VEGETATION WATER STRESS ASSESSMENT USING SHORT WAVE INFRARED (SWIR) INDICES IN WHEAT

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ABSTRACT: In the present study vegetation status in terms of water stress was evaluated using various short-wave infrared - water stress (SWIR - WSI) indices derived from the MODIS satellite data. Cloud-free MODIS/Terra Surface Reflectance data in seven bands for eight different dates during two wheat growing seasons of 2000-01 (drought) and 2001-02 (normal) was acquired through the EROS Data Gateway. Various moisture stress indices like Short Wave Infrared - Water Stress Index (SWIR-WSI), and Normalized Difference Water Index (NDWI) along with Normalized Difference Vegetation Index (NDVI) were computed using NIR and SWIR channel data.

The relationship between NDWI and NDVI for normal and drought crop seasons was generated in the Dharmshala and Pong dam regions to study the impact of drought on wheat. The study revealed that as the crop experiences moisture stress, the NDWI values progressively become negative. However, during normal crop season, the NDWI values were positive throughout the growing season. The positive values of NDWI were due to higher NIR-Channel reflectance than SWIR-channel, which indicates sufficient quantities of water in the vegetation canopy. The NDWI is significantly correlated with NDVI, indicating a strong link between canopy water content and green vegetation canopy structure, which varies with canopy moisture status during different growth stages of wheat. The results derived from two Shortwave Infrared Water Stress Indices namely SWIR-WSI-1 (5, 2) and SWIR-WSI-2 (6, 2) indicate that combined information from MODIS near and shortwave infrared wavelengths is useful as an indicator of canopy water stress in rainfed agriculture. Wheat yields were drastically reduced due to poor rainfall during the vegetative and reproductive phases leading to the failure of the crop as compared to normal crop season of 2001-02 in the wheat growing districts.

KEY WORDS: Vegetation water stress, Short-Wave Infrared-Water Stress Indices (SWIR-WSI), Normalized Difference Water Index (NDWI), MODIS/Terra Surface Reflectance, IRS-P6 (Resourcesat-1) LISS-III

1. INTRODUCTION

Physically based radiative transfer models and laboratory studies have shown that changes in water content in plant tissues have a large effect on the leaf reflectance in several regions of the 1300 – 2500 nm. It is well known that a large absorption by leaf water occurs in the range from 1550 – 1750 nm wavelengths (Tucker, 1980) and therefore short-wave infrared (SWIR) reflectance is negatively related to leaf water content. The MODIS satellite instrument has the advantage of narrow discrete Channels (channel-5: 1230 - 1250 nm & channel-6: 1628 – 1652 nm), which potentially can be useful for monitoring canopy water content (Gao, 1996). Variations in leaf internal structure and leaf dry matter content also causes variations in MODIS Channels 5 & 6 reflectances; consequently SWIR reflectance values alone are not suitable for retrieving vegetation water content. NIR reflectance is affected by leaf internal structure and leaf dry matter content but not by water content. Variations induced by leaf internal structure and leaf dry matter content can thus be suppressed by combining NIR reflectance information with SWIR reflectance information (Ceccato et al., 2001).

1.1 Canopy Water Stress Monitoring

Several studies suggest that the ideal wavelengths for predicting water content are wavelengths with weak absorption coefficients that allow the radiation to penetrate far into canopies (Sims and Gamon, 2003; Penuela et al., 1993). A number of studies have focused on the derivation of information on plant water stress using Near Infrared (NIR) and Short Wave Infrared (SWIR) data. It is well known that large absorption by leaf water occurs in these wavelengths and therefore short-wave infrared (SWIR) reflectance is negatively related to leaf water content (Tucker, 1980, Ceccato et. al., 2001). The largest of these regions is 1.3 – 2.5 μm interval (SWIR) where the amount of water available in the internal leaf structure largely controls the spectral reflectance (Tucker, 1980). The MODIS channels 5 and 6 are located in wavelength areas where the leaf water content plays a decisive role on the leaf reflectance. This makes the MODIS channels 5 and 6 well suited for canopy water monitoring because of the plant water sensitivity in these wavelengths combined with the high atmospheric water vapour transmittance (Fensholt and Sandholt, 2003). Canopy water content is not the only parameter responsible for reflectance variations in the MODIS channels 5 & 6 (SWIR). Variations in leaf internal structure and leaf dry matter content also influences the SWIR reflectance and consequently SWIR reflectance values alone are not suitable for retrieving vegetation water content. A method to isolate the reflectance contribution due to variations in leaf internal structure and leaf dry matter content is to exploit reflectance information from near infrared (NIR) wavelength from 700 to 900 nm. The NIR reflectance is affected by leaf internal structure and leaf dry matter content but not by water content. By combining the NIR reflectance information with the SWIR reflectance information, variations induced by leaf internal structure and leaf dry matter content can be removed and thus improve the accuracy in retrieving the vegetation water content (Ceccato et al., 2001). Fensholt and Sandholt, 2003 formulated two configurations namely Shortwave Infrared Water Stress Index (SWI-WSI) using MODIS NIR and SWIR channels as follows:

