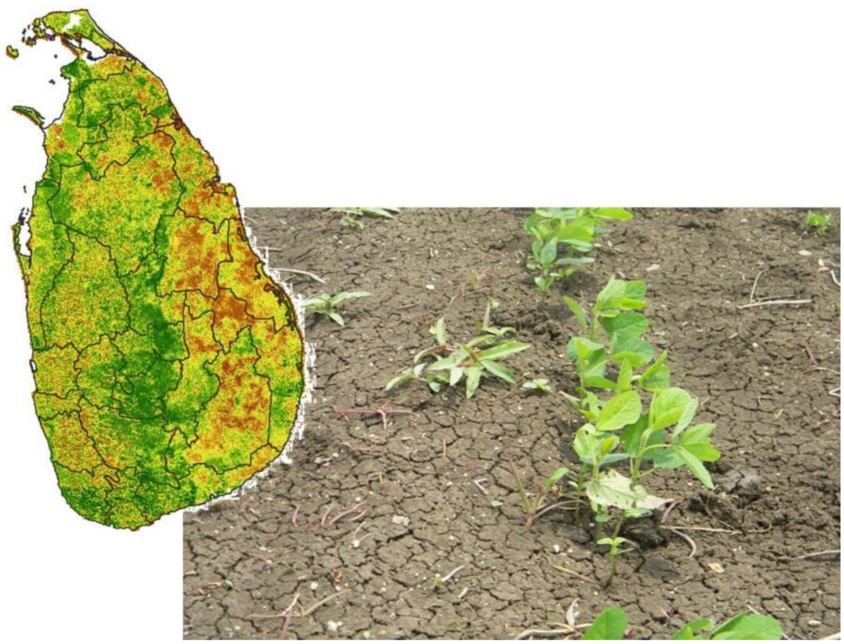
Project Report June 2015

Development of South Asia Drought Monitoring System



Submitted by

International Water Management Institute (IWMI), Colombo, Sri Lanka

Grant Supported by:

Global Water Partnership (GWP) - World Meteorological Organization (WMO) as part of the *Integrated Drought Management Programme (IDMP)* and

Climate Change, Agriculture and Food Security (CCAFS) and IWMI

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1. Project Summary

Drought is a complex hazard caused by the breaking of water balance and it has always an impact on agricultural, ecological and socio-economic spheres. Although the drought indices deriving from remote sensing data have been used to monitor meteorological or agricultural drought, there are no indices that can suitably reflect the comprehensive information of drought from meteorological to agricultural aspects. The "South Asia Drought Monitoring System" project proposed innovative approach of developing integrated drought severity index (IDSI) is defined as a principal component of vegetation condition index (VCI), temperature condition index (TCI) and precipitation condition index (PCI), Soil condition index (SCI). IDSI integrates multi-source remote sensing data from moderate resolution imaging spectroradiometer (MODIS) and tropical rainfall measuring mission (TRMM), ESA Soil Moisture (ASCAT) Products and it synthesizes precipitation deficits, soil thermal stress and vegetation growth status in drought process. Therefore, this method is favorable to monitor the comprehensive drought over South Asia. In our research, a heavy drought process was accurately explored using IDSI in Sri Lanka and South India from 2000 to 2014. Finally, a validation was implemented and its results show that IDSI is not only strongly correlated with 3-month scales standardized precipitation index (SPI3), but also with variation of crop yield and drought-affected crop areas. It was proved that this index is a comprehensive drought monitoring indicator and it can contain not only the meteorological drought information but also it can reflect the drought influence on agriculture. Below section provides detail description on various drought indices utilized and satellite data image processing and results on drought maps, validation of drought product and field investigation.

