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# Assessment of vegetation water content in wheat using near and shortwave infrared SPOT-5 Data in an irrigated area

# Évaluation de la teneur en eau du blé en utilisant des données du proche et moyen infrarouge de SPOT-5 dans une zone irriguée

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Résumé de l'article

Au Maroc, la disponibilité de l'eau est devenue une priorité nationale pour le secteur agricole. Dans ce contexte, les acteurs et les décideurs essaient en permanence d'améliorer les stratégies de gestion de l'irrigation, d'une part, pour évaluer l'état de l'humidité du couvert végétal et d'autre part, afin d'améliorer la planification de l'irrigation et éviter le stress hydrique qui affecte le rendement. Le but de cet article était d'évaluer le potentiel de deux indices spectraux, calculés à partir des données du proche infrarouge et du moyen infrarouge du capteur à haute résolution visible (HRV) de SPOT-5, pour estimer la teneur en eau du blé dans une zone irriguée. Les valeurs de l'indice normalisé d'eau (NDWI) et de l'indice de stress hydrique (MSI) ont été comparées avec les valeurs correspondantes à la teneur en eau de la végétation mesurée *in situ* dans 16 parcelles de blé au cours de la campagne agricole 2012-2013. Les indices NDWI et MSI ont montré une bonne concordance en comparaison aux mesures de terrain collectées entre la floraison et le remplissage des grains du blé. Ces résultats ont été validés à l'aide de la méthode de validation croisée *k*-fold et ils montrent une bonne stabilité des deux modèles proposés avec un léger avantage du NDWI. Sur la base de ces résultats, le NDWI a été choisi pour cartographier la variabilité spatiale de la teneur en eau du blé à l'est du périmètre irrigué de Beni-Moussa. Ces résultats ont prouvé que les indices utilisant la bande spectrale du moyen infrarouge et du proche infrarouge sont capables d'assurer le suivi de la teneur en eau du blé de la floraison au remplissage des grains. Ces indices pourraient être utilisés pour améliorer la gestion de l'irrigation du blé à l'échelle de la parcelle et/ou de la région.

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# ASSESSMENT OF VEGETATION WATER CONTENT IN WHEAT USING NEAR AND SHORTWAVE INFRARED SPOT-5 DATA IN AN IRRIGATED AREA

*Évaluation de la teneur en eau du blé en utilisant des données du proche et moyen infrarouge de SPOT-5 dans une zone irriguée*

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## ABSTRACT

In Morocco, water availability is becoming a national priority for the agricultural sector. In this context, the stakeholders try continuously to improve strategies of water irrigation management, on one hand, and to assess vegetation water content status, on the other hand, in order to improve irrigation scheduling and prevent water stress that affects yield adversely. The aim of this study was to evaluate the potential of two spectral indices, calculated from SPOT-5 high resolution visible (HRV) data, to retrieve the vegetation water content values of wheat in an irrigated area. These indices were the normalized difference water index (NDWI) and the moisture stress index (MSI). The values of these indices were compared with corresponding values of *in situ*-measured vegetation water content in 16 fields of wheat during the 2012-2013 cropping season. Good correlations were found between observed vegetation water content values and NDWI and MSI values during the crop growth period from anthesis to grain filling. These results were validated using the *k*-fold cross validation method and showed a good stability of the proposed regression models with a slight advantage for the NDWI. Based on these results, the NDWI was chosen to map the spatial variability of vegetation water content of wheat at the east of the Beni-Moussa irrigated perimeter. These results proved that the indices based on near and shortwave infrared band (NIR and SWIR) are able to monitor vegetation water content changes in wheat from anthesis to the grain filling stage. These indices could be used to improve irrigation and crop management of wheat at both the field and regional levels.

***Key Words: Normalized difference water index, moisture stress index, vegetation water content, wheat, semi-arid, irrigated area.***

## RÉSUMÉ

Au Maroc, la disponibilité de l'eau est devenue une priorité nationale pour le secteur agricole. Dans ce contexte, les acteurs et les décideurs essaient en permanence d'améliorer les stratégies de gestion de l'irrigation, d'une part, pour évaluer l'état de l'humidité du couvert végétal et d'autre part, afin

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d'améliorer la planification de l'irrigation et éviter le stress hydrique qui affecte le rendement. Le but de cet article était d'évaluer le potentiel de deux indices spectraux, calculés à partir des données du proche infrarouge et du moyen infrarouge du capteur à haute résolution visible (HRV) de SPOT-5, pour estimer la teneur en eau du blé dans une zone irriguée. Les valeurs de l'indice normalisé d'eau (NDWI) et de l'indice de stress hydrique (MSI) ont été comparées avec les valeurs correspondantes à la teneur en eau de la végétation mesurée *in situ* dans 16 parcelles de blé au cours de la campagne agricole 2012-2013. Les indices NDWI et MSI ont montré une bonne concordance en comparaison aux mesures de terrain collectées entre la floraison et le remplissage des grains du blé. Ces résultats ont été validés à l'aide de la méthode de validation croisée *k*-fold et ils montrent une bonne stabilité des deux modèles proposés avec un léger avantage du NDWI. Sur la base de ces résultats, le NDWI a été choisi pour cartographier la variabilité spatiale de la teneur en eau du blé à l'est du périmètre irrigué de Beni-Moussa. Ces résultats ont prouvé que les indices utilisant la bande spectrale du moyen infrarouge et du proche infrarouge sont capables d'assurer le suivi de la teneur en eau du blé de la floraison au remplissage des grains. Ces indices pourraient être utilisés pour améliorer la gestion de l'irrigation du blé à l'échelle de la parcelle et/ou de la région.

