moisture around Point 2. The RVI value in Point 2, in January 2010 was 4,02 following the pipeline repair, it decreased to 1,21. It seems that vegetation developed on the soil around Point 2, and subsequently dried after the repair of the water pipe and the evaporation of the soil water.

In addition, the study of the meteorological data, provided from the Meteorological Service of Cyprus, indicate that during the study years the main precipitation was recorded during December, January and February in all meteorological stations. Examination of the precipitation by each month-day separately(especially during February 2010 in Larnaca station, the closest station to Point 2), the main rainfalls were recorded on 25, 26 and 27-02-2010, after the pipe line repair date of Point 2 (18-02-2010). Therefore, in the case of Point 2, the main factor affecting the vegetation indices values could be the development/reduction of vegetation due to increasing/ decreasing soil moisture content, before and after the repair of the pipeline . During March and April of 2010, only 1.0 and 2.1 mm of rain were recorded in correspondence for the same location. However, for Point 3, in *Anglisides* area, September precipitation data for Larnaca meteorological station did not affect the pipe leakage since no significant precipitation was recorded before and after the pipeline repair (17-09-2008). For Point 1, in *Pyla* area, the pipeline repair date was 20 July 2007. For point 1, the increase NDVI values from -0.7 to 0.1 between the 2nd and the 3rd image (23 May and 27 August 2007) may be related to the pipeline leakage. Rainfall in the area occurred on the 10th and 11th of May, which is over a 2 month time interval 20 July, indicating that the NDVI, SAVI and RVI values increasing are related to increased soil moisture resulting from the pipeline leakage. An image closer to the Point 1 repair date could be of great help for the delineation of this situation. Such information provides additional validation that, in some cases, the main factor affecting the NDVI, SAVI and RVI values is the presence or absence of vegetation as a result of soil moisture before and after the pipeline leakage repair.

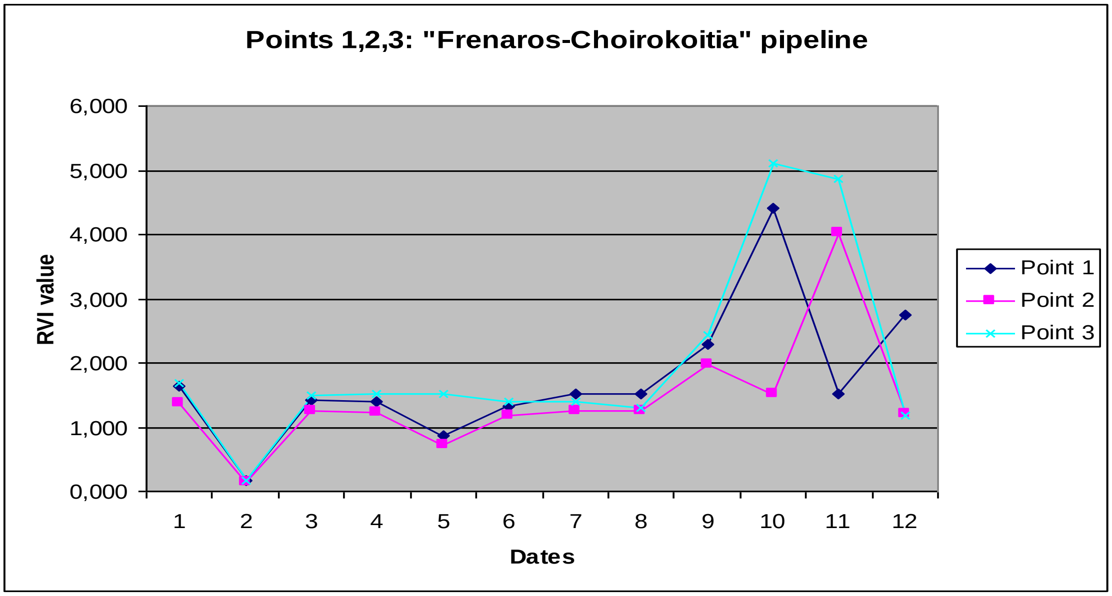

Figure 8. RVI reflectance (calculated with Reflectance values) development during the examined 12 dates (Landsat images) in Points 1, 2 and 3

5. DISCUSSION

Remote sensing techniques can provide useful data, both for the detection of the water pipes and for the detection of water leakages. The preliminary results of this study have shown that remote sensing techniques are able to detect areas of the pipeline with water leakages. Ground spectroradiometric data along with the low altitude system indicates significant differences in the reflectance values in areas where leakage is observed. In addition crop and soil marks can be used for mapping the real footprint of the water pipe. Although the use of medium resolution satellite images for monitoring extensive pipelines may be problematic, such as in Points 1 and 3 in the *"Khirokitia - Phrenaros"* pipeline, this may be due to the spatial resolution of the specific satellite images. However some promising results have been also reported (i.e. Point 2 in the *"Khirokitia - Phrenaros"* pipeline), where a major leakage was observed. In addition to the above, remote sensing techniques can be used on a systematic basis to monitor specific problematic areas of a water network by using time-series satellite images. Further research in this area will investigate additional ground based geophysical methods to provide a competent system for monitoring existing water pipe networks, such as electrical resistance tomography and ground penetrating radar. The resulting data can be integrated into a Geographical Information System which can be used by local authorities.

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