2. Project Overview

The aim is to develop an innovative approach for monitoring and assessment of the drought risk based on integration of meteorological data, vegetation condition from satellite imagery and targeted collection of ground truth moisture and crop-yield data that supports efforts directed at increased resilience to droughts. The approach is designed to capitalize on the strengths of both satellite- and climate-based indices (the later have been traditionally used for drought monitoring). The main monitoring tool will be *Integrated Drought Severity Index* (IDSI) that reflects the effects of drought as observed through both i) satellite-derived vegetation data and ii) the level of dryness expressed by traditional climate-based drought indices. Additional biophysical/environmental characteristics such as ecoregion, elevation, landuse / landcover (LULC) type, and soil type are also considered because they can influence climate-vegetation interactions. Overall, input data that are used to calculate IDSI can be categorized into three types: satellite, climate and biophysical. Detail description on the approach is given in project document.

This research project has been brainstormed with various national partners in the region and relevant global experts to provide necessary guidance in development of drought monitoring system. The project report provides technical details on various work packages in development of DMS, integration of satellite data sources, case study evaluation for major droughts in Sri Lanka, Maharashtra and other Indian states and finally the field assessment carried out for the 2014 droughts in India and Sri Lanka is highlighted.

3. Literature review on drought monitoring

While in the process of developing drought monitoring system, the project team members evaluated several research papers on the comparison of various drought indices in terms of usability and applicability in the region, availability of datasets, procedure to calculate several indices were assessed. Compared to in-situ indices, drought indices derived from remote sensing data are more suitable for spatial drought conditions monitoring. Among many remote sensing techniques based drought indices, the normalized difference vegetation index (NDVI)-based vegetation condition index (VCI) (Kogan and Sullivan, 1993; Kogan, 199) and land surface temperature (LST)-based temperature condition index (TCI) (Kogan, 1995) are two useful tools for monitoring the intensity, duration and impact of drought on regional or global level (Singh et al., 2003).

Earlier researchers have found that VCI is suitable for monitoring large scale drought impact on vegetation, including agricultural drought, and VCI has a strong correlation with the crop yield (Liu and Kogan, 1996; Unganai and Kogan, 1998; Kogan et al., 2005; Salazar et al., 2007, 2008). A study in a semi-arid region of the Iberian Peninsula also found that the interpretation of the VCI was more complicated than other drought indices because it provides an indirect measure of moisture (drought) conditions. Anything that stresses vegetation including insects, diseases, and lack of nutrients will be represented by VCI (Vicente-Serrano, 2007). Furthermore, some studies found that the synthesizing VCI and TCI together were better than separately and they developed a vegetation health index (VHI) (Kogan, 1997; Kogan et al., 2004). However, in the humid regions of high-latitude, where vegetation growth is primarily limited by lower temperatures which are opposite with low-latitude regions, using VHI to monitor drought condition has to be undertaken with caution (Karnieli et al., 2006). All those indices are not considering climate data, like precipitation and soil moisture variation, which is one of the influencing factors of drought in semi-arid areas. The project uses, remote sensing precipitation products of tropical rainfall measuring mission (TRMM), Advanced SCATterometer (ASCAT) data can be used as an alternative data of meteorological station and monitoring drought. Therefore, the remote sensing based drought indices synthesizing precipitation and soil moisture is more appropriate for South Asia to address the complex process of drought.

As we know, drought is a slow process which begins with precipitation deficit, then it leads to soil moisture deficit and a higher land surface temperature, and at last the vegetation growth will be influenced by this process. Therefore, to monitor the comprehensive drought we must consider these parameters which are derived from precipitation, soil and vegetation. In this project, we used TRMM, ESA CCI data as a component from precipitation, soil moisture to calculate PCI, SCI and LST as a component of temperate to calculate TCI and used NDVI as a component from vegetation to calculate VCI. But, the problem is that drought does not have a linear relation with NDVI, LST and TRMM anomalies in different season and regions, and there is always a correlation between them in some case. Therefore, SDI, a synthesized drought index was proposed through principal component analysis (PCA) method. PCA is a linear transformation which reduces redundancy by translating and/or rotating the axes of the original feature space, so that the drought information can be represented without correlation in a new component space (Lasaponara, 2006).