***Mots-clés : Indice de l'eau, indice du stress hydrique, teneur en eau de la végétation, blé, semi-aride, zone irriguée***

## 1. INTRODUCTION

In the world, irrigated areas produce more than half of all foodstuffs and thus contribute to food security. They are using about 72% of available water resources (GEERTS and RAES 2009; SECKLER *et al.*, 1999). In Morocco, water availability is considered as the main limiting factor for crop growth. Cereal production is strongly related to the amount and distribution of annual rainfall in rainfed areas and to the amount of groundwater and water stored in dams in irrigated areas. Irrigation water has to be supplied to the plants when the soil water reserves are depleted and are causing plant stress. For instance, in the Tadla irrigated area, the main crop is wheat and represents more than 36% (40 000 ha) of the total irrigated area (ORMVAT, 2009).

The average volume of water consumed by the wheat crop during the period from 1994 to 2002 reached 136 $mm^3 \cdot y^{-1}$ in the irrigated perimeter of Tadla. This amount is the equivalent of 18% of all irrigation consumed across the irrigated perimeter (ORMVAT, 2009). In this situation, knowing the vegetation water content could be an interesting basis for improving irrigation scheduling and preventing water stress adversely affecting yield (DUCHEMIN *et al.*, 2006).

In order to estimate the water content of the vegetation for various crops, remote sensing has been used through the spectral indices (CECCATO *et al.*, 2002a; HADRIA *et al.*, 2010; TROMBETTI *et al.*, 2008), taking account of the high temporal and spatial resolution of the recent satellites. During the wheat development cycle, water stress effects can be directly observed in the vegetation (FENG *et al.*, 2013; GHULAM *et al.*, 2007; NING *et al.*, 2013). Water stress indices used in irrigation management should therefore be based on the spectral bands that are sensitive to vegetation water content. Many indices designed for vegetation moisture monitoring have been developed using NIR (780-890 nm) and SWIR (1 580–1 750 nm) bands, including the normalized difference infrared index (NDII) (HARDISKY *et al.*, 1983), the global vegetation moisture index (GVMI) (CECCATO *et al.*, 2002b), the moisture stress index (MSI) (HUNT and ROCK, 1989) and the normalized difference water index (NDWI) (GAO, 1996). For wheat management, the use of these spectral indices for assessing the vegetation water content becomes essential during critical periods (flowering to grain filling) to ensure good yields.

Recent studies have confirmed the high sensitivity of the SWIR band to vegetation water content variations (CECCATO *et al.*, 2001; CHENG *et al.*, 2013; YILMAZ *et al.*, 2008; HUNT *et al.*, 2011; LIU *et al.*, 2012). Otherwise, the reflectance in the NIR spectrum (740–1 300 nm) is the most sensitive to leaf internal structure changes (JACQUEMOUD and BARET, 1990) and is insensitive to vegetation water variation (ELVIDGE and LYON, 1985), except in extremely high stress conditions, which cause severe leaf dehydration and thus affect leaf structure (JENSEN, 2007). The NIR band serves as a moisture-reference band, whereas the SWIR band is used as the moisture-measuring band. Currently, the spectral indices are widely used to estimate the biophysical properties of the vegetation, including the water content. However, the uses of these indices are often made with empirical methods.

In arid and semi-arid regions, stakeholders and managers of water resources express a strong need for tools that can assess vegetation water content. In this paper, we explored the potential of two spectral indices, the NDWI and MSI, derived from high spatial resolution SWIR and NIR, to assess and map the vegetation water content of wheat in the irrigated area of Tadla, Morocco.

## 2. MATERIALS AND METHODS

### 2.1. Study area

The study area (Figure 1) is located in the center of Morocco, between the Atlantic coast in the north-west and the Atlas Mountains in the south-east (32°23' north latitude, 6°31' west longitude, 445 m above sea level). Covering 100 000 ha, the irrigated plain of Tadla is characterized by a flat topography and composed of a right bank (Beni-Amir) and left bank (Beni-Moussa). This area is characterized by a semi-arid climate: the average annual precipitation is about 300 mm (average over the period 1970-2010), with a significant interannual variation ranging from 130 to 600 mm in the same period. This plain is managed by the Regional Office for Agricultural Development of Tadla (ORMVAT).

Wheat is one of the main crops in this area, covering 36% of the total cultivated area. The wheat-growing cycle in the region runs from November-December to June. During this period, wheat is irrigated, using the flooding irrigation technique, between two and five times, depending on the water available in autumn and the volume accumulated in dams during winter and spring seasons.

The area is divided into several hundred irrigation plots. Sixteen wheat plots of them were selected in this study. The size of these plots varied from 1.7 to 14.5 ha (the total area is 77 ha). The combination of crop management and irrigation schedule for these plots was representative of the agricultural practices for wheat in the region. Figure 1 shows the location of studied area and illustrates the position of the selected plots (P1 to P16).

### 2.2. Field experiments

Experiments were conducted during the 2012-2013 wheat growing season to record dates and amounts of irrigated water supplied and to collect crop physiological data. Data were collected from 16 fields of wheat, located at Tadla's Regional Agricultural Research or belonging to farmers, thus providing a valid representation of the soil-plant relationship in the study area. The field data related to Marzak and Achtar cultivars, which are widely cultivated in the study region.