$$\textbf{SWI-WSI (5,2)} = (\rho\ \textbf{SWIR Ch –5} - \rho\ \textbf{NIR}) / (\rho\ \textbf{SWIR Ch –5} + \rho\ \textbf{NIR}) \quad \ldots\ldots. \quad \textbf{(1)}$$

$$\textbf{SWI-WSI (6,2)} = (\rho\ \textbf{SWIR Ch –6} - \rho\ \textbf{NIR}) / (\rho\ \textbf{SWIR Ch –6} + \rho\ \textbf{NIR}) \quad \ldots\ldots. \quad \textbf{(2)}$$

Where: ρ = reflectance in different channels

Spectral range of MODIS channels is as follows:

Channel-2 (NIR):	841 – 876 nm
Channel-5 (SWIR):	1230 – 1250 nm &
Channel-6 (SWIR):	1628 – 1652 nm

The SWI-WSIs are normalized indices and the values thereby theoretically vary between – 1 and + 1. An index value above zero means that the reflectance from channel-6 is higher than channel-2 reflectance and this indicates canopy water stress. A low index value is a consequence of a higher channel-2 reflectance than channel-6, which indicates sufficient quantities of water in the canopy for photosynthetical activity. The phenology of the vegetation also plays an important role and it is evident that the presence of a certain amount of vegetation is needed for the index to be meaningful. Furthermore, when the vegetation moves from the vegetative phase into the reproductive phase finally reaching the senescent stage very little energy in the vegetation is used for photosynthesis but for respiration and thereby availability of water becomes less important.

The approach of combining optical and SWIR information makes use of the negative relation between SWIR reflectance and leaf water content in the 1.3–2.5- m interval (Bowman, 1989, Jacquemoud and Baret,1990, Hunt, et al., 1987). Because the SWIR range is not influenced by foliar pigment absorption, increased SWIR reflectance is the most consistent leaf reflectance response to plant stress, including water stress (Zarco-Tejada and Ustin, S. L, 2001, Carter, 1994). Various canopy water status estimates have been developed from recent advances in Earth Observation (EO) technology. A promising methodology is based on the sensitivity of shortwave infrared (SWIR) reflectance to variations in leaf water content. This study explores the potential of SWIR-based canopy water status detection from geostationary Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) data as compared to polar orbiting environmental satellite (POES)-based moderate resolution imaging spectroradiometer (MODIS) data. The EO-based SWIR water stress index (SIWSI) is evaluated against in situ measured canopy water content indicators at a semi-arid grassland savanna site in Senegal 2008. Daily SIWSI from both MODIS and SEVIRI data show an overall inverse relation to Normalized Difference Vegetation Index (NDVI) throughout the growing season (Fensholt, et al., 2010).

1.1.1 Normalized Difference Water Index (NDWI)

Some of the Satellite instruments, such as the Moderate Resolution Imaging Spectrometer (MODIS) and Landsat TM8, will have many narrow, discrete channels in the 0.4 – 2.5 µm solar spectral region with signal to noise ratios greater than 100. Gao, 1996 proposed Normalized Difference Water Index (NDWI) using short wave infrared channel centred around 1.24 µm and near infrared channel centred around 0.86 µm. Both channels sense similar depths through vegetation canopies, unlike the two channels used in NDVI, NDWI is a measure of liquid water molecules in vegetation canopies that interacts with the incoming solar radiation. It is less sensitive to atmospheric scattering than NDVI. Following the simplicity of NDVI, NDWI is defined as (Gao, 1996):

$$\textbf{(NDWI)} = (\rho\ \textbf{NIR} - \rho\ \textbf{SWIR}) / (\rho\textbf{NIR} + \rho\ \textbf{SWIR}) \quad \ldots\ldots\ldots\ldots.. \quad \textbf{(3)}$$

MODIS bands centered at 858 and 1240 nm, with 35 and 20 nm bandwidths respectively, are ideally suited to build NDWI for vegetation water content estimation. The location of MODIS bands R1240 on the edge of the liquid water absorption, and R858 used for normalization and insensitive to water content changes, make these indices potentially suitable for global monitoring of vegetation water content from MODIS.