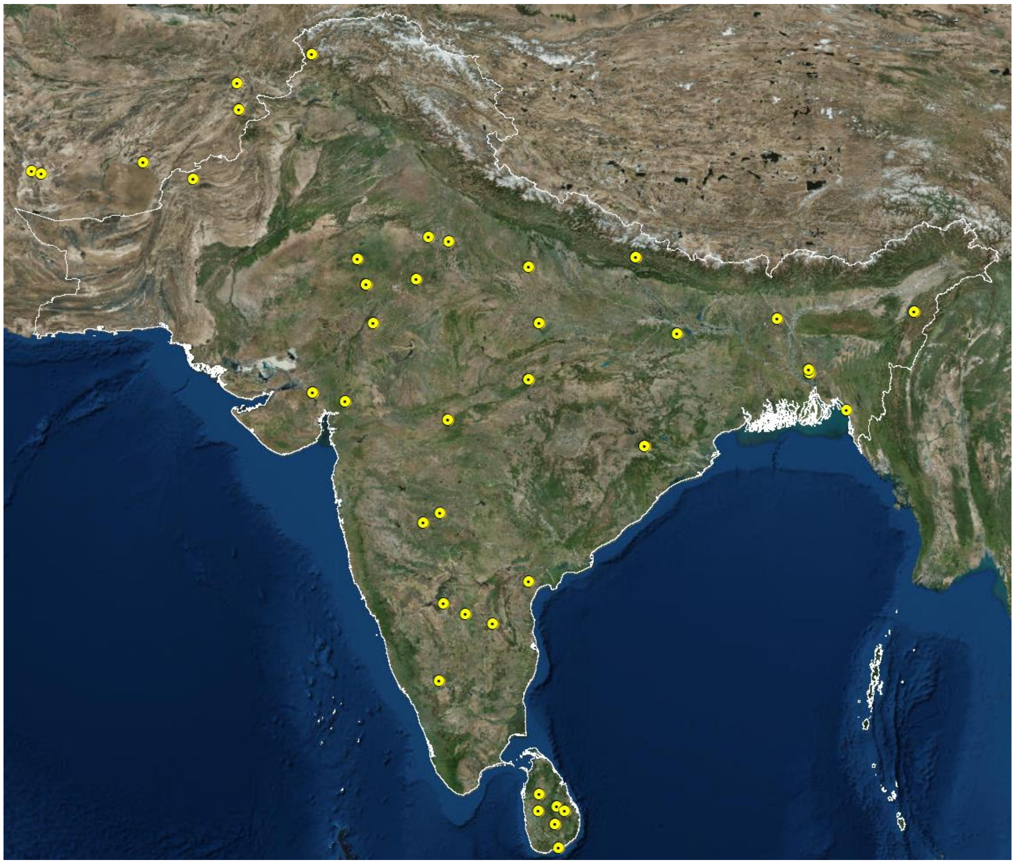


Figure 1: Historical extreme drought events for South Asia collected from various public sources

4. Integration of remote sensing data and climate information in drought indices development

The most important and crucial task is the data collection and integration of multi-source remote sensing information and in-situ observation in development of drought monitoring system. The below table 1 summarizes list of data sources identified, downloaded and are stored in IWMI. Substantial effort in the current phase involves satellite image processing, data quality and assessment on in-situ data and collaboration with relevant institution in access to data. We have procured gridded rainfall data at 0.25 degree from 1901 to 2013, gridded 1 x 1 degree temperature data from Indian Meteorological Department. The detail methodological approach and flow chart is presented in Figure 2 and Section 5.

With the huge data volume both in terms of spatial and temporal availability this requires data storage system and high-end processing system. The funding contribution from this project and IWMI's contribution from other bilateral projects has made possible to procure 2 Dell workstation and 2 data storage device of 20Terrabyte for smooth execution of this activity. However the need to upgrade the system is essential during the phase-II in view of range of products and the implementation phase.