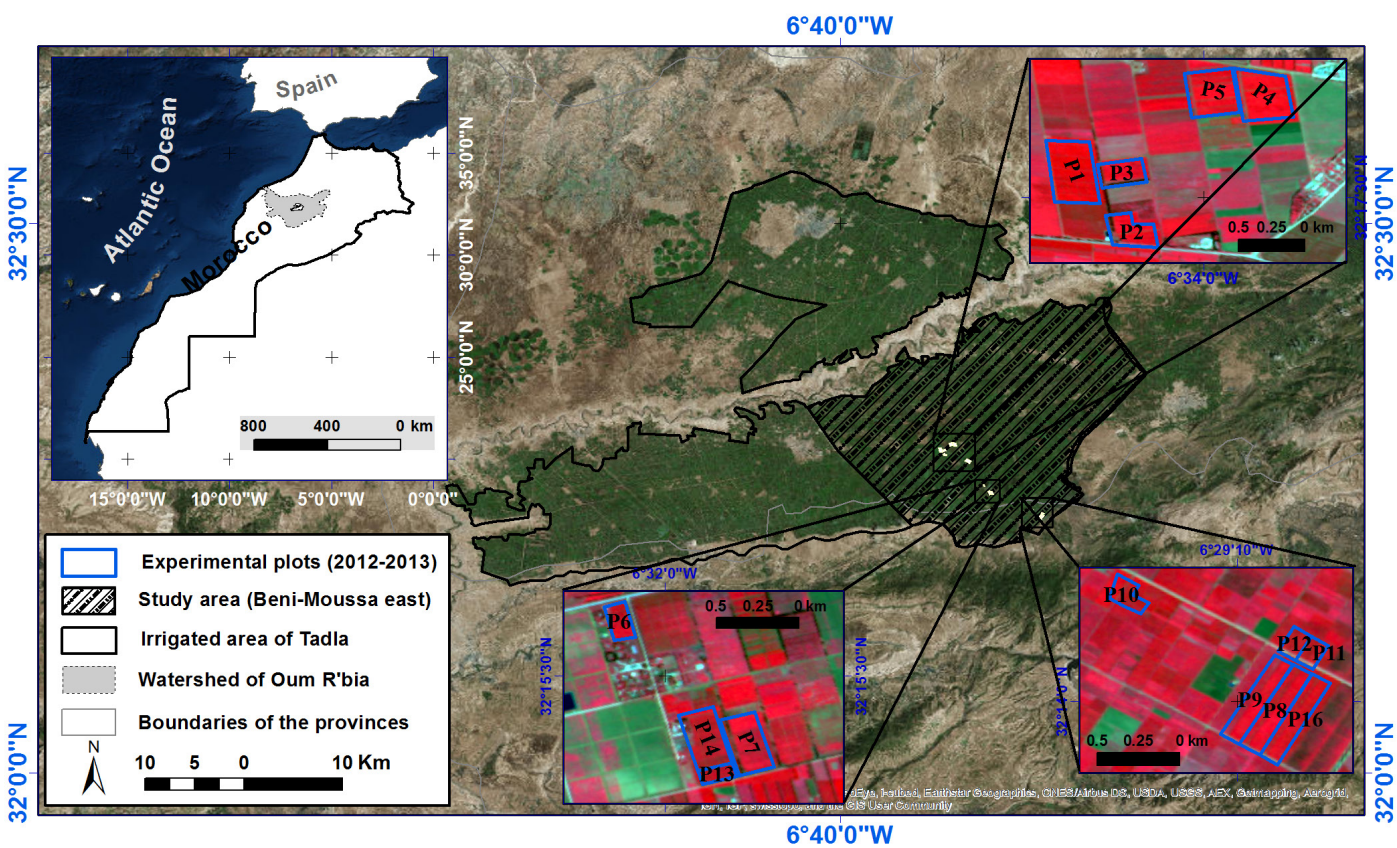


**Figure 1. Location of the Tadla irrigated perimeter : map of Morocco is in upper left inset; in the main map, the study area is shown in hatched, and the experimental plots are delineated in blue.**
***Localisation du périmètre irrigué du Tadla : la carte du Maroc est dans l'encadré en haut à gauche; dans la carte principale, la zone hachurée représente l'aire d'étude et les parcelles expérimentales sont délimitées en bleu.***

Vegetation water content was measured weekly from anthesis until wheat grain filling (March to May 2013). It was measured in four randomly selected quadrates in each plot (i.e. an area of 0.5 x 0.5 m). From each quadrate, subsamples were used to measure the weight of the fresh and dry above-ground biomass (dried in an oven at 65°C for 48 h) (IQBAL *et al.*, 2014). Water vegetation content was quantified on a gravimetric basis (gram of water/gram of vegetation) and was expressed in this document as a percentage (%).

We synchronized the field measurements with the planning for acquiring satellite images. In our case study, we only considered field measurements taken within a time lag of three days. We also ensured that during this time lag there was no rainfall event or irrigation supply.

Using geographical information system (GIS) software, we vectorized the collected field data (vegetation water content) as point and the experimental plots delimitations as polygons. We subdivided the experimental plots into units (subplots) of the same size and assigning per unit a code to identify and locate in space and time. Then, each subplot has been joined to the punctual data of vegetation water content and soil moisture corresponding to it spatially.

### *2.3. Satellite images and their processing*

Three SPOT-5 HRV satellite images were acquired on 21 March 2013, 26 March 2013 and 11 April 2013 when the soil was completely covered by vegetation. They covered the period between anthesis (March) and grain filling (April) in the 2012-2013 cropping season. These wheat growth stages are crucial to ensure good yield (DE SAN CELEDONIO *et al.*, 2014).