1.1.2 Normalized Moisture Index (NMI)

The vegetation indices namely NDVI and NDWI, each one of them provides additional information about the vegetation canopy. The comparison of these two indices normally results in a strong positive correlation. However, it is necessary to use both indices for evaluating the vegetation canopy status. Therefore, Jang, et al., 2006 proposed a new index that integrates the two vegetation indices which reveals not only the vegetation density but also the water status of vegetation by using the SWIR channel. This index is computed as follows:

Normalized Moisture Index (NMI) = NDVI + NDWI … (4)

2. MATERIAL AND METHODS

2.1 Study Area and its Location

Himachal Pradesh located between 320 22' 40" to 330 12' 40" N latitude and 750 37' 55" to 790 04' 22" E longitude, is a hilly state. The six major wheat growing districts namely Bilaspur, Hamirpur, Kangra, Mandi, Solon and Una, which account for 76 % wheat acreage and 78 % of total wheat production in the state were selected for this study. Wheat is principal Rabi crop of Himachal Pradesh grown under different physiographic conditions namely, riverbeds, valleys and terraces. It is sown from second week of November to second week of December in low and mid hills. The crop reaches flowering stage around mid-February and harvesting commences from mid-April to first week of May. The crop duration is about 120-135 days. Wheat is predominantly grown as rainfed crop as a result yield levels are much below the national average yields being 1574.0 kg/ha only. The location map of the wheat growing districts in Himachal Pradesh is shown in **Figure-1**.

2.1 Data Used

2.1.1 MODIS Surface Reflectance products

In the present study MODIS level 2G 500 m daily surface reflectance product (MOD09GHK) for the wheat growing seasons of 2000-01 and 2001-02 covering study districts in Himachal Pradesh was acquired. The MODIS reflectance product and extracted geo-referenced sub-scene with district boundaries is presented in **Figure-2**.

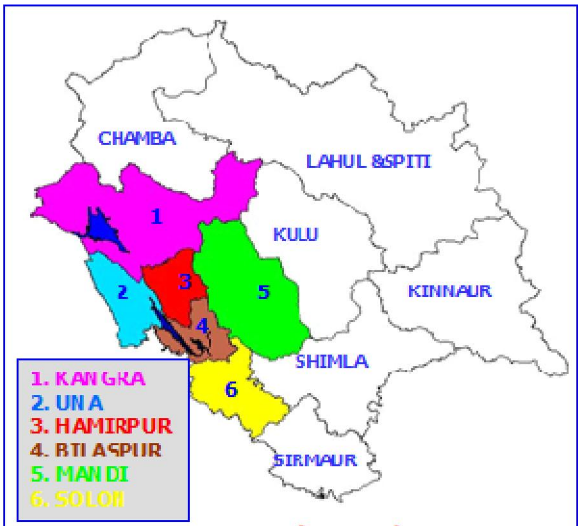

Figure-1: Location Map of Major Wheat Growing Districts in Himachal Pradesh

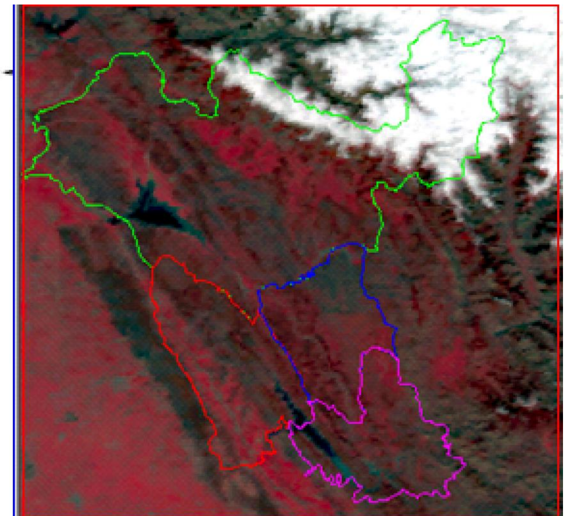

Figure-2: Georeferenced Sub-scene Covering Study Area with district boundaries

2.1.2 IRS-1C/1D LISS-III Digital Data

Single date, cloud-free IRS-1C/1D LISS III digital data of second fortnight of February-2001 & April-2001 and March-2002, coinciding with flowering stage of wheat was acquired for district-level wheat acreage estimation. The IRS LISS-III digital data of drought season covering study districts is presented in **Figure-3**.

2.1.3 Wheat Statistics

Historical district-level wheat statistics published by Bureau of Economics and Statistics (BES) from 1980-81 to 2001-02 for Kangra, Mandi, Una and Solan districts and from 1985-86 to 2001-02 for Bilaspur and Hamirpur districts were compiled and fluctuations were studied. The State-level wheat acreage and production from 1972-73 to 2004-05 are presented in **Figure-4**.