Table 1: List of various data sources collected and processed in development of drought monitoring system

Satellite Data Sources		Satellite	Product Details	Tile	Spatial Resolution	Temporal Resolution	Period From	Period To	Available	Format	Data Source
Surface Reflectance	MOD09A1	Terra	Surface Reflectance Bands 1–7	H25V07	500m	8 day	2000	2014	Yes	.hdf, .tif	
Surface Temperature	MOD11A1	Terra	Land Surface Temperature & Emissivity	H25V07	1000m	Daily	2000	2014	Yes	.hdf, .tif	
	MOD11A2	Terra	Land Surface Temperature & Emissivity	H25V07	1000m	8 day	2000	2014	Yes	.hdf, .tif	
	MOD11C1	Terra	Land Surface Temperature & Emissivity	CMG	5600m	Daily	2000	2008	Yes	.hdf, .tif	
	MOD11C2	Terra	Land Surface Temperature & Emissivity	CMG	5600m	8 day	2000	2014	Yes	.hdf, .tif	
	MOD11C3	Terra	Land Surface Temperature & Emissivity	CMG	5600m	Monthly	2000	2014	Yes	.hdf..tif	NASA
Vegetation	MOD15A2	Terra	Leaf Area Index - FPAR	H25V07	1000m	8 day	2000	2014	Yes	.hdf, .tif	
	MOD13A1	Terra	Vegetation Indices	H25V07	500m	16 day	2000	2014	Yes	.hdf, .tif	
	MOD13A2	Terra	Vegetation Indices	H25V07	1000m	16 day	2001	2013	Yes	.hdf, .tif	
	MOD13A3	Terra	Vegetation Indices	H25V07	1000m	Monthly	2000	2014	Yes	.hdf, .tif	
	MOD13C1	Terra	Vegetation Indices	CMG	5600m	16 day	2000	2014	Yes	.hdf, .tif	
	MOD13C2	Terra	Vegetation Indices	CMG	5600m	Monthly	2000	2005	completed (2000-2005) rest Downloading	.hdf, .tif	
	MOD13Q1	Terra	Vegetation Indices	H25V07	250m	16 day	2000	2003	completed (2000-2003) rest Downloading	.hdf, .tif	
Rainfall	TRMM	3B42	Rainfall Estimates		0.25	Daily	1998	2014	yes	.tif	NASA
		3B43	Rainfall Estimates		0.25	Monthly	1998	2014	yes	.tif	NASA
	Aphrodite		Rainfall Estimates		0.25	Daily	1951	2007	yes	.tif	NASA
	Point Data GHCN		Rainfall actual			Daily	1901	2013	Yes		GHCN
	SPI Derived from Aphrodite and TRMM					1month, 2month, 3, 6,9,12,24	1951	2013	yes	.tif	IWMI
	IMD Rainfall Data		Daily Gridded Rainfall data		0.25		1901	2013	Yes	.grd	IMD
	IMD Temperature Data		Daily Gridded Temp data		1		1951	2013	Yes	.grd	IMD
Others	ET (MOD16)				1000m	8day	2000	2013	Yes	.hdf, .tif	http://ntsg.umt.edu/project/mod16
	Soil Gridded Data				1km				yes	.tif	http://soilgrids.org/
	LULC	Chinese	Land cover		30m				yes	.tif	http://glc30.tianditu.com/
		MERIS	Land cover		300m				yes	.tif	http://due.esrin.esa.int/globcover/
		MCD12Q1	Land cover	H25V07	500m		2001	2012	Yes		NASA
	Soil Moisture ASCAT								Yes		ESA
Global Products	DSI Drought Products				0.05	Annual	2000	2011	yes	.hdf, .tif	University of Montana
	DEM				30m				No Data Available		USGS
					90m				Yes	.tif	USGS
	Boundaries	National							yes	.shp	
		State							yes	.shp	
		District							yes	.shp	
		Taluk							yes	.shp	
Others	Maharashtra Drought Report								Yes	.pdf	
	Crop yield statistics										
	MOD17A2	Terra	Gross Primary Productivity	Tile	1000m	8 day	2000	2013	Yes	.hdf, .tif	NASA
	MOD17A3	Terra	Net Primary Productivity	Tile	1000m	Yearly	2000	2010	Yes	.hdf, .tif	NASA
	Ground Water Table								no		http://www.india-wris.nrsc.gov.in/GeoVisualization.html?UType=R2VuZXJhbA==?UName=
	Food Production in District								no		
	Soil Moisture								no		
	Soil Water deficit data								no		