SPOT-5 scenes have 10 m pixel resolution and four spectral bands: B1 (green: 0.50–0.59 μm), B2 (red: 0.61–0.68 μm), B3 (near infrared NIR: 0.79–0.89 μm) and B4 (short-wave infrared SWIR: 1.58–1.75 μm). One of the big advantages of SPOT-5 images compared to other VHR images is the large swath (60 x 60 km) that allows a complete view of our region of interest. We also had the opportunity to program the satellite passes when the vegetation covered completely the soil and to match the critical time for the wheat crop.

The processing level of the acquired images was (1 B), which included radiometric and geometric corrections. We conducted an atmospheric correction from the images of radiance, using the FLAASH model (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) included in the ENVI 5 software. The latter model is considered more accurate compared to other models for SPOT-5 images (GUO and ZENG, 2012).

We computed two spectral indices, the NDWI (GAO, 1996; HARDISKY *et al.*, 1983) and the MSI (CECCATO *et al.*, 2001; CECCATO *et al.*, 2002b; HUNT and ROCK, 1989), using the NIR and SWIR spectral reflectance for each SPOT-5 HRV image acquisition date (Table 1).

The next step consisted in generation of a mask of wheat subplots, using ENVI 5 software. The average values of the spectral indices (NDWI and MSI) were then computed for each corresponding subplot (7 x 7 pixels) where field measurements were conducted (Figure 2). In our case study, we took 1.5 ha (7 x 7 pixels) as a reference area, where irrigation applications are synchronous and homogeneous at this scale. Regression analysis was carried out between vegetation water content measurements, MSI and NDWI values. This permitted to establish the relationships between the NDWI and MSI values derived from the SPOT-5 images dataset and the ground studied measurements.

### *2.4. Supervised classification*

In order to define the cereal area, which is our region of interest, we used a supervised classification method where 65 datasets have been taken for calibration and 112 sets for validation data. Separability analysis allow to determine how distinct, and thus separable, different surface types are from each other. Wheat, as a cereal, and other land occupations were categorized into two different classes to analyze their spectral separability. The Jeffries-Matusita (JM) distance was used to assess the potential of band pairs to discriminate between two different region classes. The values range between 0 and 2 (RICHARDS, 1995).

### *2.5. Model validation*

Cross-validation is a technique to explore the reliability of a model to assess how the results of a statistical analysis will be applied to an independent data set (KOHAVI, 1995). It is mainly used to estimate the accuracy of a predictive model. Several cross-validation techniques are used: holdout method, *k*-fold cross-validation and leave-one-out cross-validation (LOOCV).

The *k*-fold cross validation (*k*-fold CV) approach was used to evaluate the accuracy of the obtained regression models between the two spectral indices and surface water content (CASSEL, 2007). This approach uses *k* replicate samples of observation data, builds models with $(k\text{-}1)/k$ of data and tests with the remaining $1/k$. *K*-fold CV is an effective and widely used method. In our case, it involved 20% of the observations as the validation data, with the remaining 80% of the observations

**Table 1. Studied spectral indices derived from SPOT-5 sensor.**
***Tableau 1. Les indices spectraux étudiés dérivés du capteur SPOT-5.***

| Index | Abbreviation | Equation[a] | Properties | References |
|---|---|---|---|---|
| Normalised difference water index | NDWI | (NIR - SWIR)/(NIR + SWIR) | Vegetation water content<br>Soil moisture content | GAO, 1996<br>HARDISKY *et al.*, 1983 |
| Moisture stress index | MSI | (SWIR/NIR) | Water content of leaves in vegetation canopies increases | HUNT *et al.*, 1989<br>CECCATO *et al.*, 2001 |

[a]NIR: index based on near infrared band; SWIR: index based on shortwave infrared band