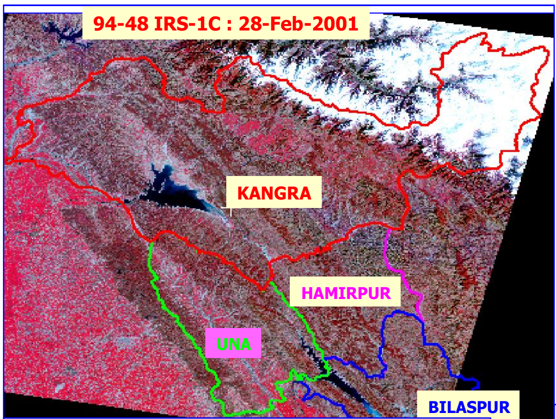

Figure-3:IRS-1C LISS-III of Drought Season

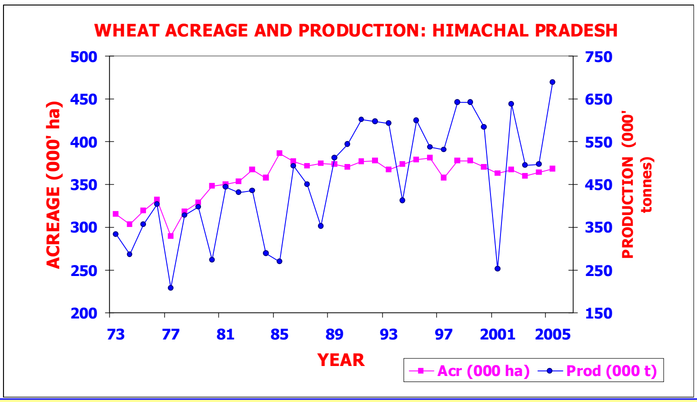

Figure-4: Wheat Acreage and Production in Himachal Pradesh

2.1.4 Meteorological Data

The meteorological variables such as minimum-maximum temperatures and rainfall were collected from meteorological stations in Kangra, Una and Bilaspur districts. The weekly meteorological variables of one of these districts for two crop seasons encompassing a severe drought season (2000-01) followed by a normal precipitation crop season (2001-02) is presented in **Figures-5**. The total rainfall during three important growth phases of wheat viz. Active Vegetative Phase (AVP) encompassing period from December second fortnight to March first fortnight (Std. Week numbers 51 -6), Reproductive Phase (RP) covering the period from second fortnight of February to first fortnight of March (Std week Numbers 7 – 11) and Maturity Phase (MP) covering the wheat growth period from second fortnight of March to first fortnight of April (Std week Numbers 12 – 16), is also computed and presented in this figure.

3. DIGITAL DATA ANALYSIS

3.1 Digital Data Extraction and Geo-referencing

Multi-date MODIS digital data of 16 dates were registered with Wide Field Sensor (WiFS) digital data from Indian Remote Sensing Satellites-1C Satellite, which was registered with Survey of India (SOI) topographical maps on 1:250,000 scales. Using these GCPs and second order polynomial with Cubic Convolution (CC) resampling procedure, the georeferenced images were generated with Root Mean Square (RMS) errors within + 0.4 to 0.5 pixels (<250 m). From the eight dates data acquired for each wheat season, the sub-scenes covering the study districts were extracted. Some of these georeferenced sub-scenes covering major wheat-growing districts in Himachal Pradesh with the district-boundaries for 2000-01 and 2001-02 wheat seasons are presented in **Figure-6** and **Figure-7**, respectively.