5. Developing of Integrated Drought Severity Index (IDSI) and product evaluation in South Asia

There are four broad data classification in the development of IDSI that includes climate, vegetation, and temperature and soil moisture. Specifically for vegetation, wide-range of satellite data is being tested for its usability. To determine **vegetation anomaly** two widely used vegetation indices namely Normalized Difference Vegetation Indices (NDVI), Normalized Difference Water Index (NDWI) were utilized. MODIS Surface Reflectance product (MOD09A1 and MOD13Q1) at every 8-day and 16-day interval was used to calculate vegetation anomaly. Prior using the satellite datasets, once has to lot of pre-processing due to cloud contamination this includes filtering, noise elimination and gap filling to improving the data quality. The final step is to smooth reflectance values using time-series analysis that allow understanding on the crop seasonal pattern and its anomaly.

For vegetation regions, the weather-related NDVI changes are smaller than the ecosystem related one and the drought impacts on vegetation cannot be easily detected from NDVI data directly. Thus use of vegetation condition index (VCI) is a pixel based normalization of the NDVI in which the short term climate signal of the NDVI was filtered by separating it from the long-term ecological signal. VCI is a better indicator of drought stress on vegetation than NDVI (Figure 3).

On the **temperature module**, MODIS Land Surface temperature (MOD11A2) was used to derive temperature condition index. Basically the land surface will meet a thermal stress. Hence, the temperature condition index (TCI), a remote sensing based thermal stress indicator is proposed to determine temperature-related drought phenomenon. The TCI algorithm was similar to the VCI one and its conditions was estimated relative to the maximum/minimum temperatures is a given time series.