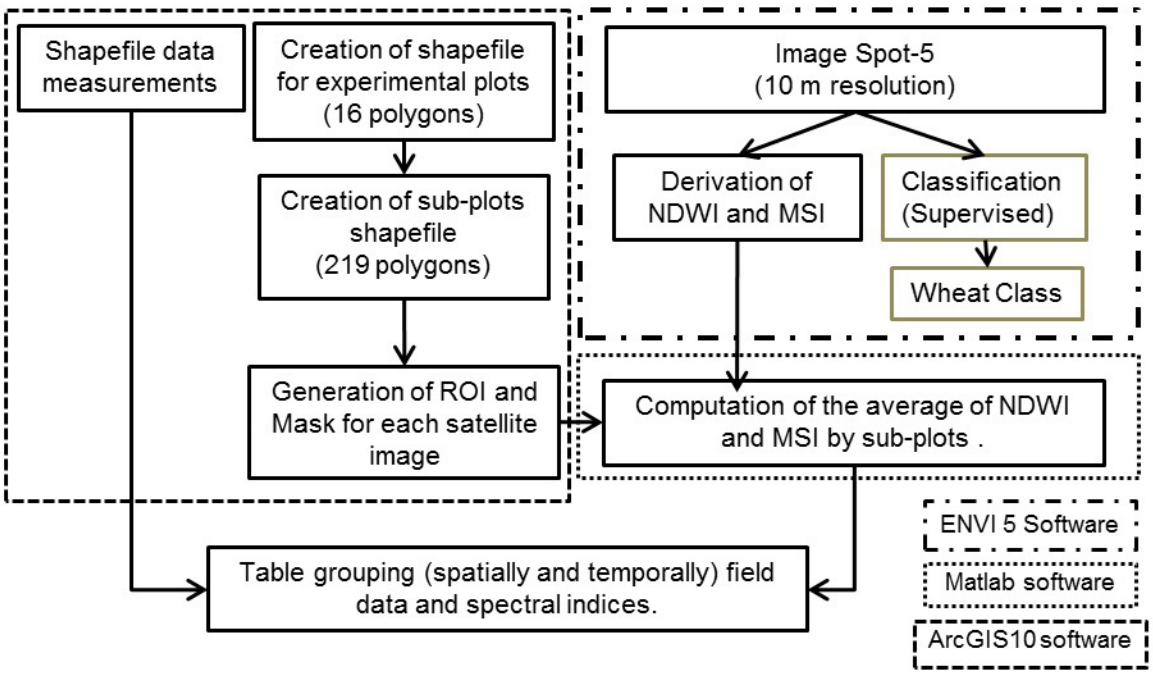


**Figure 2. Schematic diagram illustrating field data and satellite image processing**
***Schéma illustrant le traitement des images satellite et des données de terrain.***

being the training data. We emphasize that the random *k*-fold CV takes *k* independent samples of size $N(k\text{-}1)/k$ (CASSEL, 2007). We performed the cross-validation analysis using SAS 9.1 software.

### 2.6. Model evaluation

Different statistical indices were used to compare predicted and observed values. These indices were the coefficient of determination ($R^2$), the root mean square error (RMSE), the normalized RMSE (nRMSE) expressed as a percentage of the RMSE divided by the mean of observed values (RICHTER *et al.*, 2012) and the mean absolute error (MAE):

$$\mathrm{RMSE} = \left[ \sum_{i=1}^{n} \frac{(Si - Oi)^2}{n} \right]^{0.5} \quad (1)$$

$$\mathrm{nRMSE} = \left[ \sum_{i=1}^{n} \frac{(Si - Oi)^2}{n} \right]^{0.5} \frac{100}{M} \quad (2)$$

where *Si* and *Oi* refer to simulated and observed values of the studied variable, respectively; *n* is the number of observations; and *M* is the mean of the observed variable. The nRMSE indicates the accuracy of the model and the dispersion around the mean of the observed values.

### 2.7. Mapping of vegetation water content

To illustrate the practical use of this study, vegetation water content was mapped by using the validated linear regression model between vegetation water content and NDWI index. Three maps were presented here for the east of Beni-Moussa irrigated area.

# 3. RESULTS AND DISCUSSION

## *3.1. Vegetation water content assessment at full vegetation cover*

We compared the values of observed vegetation water content of 32 studied subplots and their spectral indices values derived from the three images acquired on 21 March 2013, 26 March 2013 and 11 April 2013. The results of this comparison are presented in Figure 3.

The statistical indicators obtained from the previous comparison, presented in Figure 3, showed that both spectral indices simulated well the vegetation water content. The values of statistical indicators $R^2$, RMSE, and nRMSE were 0.63, 3.19% and 4.24% for the NDWI, and 0.58, 3.22% and 4.27% for the MSI, respectively. Similar results were reported for the indices based on shortwave infrared band by QIUXIANG *et al.* (2012) and HUNT and ROCK (1989) when simulating the vegetation water content.

In order to validate these results, we compared observed vegetation water content values and those predicted using the *k*-fold CV method. As shown in Figure 4, the errors were minimal for both the NDWI and MSI. The evaluation model indicators obtained for predicted vegetation water content from the NDWI were 0.52, 3.39% and 4.52% for $R^2$, RMSE and nRMSE, respectively. For the MSI, these values were 0.48, 3.55% and 4.74% for $R^2$, RMSE and nRMSE, respectively (Figure 4). These results confirmed the ability of NDWI to retrieve well the vegetation water content of wheat, while the values in MSI were comparatively less in agreement with the observed values.

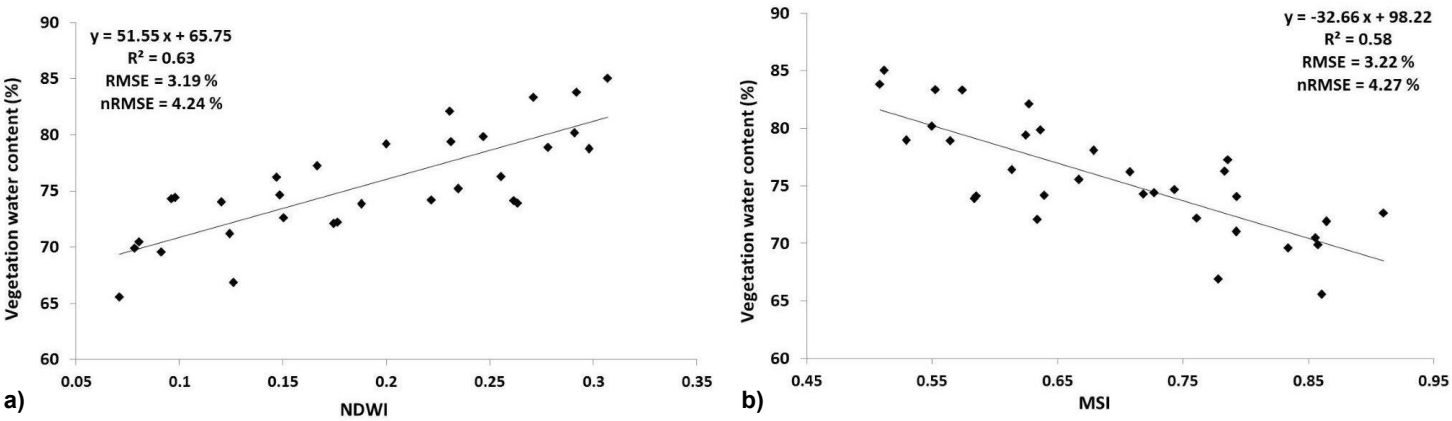


**Figure 3. Relationship between observed vegetation water content and derived spectral indices: a) normalized difference water index (NDWI), and b) moisture stress index (MSI)**
***Relation entre la teneur en eau observée de la végétation et les indices spectraux dérivés : a) indice normalisé d'eau (NDWI) et b) indice de stress hydrique (MSI) .***