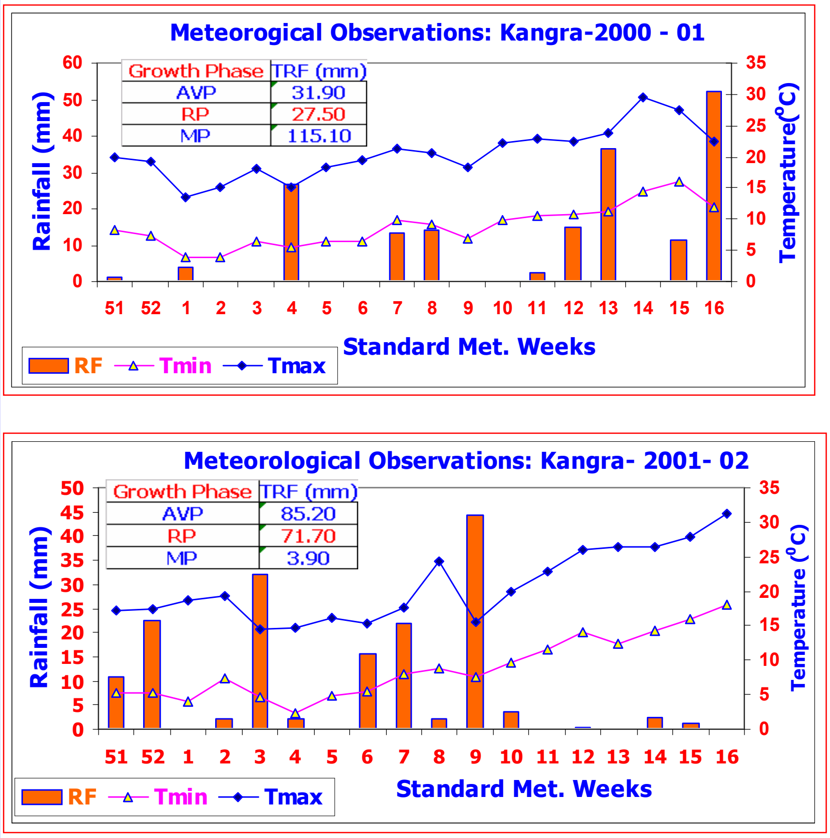

Figure-5: Meteorological Observations during Wheat Seasons of 2000-01 (drought) and 2001-02 (Normal) in Kangra District.

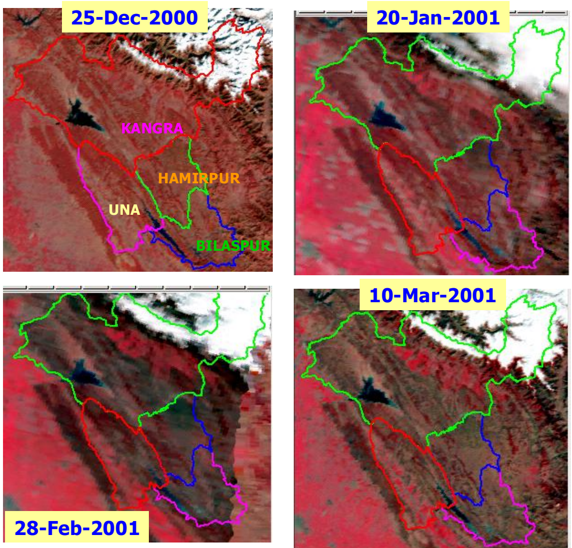

Figure-6: Georeferenced Sub-scenes Covering Study Area with District boundaries (Wheat Season 2001-02)

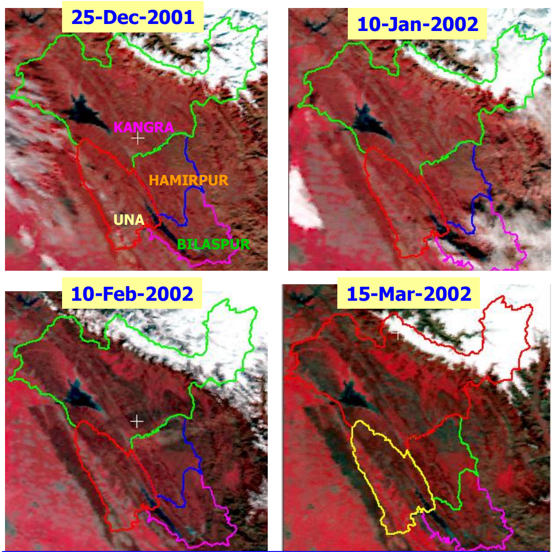

Figure-7: Georeferenced Sub-scenes Covering Study Area with District boundaries (Wheat Season 2001-02)

3.2 Supervised Classification and Computation of Vegetation Indices

The images of the peak vegetative growth phase of wheat (February-10 & March-15) of each season were used for generating multi-band training signatures which were used in supervised classification. The wheat crop mask was generated for computing acreage under wheat in different districts as well as for computing district-level average band values of wheat pixels for computing various vegetation indices. The l reflectance values of wheat pixels in

Green, Red, NIR, and two SWIR channels were extracted using boundary mask and wheat crop mask for each date of the two wheat seasons. Various moisture stress indices like SWIR-WSI-1, SWIR-WSI-2, NDWI and NMI along with Normalized Difference Vegetation Index (NDVI) were computed.

4. RESULTS AND DISCUSSION

4.1 Short Wave Infrared-Water Stress Indices (SWIR-WSI)

The wheat crop season of 2000-01 was an extremely drought year with annual total rainfall of about 1350 mm in Kangra and Hamirpur districts and 870 mm in Una district, which is almost 50-60 per cent less as compared to the normal annual rainfall. Furthermore, the seasonal distribution of rainfall was also uneven with long dry spells resulting in a very short growing season characterized by an extremely low wheat canopy cover. The total rainfall (TRF) during the Active Vegetative Phase (AVP) and Reproductive Phase (RP) was also less by almost 60 per cent as compared to TRF during normal crop season of 2001-02 in all the districts.