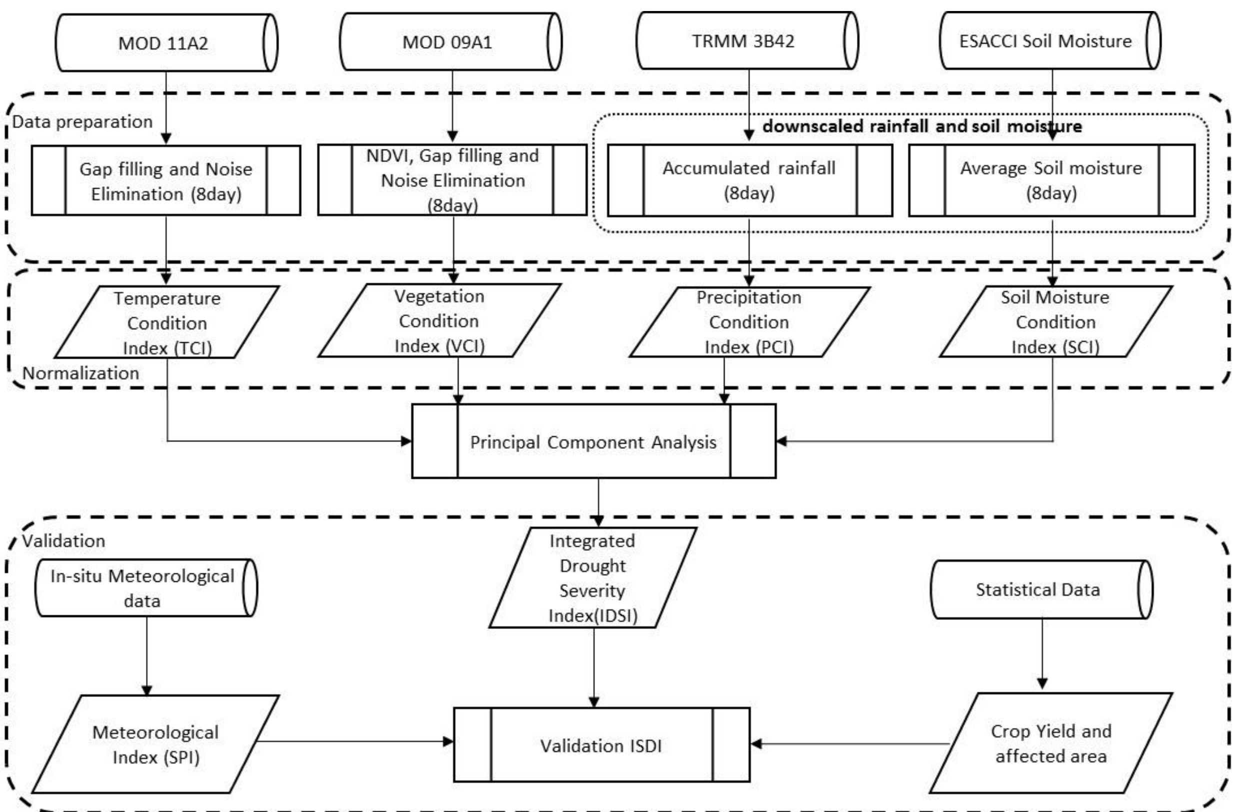


Figure 2: Flowchart of comprehensive drought monitoring based on multi-source remote sensing data

On the **precipitation module**, wide range of rainfall products were used to derive Precipitation Condition Index (PCI). TRMM 3B42 and Aphrodite was used provides estimation of daily precipitation, and from it the meteorological drought can be taken. The precipitation estimation has a spatial and temporal climate component but it cannot be directly analyzed with VCI and TCI. Therefore, in this research, PCI which normalized by the TRMM 34B2 data using a similar algorithm of VCI, was defined for the detection of the precipitation deficits from climate signal.

On the **Soil Moisture module**, Soil moisture monitoring is generally a superior executive mean for agricultural drought assessment than precipitation. In India, rain-fed agriculture dominates over irrigated agricultural systems, due to which precipitation is considered as the indicator for agricultural drought. But only precipitation cannot serve as reliable indicator for assessment of agricultural drought because of variability in water supply modes (Irrigation from canal, ground water, storage tank, rainfall harvested and rain-fed water). Only rain-fed agricultural practices have a strong relationship between rainfall amount and soil moisture. For the drought severity index, the ESA CCI global soil moisture product is being used to develop IDSI. Basically the CCI uses active and passive microwave space borne instruments and are freely distributed by ESA. Similar to PCI, Soil Moisture index (SCI) was defined for the detection of the soil moisture deficits that affects crop stress and affects the crop productivity.