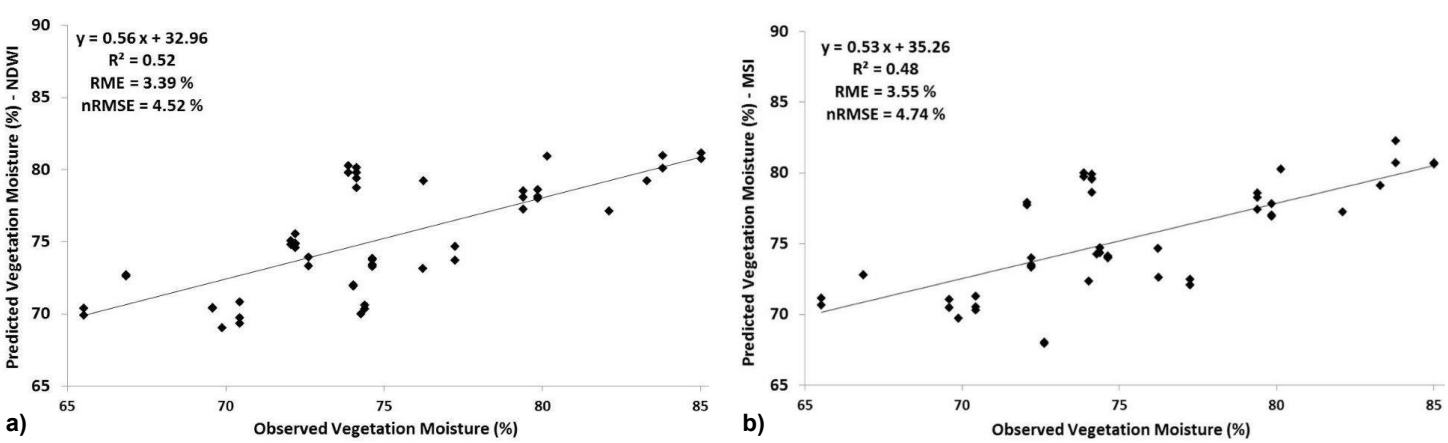


**Figure 4. Comparison between observed and predicted vegetation water content (%) using the *k*-fold CV of all acquired images. a) NDWI: normalized difference water index; b) MSI: moisture stress index.**
***Comparaison entre la teneur en eau de la végétation (%) observée et prédite en utilisant le k-fold CV pour toutes les images acquises. a) NDWI : indice normalisé d'eau; b) MSI : indice de stress hydrique.***

### 3.2. Supervised classification

We performed a supervised classification to identify cereal area (Figure 5). The analysis of the numerical JM values allowed us to conclude that the separability results for training samples on final classification scheme are good. The estimated value of separability was 1.99.

The contingency matrix was used to evaluate the percentage of sampled pixels that were classified as expected. This classification was validated and the accuracy assessment and Kappa statistic indicated that it was a good classification. The overall accuracy is 0.95 while the overall Kappa is 96.7%.

### 3.3. Mapping of vegetation water content

Figures 6 and 7 show three maps of vegetation water content (VWC) of wheat class derived from the five SPOT-5 images. These maps were generated using the regression model (VWC = 51.55NDWI + 65.75) obtained by comparing the three images on a pixel basis and field measurements. The analysis of the three maps showed that vegetation water content ranged from 58 to 87% between the three considered dates. For these maps we had an RMSE of 3.19% and an nRMSE of 4.24%.

Figure 6 presents a high homogeneity of vegetation water content (dominance of green color). Indeed, vegetation water content exceeded 70% for all plots. This is explained by important precipitation events that were recorded between 14 and 18 March 2013 (31.3 mm) and on 24 March 2013 (14 mm).

On the opposite, Figure 7 shows a strong heterogeneity in vegetation water content values after three weeks of precipitation and a homogeneous drying of several plots, with vegetation water content ranging from 58 to 76%.

Obtained maps allowed monitoring the variability of vegetation water content in wheat for each agricultural development center (ADC). Irrigation management is done independently at each development center. An overview of the maps allowed distinguishing between different levels of vegetation water content. Such information could be valuable for stakeholders and decision-makers in charge of irrigation areas and could help them to better manage irrigation at a large scale. It could also help judge the priority ADC to receive irrigation supplies according to the given state of vegetation water content.

