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Identification of WorldView-2 spectral and spatial factors in detecting salt accumulation in cultivated fields

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ABSTRACT

Soil salinity is a global threat to agricultural production and necessitates the monitoring thereof. Saline conditions in South African irrigation schemes generally occur in small patches (some only a few metres in diameter) and this study, which forms part of a Water Research Commission (WRC) project, evaluates the use of very high resolution (VHR) satellite imagery, in particular those produced by the WorldView 2 (WV2) sensor, for the detection of salt accumulation in irrigated areas. A range of features derived from the WV2 image were evaluated, namely 8 WV2 bands, 10 vegetation indices (VIs), 25 texture measures and 2 principle component analysis (PCA) components. These features were generated at six spatial resolutions (0.5 m, 2 m, 6 m, 10 m, 15 m and 20 m) to investigate the value of high spatial resolution for detecting affected areas. The relationships between the image features and electric conductivity measurements of 30 soil samples were studied by means of regression analysis and classification and regression tree (CART) modelling. The regression analysis results showed that a spatial resolution of 6 m or higher is ideal when VIs are used as input. When texture measures are used, higher spatial resolution (0.5 m) produced better models. The regression results also showed that the relatively high spectral resolution of the WV2 sensor (compared to other VHR sensors) did not provide a significant improvement in accuracy. The CART results provided a categorical quantification of salt accumulation and showed that VIs generated at 0.5 m resolution were the best features to use. Because the use of WV2 images is not financially viable for operational use in very large irrigation schemes, the study concludes with some guidelines on the spectral and spatial requirements of images when monitoring salt accumulation in irrigation schemes with similar conditions.

1. Introduction

Soil salinity refers to the accumulation of soluble salts in soils (Al-Khaier, 2003). Salt accumulation in soils is a naturally occurring process, but can be induced by human interference, known as secondary salinity. Factors such as vegetation clearing, landscape reshaping through earth works, and irrigation can lead to an increase of water and salt in soils and change where they accumulate (McGhie and Ryan, 2005). About 77 million ha of the estimated 1 billion ha associated with salt accumulation are caused by secondary salinity, of which irrigation has the largest impact (Ghassemi et al., 1995; Metternicht and Zinck, 2003).

A plant's ability to take up water is reduced when an excess of salt is present in the root zone. The salts reduce the osmotic potential of water and hinder its movement from the soil into the roots which is known as the osmotic effect. When saline conditions persist, a toxic effect can occur, caused by the continuous accumulation of salts in the plant through the process of water absorption (Hillel, 2000; McGhie and Ryan, 2005). The osmotic and toxic effects lead to visible indicators such as spotty/uneven growth of vegetation, plant wilting, a blue–green tinge and moisture stress. Depending on the quantity and mineralogy of salt accumulation, it can also result in the formation of white salt crusts, puffy soil, dark greasy surfaces, dehydrated cracks and coarser topsoil (Ghassemi et al., 1995; McGhie and Ryan, 2005; Metternicht and Zinck, 2003).

Soil salinity can be detected using remotely sensed data either directly, by attempting to identify indicators of salt accumulation on the bare soil, or indirectly, by monitoring vegetation responses to saline conditions (Bastiaanssen, 1998; Mougenot et al., 1993). Challenges in identifying salt accumulation through direct indicators include spectral ambiguity caused by variance in salt mineralogy, quantity, soil moisture,

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Abbreviations: AUC, area under the curve; BRE, best relative error; CART, classification and regression tree; DN, digital numbers; DT, decision tree; EC, electric conductivity; EVI, enhanced vegetation index; LO, longitude of origin; NDVI, normalized difference vegetation index; NIR, near-infrared; NN, nearest neighbour; PCA, principal component analysis; PLS, partial least squares; RF, random forests; ROCs, receiver operating characteristics; SAVI, soil-adjusted vegetation index; SVM, support vector machines; VHR, very high resolution; VIL, variable importance list; VIs, vegetation indices; WV2, WorldView 2.

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colour and surface roughness which is exacerbated by farming practices such as tillage and irrigation(Metternicht and Zinck, 2003; Zhang et al., 2011). Different vegetation types also respond differently to salt accumulation due to their varying tolerances to saline conditions (Zhang et al., 2011). This is particularly problematic in highly dynamic irrigation schemes where multiple crops can be planted per season. Temporal variability within irrigation schemes is less of a problem when an indirect approach is used. Several authors have successfully applied the indirect approach to monitor plant stress caused by salt accumulation (Abood et al., 2011; Fernández-Buces et al., 2006; Lenney et al., 1996; Lobell et al., 2010; Peñuelas et al., 1997; Wiegand et al., 1994; Zhang et al., 2011). All of these studies relied on vegetation indices (VIs) (e.g. NDVI, EVI and SAVI). However, poor farming practices and soil preparation can also lead to poor VI responses, which can easily be mistaken for saline conditions (Furby et al., 2010). Further limitations of the use of VIs for detecting areas affected by salt accumulation include the negative impact of bare ground backscatter/noise, especially during the early stages of growth (Dehni and Lounis, 2012; Douaoui et al., 2006) and the varying salinity tolerances of vegetation types (Zhang et al., 2011). Other indirect indicators of salt accumulation can include soil properties, terrain characteristics and surface texture features (Caccetta et al., 2000; Furby et al., 2010; García Rodríguez et al., 2007; Howari, 2003; Jenkin, 1981; Metternicht and Zinck, 2003). Data related to these indirect indicators can be sourced from previous soil surveys, digital elevation models (DEM) and image texture information respectively.