4.2 Relationship Between NDVI and Water Stress Indices

4.2.1 Normalized Difference Water Index (NDWI) Vs. NDVI

Tucker (1980) first suggested that the 1.55 – 1.75 µm spectral interval (the band pass of Landsat TM channel-5) was the best-suited band in the 0.7 - 2.5 µm region for monitoring plant canopy water stress from space. Some experimental studies showed that the reflectance of vegetation over the band pass of TM channel-5 increased as leaf water content decreased (Cibula et al., 1992). The NDWI proposed by Gao, 1996, uses NIR channel centred approximately at 0.86 µm and SWIR channel centred around 1.24 µm. In the present study NDWI is computed using MODIS Channel-2 (NIR: 841 -876 nm) and Channel-6 (SWIR-2: 1628 – 1652 nm) using equation-3. The NDWI was computed from the windows of 5x4 pixels at 30 different locations in the wheat cultivated Dharmashala region in Kangra district. The average NDWI and NDVI for each window were computed for eight different dates during two wheat growing seasons of 2000-01 (drought) and 2001-02 (Normal). The relationship between NDWI and NDVI of wheat pixels during Drought and Normal crop seasons in Dharamshala and Pong Dam regions is presented in **Figure-8.**

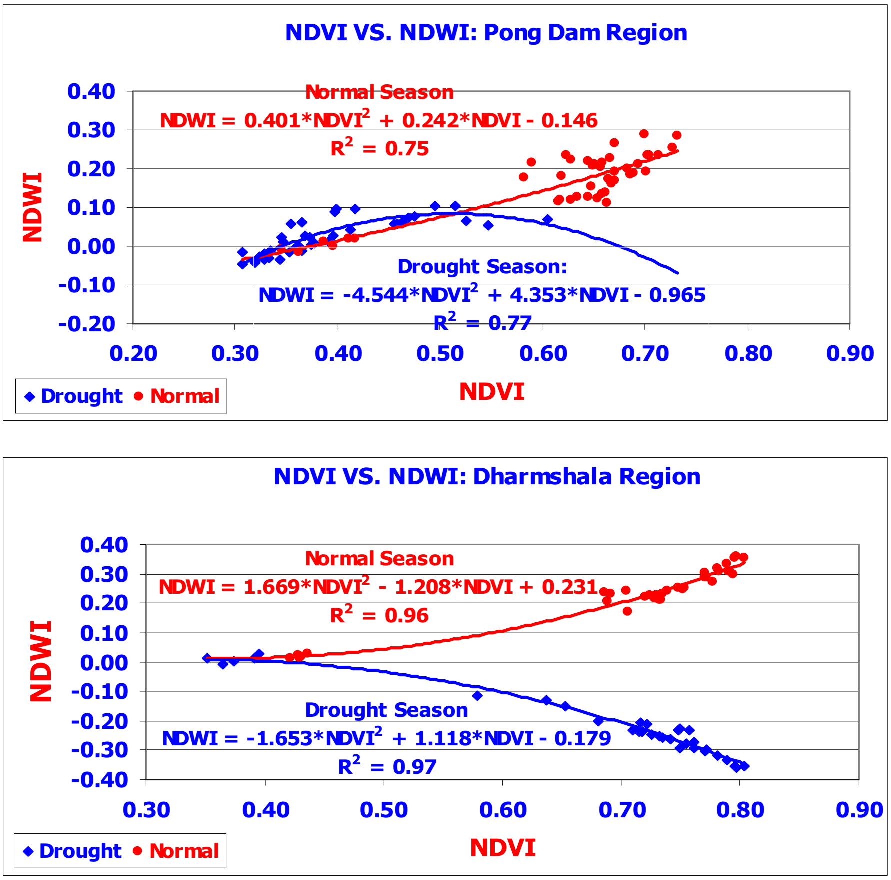

Figure-8: Relationship of NDWI and NDVI for Normal and Drought Wheat Seasons in Kangra District

It was observed by Gao, 1996 that the value of NDWI for the dry vegetation spectrum is negative and in general, NDWI value for green vegetation is positive due to weak liquid water absorption in SWIR channels. Figure-8 shows that during early vegetative phase of the wheat crop NDWI values were positive ranging from 0.02 to 0.05 during normal as well as drought crop seasons. During reproductive and grain filling stages the NDWI values were negative (ranging from -0.12 to -0.36) during drought season and they were positive (ranging from 0.18 to 0.38) during normal crop season. The negative NDWI values indicate that crop was experiencing moisture stress during active vegetative and reproductive phases of the crop due to poor and erratic rainfall in the Kangra district as seen from Figure-5. Similar pattern was observed in the Pong Dam region also. However, the drought was very severe in this region, as seen from very poor NDVI values due to very poor vigour during flowering and grain-filling stages of wheat. The Figure-8 indicates that as the crop experiences moisture stress, the NDWI values progressively become negative. However, during normal crop season, the NDWI values were positive throughout the growing season. The positive values of NDWI were due to higher Channel-2 (NIR) reflectance than channel-6 (SWIR), which indicates sufficient quantities of water in the vegetation canopy.