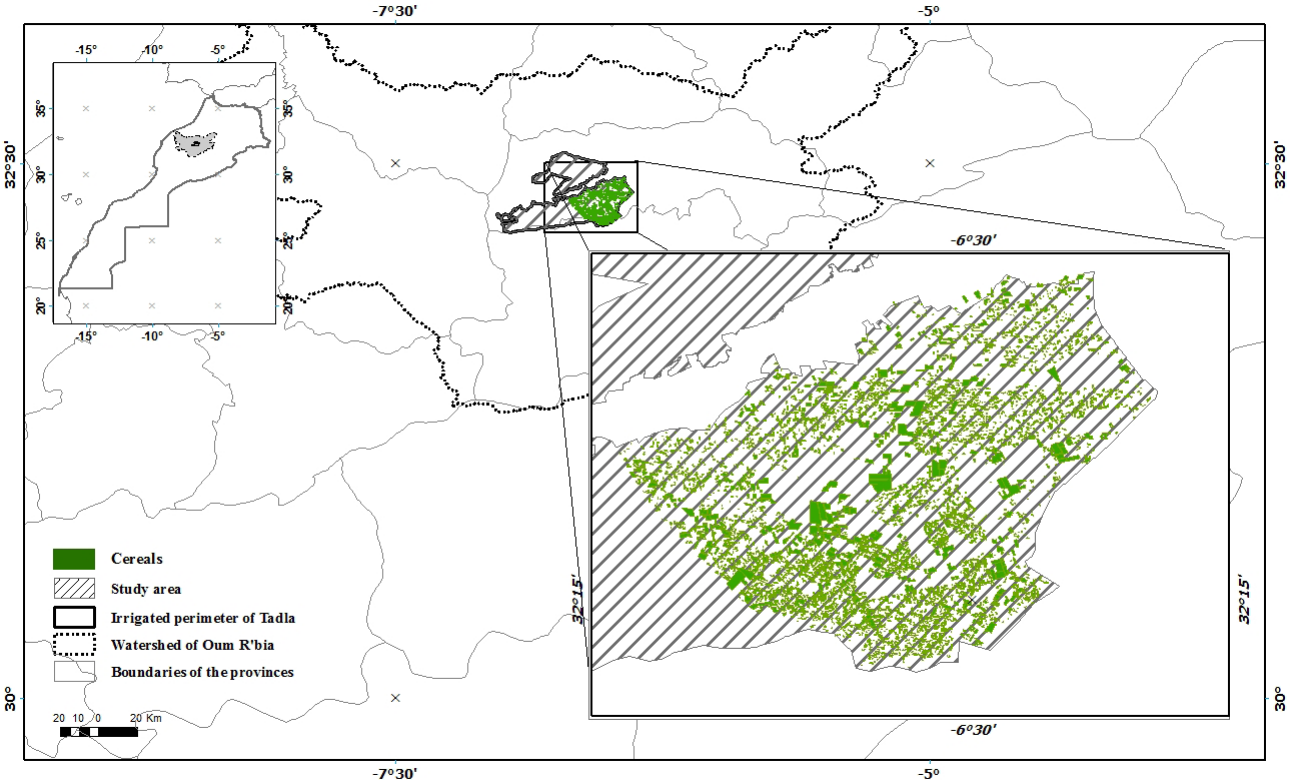


**Figure 5. Supervised classification map of wheat over the region of Beni-Moussa East (2012-2013).**
***Carte de classification supervisée du blé pour la région est de Beni-Moussa (2012-2013).***