An estimated 10% to 18% of irrigated areas in South Africa are affected by waterlogging, sodicity or salinity (Backenberg et al., 1996). Ghassemi et al. (1995) observed that, in general, the extent of salt accumulation and waterlogging in South Africa is less than in many other countries and seems to be largely under control. This is perceived to be due to sound planning in the selection of irrigated soils, good drainage and the fact that the irrigated areas of South African are generally small (Ghassemi et al., 1995). Consequently, salt accumulation often occurs in small patches of a few metres in diameter.

Although the extent of salt accumulation in South Africa is relatively small compared to many other countries (e.g. Egypt, Iran and Argentina) (Ghassemi et al., 1995), proactive monitoring is needed to keep track of the negative effects of salt accumulation and to determine if it is adequately managed.

From the literature it is apparent that the majority of remote sensing applications for salt accumulation monitoring are focussed on areas where salinity occurs on a grand scale in relatively large cultivated fields. As a result, medium to low resolution satellite imagery is often favoured with Landsat (30 m) (Abdelfattah et al., 2009; Aldakheel, 2011; Al-Khaier, 2003; Caccetta et al., 2000; Dehni and Lounis, 2012; Elnaggar and Noller, 2010; Fernández-Buces et al., 2006; Furby et al., 2010; Gao and Liu, 2008; García Rodríguez et al., 2007; Howari, 2003; Lenney et al., 1996; Mohamed et al., 2011) and IRS (20 m) (Abbas et al., 2013; Dwivedi and Sreenivas, 1998; Dwivedi et al., 2001; Eldiery et al., 2005; Khan et al., 2001; Koshal, 2010) being the most popular. Given that the mean field sizes are relatively small (e.g. 2 ha) in some of South Africa's irrigation schemes, medium to low resolution imagery will have little value, particularly when fields are elongated. Salt-affected areas in South Africa are also generally much smaller than what can be detected with medium resolution imagery (Nell and van Niekerk, 2014).

Very few applications of very high resolution (VHR) imagery for salt accumulation monitoring exist. Notable exceptions are Abood et al. (2011) and Douaoui and El Ghadiri (2015) who used 2 m resolution WorldView 2 (WV2) imagery; and Eldiery (2005) who used 4 m resolution Ikonos imagery. However, none of these studies investigated the value of spatial features (such as texture measures) for the identification of salt-affected areas. Also, VHR imagery has, to our knowledge, never been used for monitoring salt accumulation in South Africa. The primary aim of this study, which forms part of a Water Research Commission (WRC) project, is thus to evaluate the use of VHR satellite imagery, specifically WV2, to identify suitable spectral and spatial features for the identification of salt accumulation in a cultivated field within the Vaalharts irrigation scheme. A secondary aim is to improve the understanding of the importance of spatial resolution for detecting salt-affected areas with small spatial extents. Several fields in the Vaalharts irrigation scheme have been abandoned due to uncontrolled salt accumulation. Proactively identifying salt-affected areas while they are still relatively small in size will improve rehabilitation strategies. In South Africa, soils with electroconductivity (EC) values of 4.0 dS/m (millisiemens per metre) are considered as being salt-affected (Bresler et al., 1982; SASA, 2007). This corresponds to the USDA classification of slightly, moderately and strongly saline (USADA, 2015).

These objectives will be evaluated by analysing the WV2 derived features at six different spatial resolutions. Regression modelling and classification and regression tree (CART) analysis will be used. The results are interpreted in the context of finding the best image features and optimal spatial resolution for predicting/identifying salt-affected areas in South African irrigation systems.

2. Methods

2.1. Study area

A 2.8 ha irrigated lucern (alfalfa) field in the Vaalharts irrigation scheme was chosen as the study site (Fig. 1). The Vaalharts irrigation scheme is situated near the towns of Jan. Kempdorp and Hartswater at the juncture of the Northern Cape, North West and the Freestate provinces. The scheme is drained by the low gradient, non-incising Harts River and consequently has very limited topographical variance (Gombar and Erasmus, 1976; Liebenberg, 1977). The irrigation scheme has a semi-arid climate with cold, dry winters (June to August) and long warm summers (December to February) with a mean annual temperature of 19 °C (Schulze, 2006). It receives a mean annual rainfall of 400 mm (mostly during late summer) which necessitates irrigation (Schulze, 2006). The irrigation methods applied in the scheme comprises roughly 70% flood irrigation and 30% pivot irrigation (Maisela, 2007). The principal cash crops of the scheme are maize, wheat barley, lucern and groundnuts (Kruger et al., 2009).

The selected lucern field is supplied with flood irrigation to supplement the rainfall. Lucern was targeted for this study because it is moderately sensitive to saline conditions and starts wilting at electric conductivity (EC) levels of 2.0 dS/m and above (at root zone level) (Hanson et al., 2006). For this study, a single crop was selected so as to eliminate the complexities associated with multiple crop types which have varied spectral properties and tolerances to salt accumulation (Hanson et al., 2006; Zhang et al., 2011).

2.2. Data acquisition and preparation

The timing of image acquisition is important for discriminating between saline and non-saline conditions. When using features like VIs, image data from the time of maximum growth (i.e. the end of a wet season) should ideally be used (Furby et al., 2010; Hick and Russell, 1990). Since crop production and irrigation occurs almost continuously throughout the year in Vaalharts, the timing of image acquisition was less critical. A WV2 image covering a 100 km^2 section (Fig. 1) of the Vaalharts irrigation scheme captured on 23 May 2012 was acquired. At the time of capture, the WV2 sensor offered higher spectral and spatial resolution compared to other VHR sensors, with eight 2 m resolution relatively narrow bands in the visible and near-infrared spectral range (Table 1).

Geometric corrections were carried out on the image using PCI Geomatica (version 2013 Service Pack 2). A north-orientated implementation of the Gauss conform coordinate system (also known as the LO coordinate system) was used with central meridian set to 25