4.2.2 SWIR Water Stress Indices and NDVI

Two Short Wave Infrared (SWIR) Water Stress Indices (WSI) namely SWIR-WSI-1 (5, 2) and SWIR-WSI-2 (6, 2) and NDVI were computed at various sites in Pong Dam region in Kangra District for eight different dates during the 2000-01 (Drought) and 2001-02 (Normal) crop seasons. The relationship between NDVI and SWIR-WSIs for normal and drought seasons is given in **Figure-9**.

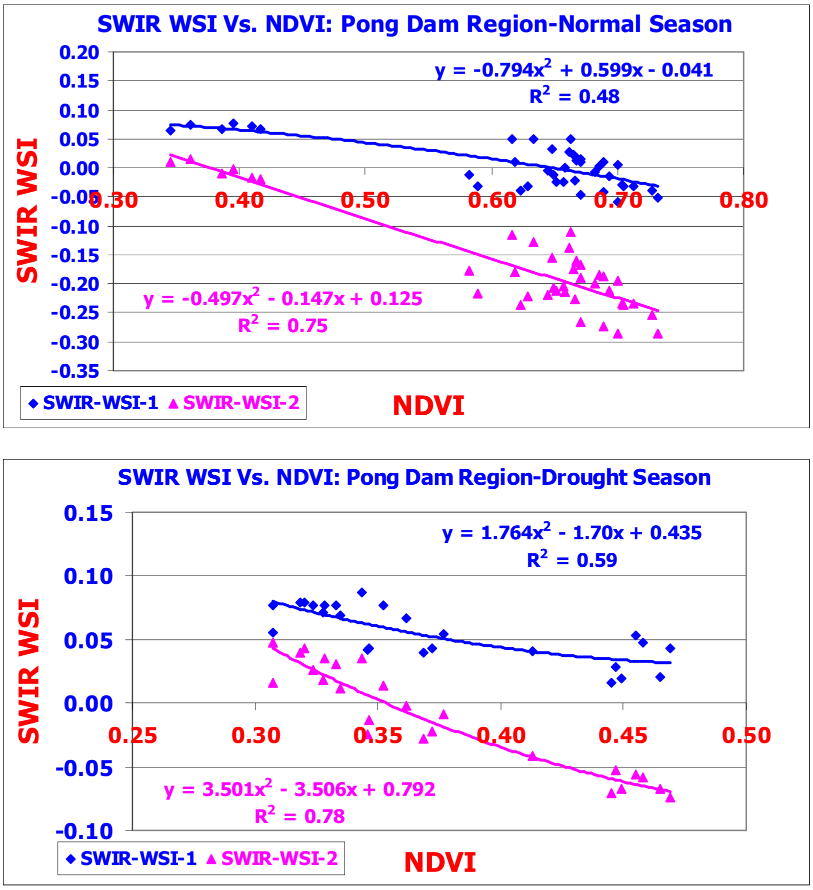

Figure-9: Relationship between SWIR-WSI and NDVI for Normal and Drought Seasons in Pong Dam Region

In the Pong Dam region the SWIR-WSI-1 (5, 2) values remain positive (ranging from 0.08 to 0.02) throughout the growing season. However, the SWIR-WSI-2 (6, 2) values are positive during the early vegetative phase and becomes slightly negative (ranging from -0.04 to -0.07) during the reproductive phase. The NDVI values during normal season were very high (ranging from 0.35 to 0.75) due to good crop vigour because of normal and well distributed rainfall during the crop season. However, the NDVI values were very low during the drought season (ranging from 0.32 to 0.47) indicating poor crop vigour due to poor rainfall. It was observed that among the

SWIR-WSI-1 (5, 2)and SWIR-WSI-2 (6, 2) indices SWIR-WSI-2 (6, 2) is very sensitive to moisture content in the canopy as seen from Figures 15 for Pong dam region in Kangra district. It is well known that large absorption by leaf water occurs in the SWIR wavelengths and therefore, SWIR reflectance is negatively related to leaf water content (Tucker, 1980; Ceccato et. al., 2001). It was observed by Fensholt & Sandholt, 2005 that a low and negative SWIR index value is a consequence of a higher channel-2 (NIR) reflectance than Channel-6 (SWIR), which indicates sufficient quantities of water in the canopy for photosynthetic activity.

4.2.3 Normalized Moisture Index (NMI) Vs. NDVI

The Normalized Moisture Index (NMI) integrates two indices namely NDVI and NDWI, for monitoring the water status of the vegetation as well as the vegetation density. This index reveals not only the density of vegetation but also the water content of the vegetation by using the SWIR channel data. **Figure-10** shows the scatter plot of NDVI Vs NMI in the Pong Dam region during normal and drought crop seasons. The scatter plot clearly shows two distinct distributions of NMI Vs. NDVI during normal and drought seasons. The NMI during drought season of 2000-01 was in the range of 0.275 to 0.575 with maximum NDVI of 0.48 throughout the growing season, whereas it was ranging from 0.32 to 0.98 with maximum NDVI of 0.73 during the normal crop season of 2001-02.