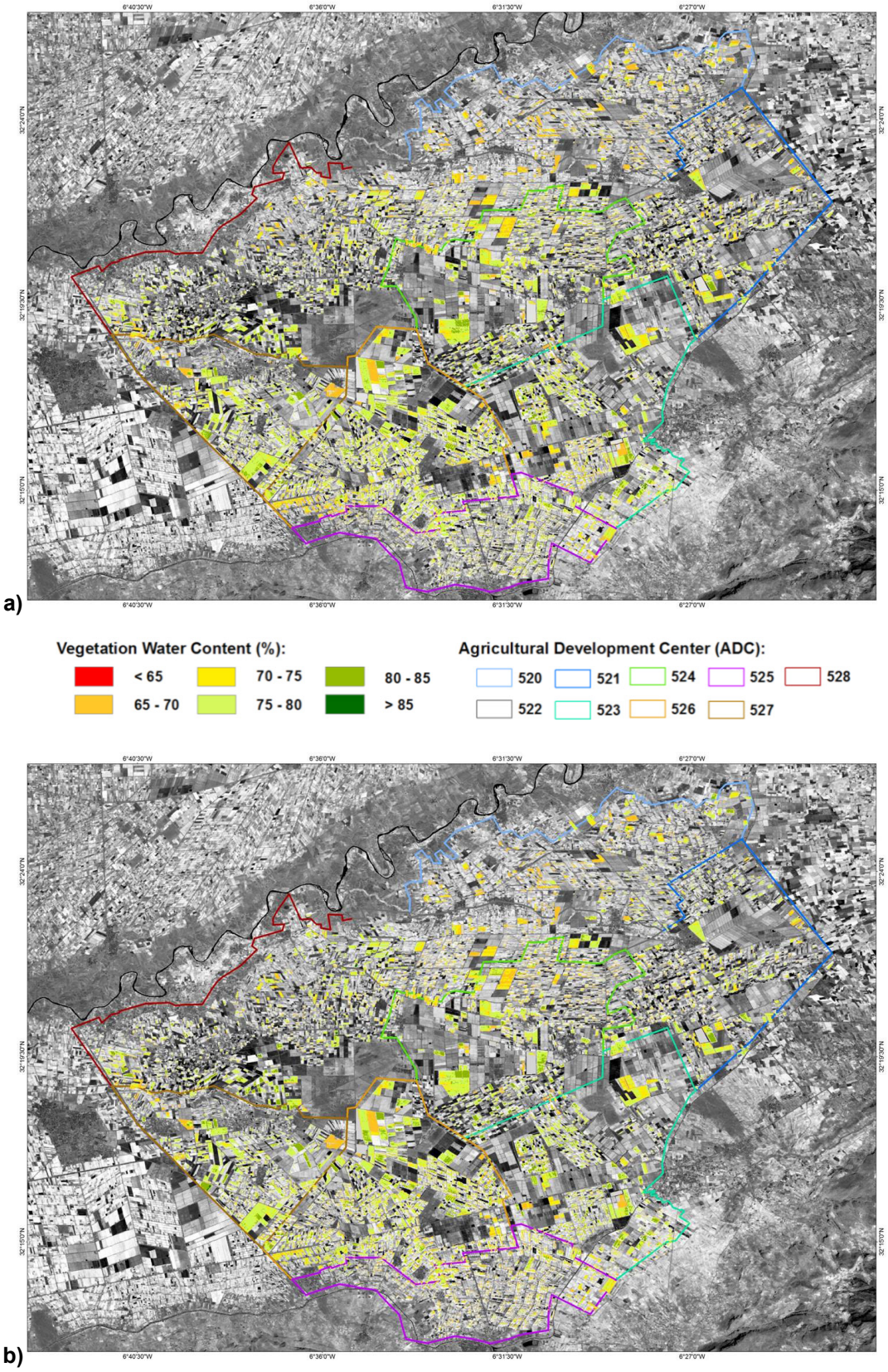


**Figure 6.** **Vegetation water content maps derived from NDWI (normalized difference water index) data: a) 2013-03-21, and b) 2013-03-26.**
***Cartes de teneur en eau de la végétation provenant de données de l'indice normalisé d'eau (NDWI) : a) 2013-03-21 et b) 2013-03-26.***

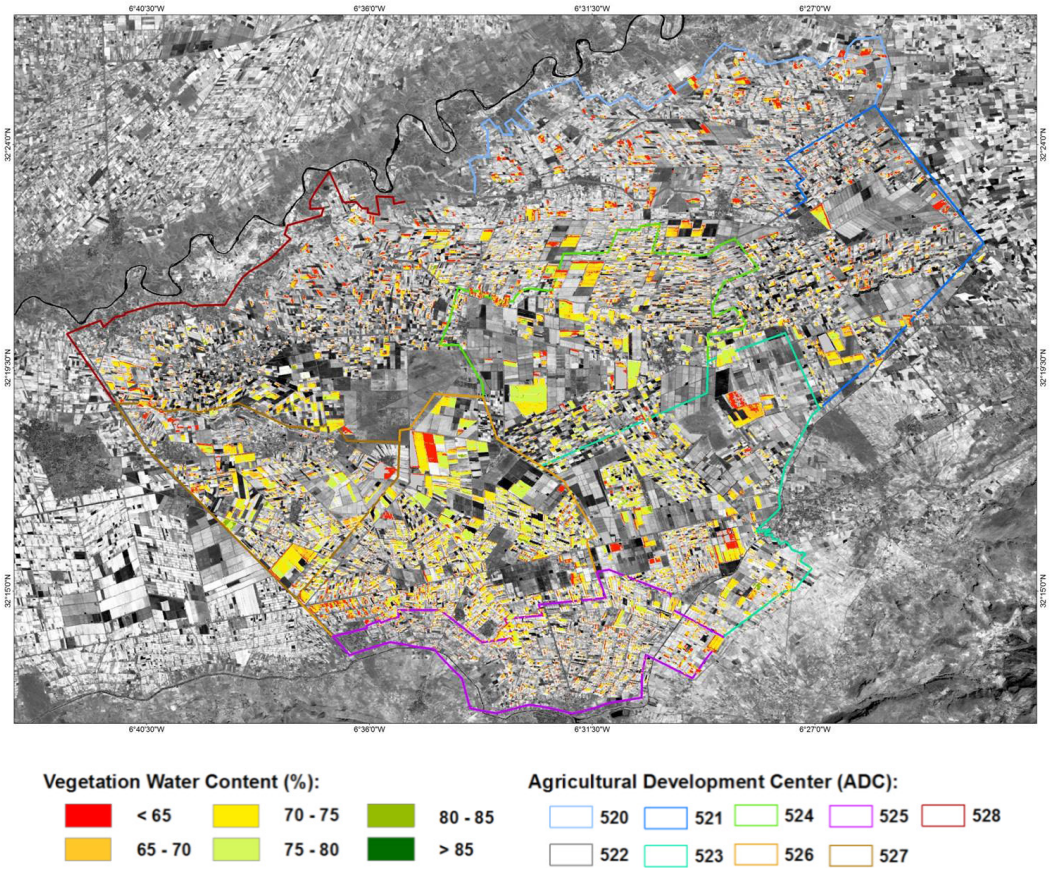


**Figure 7.** **Vegetation water content map derived from NDWI (normalized difference water index) data (2013-04-11).**
***Cartes de teneur en eau de la végétation provenant de données de l'indice normalisé d'eau (NDWI) (2013-04-11).***

## 4. CONCLUSION

In this study, the ability of the two spectral indices (NDWI and MSI) to monitor vegetation water content of wheat was assessed in a semi-arid irrigated area. These indices were calculated using the near and shortwave infrared band derived from SPOT-5 HRV satellite images. The comparison between studied spectral indices values, based on SWIR and NIR, and vegetation water content measurements showed good correlations. This result demonstrated the potential of SWIR and NIR bands to improve irrigation and crop management based on vegetation water content changes per surface unit. These indices (NDWI and MSI) allowed vegetation water content to be assessed and quantified from anthesis to grain filling and showed their potential as an important tool for improving irrigation monitoring and water stress management at field and regional levels.

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