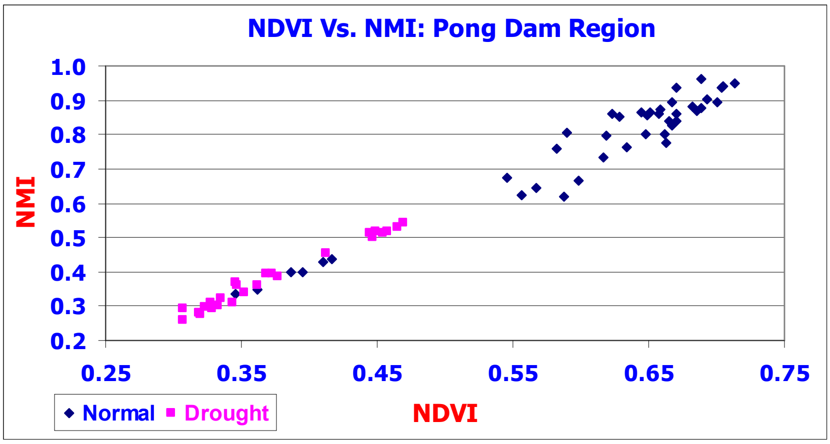

Figure-10: Scatter plot of NDVI Vs. NMI for Normal and Drought Seasons in Pong Dam Region

4.2.4 Impact of Drought on Wheat Production

The wheat production and average yields during 2000-01 (drought) crop season in all the wheat growing districts as well as in the state were one of the lowest during last two decades (Figure-4). However, wheat acreage in different districts and in the state does not show appreciable change. This indicates that wheat sowing was normal due to good rainfall during the month of December in most of the districts. But due to poor rainfall during the vegetative and reproductive phases of the wheat crop (Figures 5, 6 & 7) yields have drastically reduced due to long spell of drought leading to the failure of the crop as compared to normal crop season of 2001-02 in the wheat growing districts.

CONCLUSIONS

Wheat vegetation status in terms of water stress during normal and severe drought years was evaluated using various Short Wave Infrared- Water Stress Indices (SWIR - WSI) derived from NIR and SWIR channel data from MODIS satellite for two crop seasons of 2000 – 01 and 2001 – 02 covering wheat growing districts in Himachal Pradesh.

The major conclusions of this study are as follows:

- It was observed that as the crop experiences moisture stress, even though the NDVI increases during early vegetative stage, the NDWI values progressively become negative. However, during normal crop season, the NDWI values were positive throughout the growing season. The positive values of NDWI were due to higher Channel-2 (NIR) reflectance than channel-6 (SWIR), which indicates sufficient quantities of water in the vegetation canopy.

- The NDWI is significantly correlated with NDVI, separately for drought and normal seasons, indicating a strong link between canopy water content and green vegetation canopy structure, which varies with canopy moisture status during different growth stages of wheat.

- The results from Shortwave Infrared Water Stress Indices (SWIR-SWI) namely SWIR-WSI-1 (5, 2) and SWIR-WSI-2 (6, 2) indicate that combined information from MODIS near and shortwave infrared wavelengths is useful as an indicator of canopy water stress in rainfed agriculture. The SWIR-WSI-2 (6, 2) index was found to be more sensitive to changes in canopy water content as compared to SWIR-WSI-1 (5, 2).

- The Normalized Moisture Index (NMI) integrates two indices namely NDVI and NDWI, for monitoring the water status of the vegetation as well as the vegetation density. This index reveals not only the density of vegetation but also the water content of the vegetation by using the SWIR channel data. The scatter plot clearly shows two distinct distributions of NMI Vs. NDVI during normal and drought seasons.

- The comparison of drought and normal crop season values of NDVI, NDWI and NMI indicates that these values drastically declined during the drought periods, indicating lesser amount of canopy moisture and green leaf vegetation.

- Wheat yields were drastically reduced due to poor rainfall during the vegetative and reproductive phases of the due to long spell of drought leading to the failure of the crop as compared to normal crop season of 2001-02 in the wheat growing districts.

ACKNOWLEDGEMENTS

The first author is grateful to Shri T.P. Singh, Director, Bhaskaracharya Institute for Space Applications and Geo-Informatics (BISAG), Department of Science and Technology, Government of Gujarat, Gandhinagar, India for his kind encouragement.

Thanks are also due to Director, Space Applications Centre (ISRO) for his support for conducting this study under the **F**orecasting **A**gricultural output using **S**pace, **A**grometeorology and **L**and (FASAL)-based observations, project funded by the Ministry of Agriculture, Government of India.

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