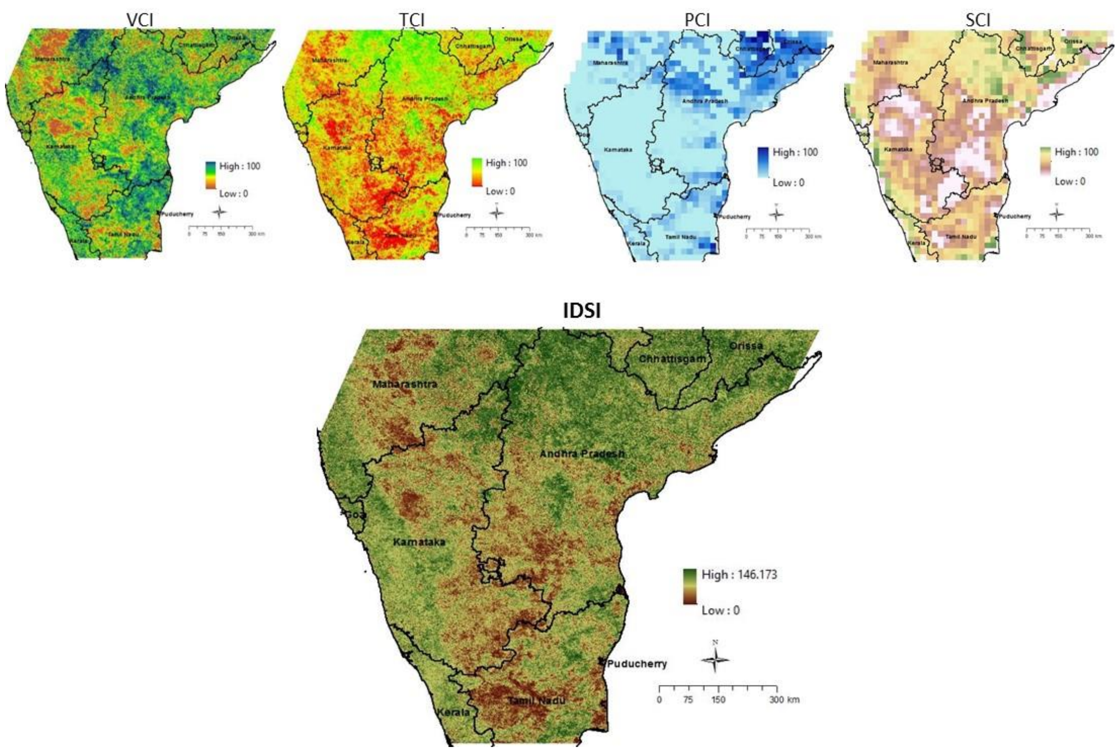


Figure 3: Drought calculation process of South India MODIS tile (h25v07) which was monitored by IDSI in 2012. The top images are the primarily products including VCI, TCI, PCI and SCI to generate Integrated Drought Severity Index (IDSI)

6. Integrated Drought Severity Index (IDSI) using principal component analysis (PCA)

The final phase in the drought product development is integration of four different parameters to determine IDSI through statistical modeling. This was achieved using principal component analysis (PCA) as it reduces the dimensionality of a data set. It undertakes an orthogonal transformation of a set of possibly correlated variables to create a new variable set with principal components that are uncorrelated and are ordered in terms of the amount of variance exposed in the original data. As a useful mathematical tool, PCA is mostly used in exploratory data analysis and for making predictive models. The PCA procedure firstly computes the covariance matrix and eigenvalues, eigenvectors among all input data, secondly it obtains the percent of total data set variance explained by each component, and finally a series of new data (called eigen channels or components) are computed by multiplying the eigenvector for the original input data (Lasaponara, 2006).

In remote sensing applications, PCA has been used for long as a data compression tool by discarding minor components with little explanatory values. Although VCI, TCI, PCI and SCI can be used to monitor drought from vegetation, soil and climate aspect respectively, there are correlated information among them for to monitor the comprehensive drought. Besides, the contribution of VCI, TCI, SCI and PCI to drought monitoring does not have a linear relation in different seasons. For example, if other conditions are near normal, vegetation may be more sensitive to moisture during canopy formation (leaf appearance) and to temperature during flowering. Therefore, in this study, PCA was used to get the principal information from VCI, TCI and PCI and discard the correlated signal from them. The principal components transformation was finished in ArcGIS software environment. The VCI, TCI, SCI and PCI in each weekly/monthly are input as original spectral bands and it calculated the same number of principal components bands. Since the first principal component (PC1) always contains more than 75% information from VCI, TCI, SCI and PCI and it is defined as a new drought index, namely the integrated drought severity index (IDSI) (Figure 3 and 4). With the development of the validation data set, the classification schemes could be reexamined based on new studies. The initial version of Integrated Drought Severity Index product covering Sri Lanka and several states in South India is given in Figure 4-6.

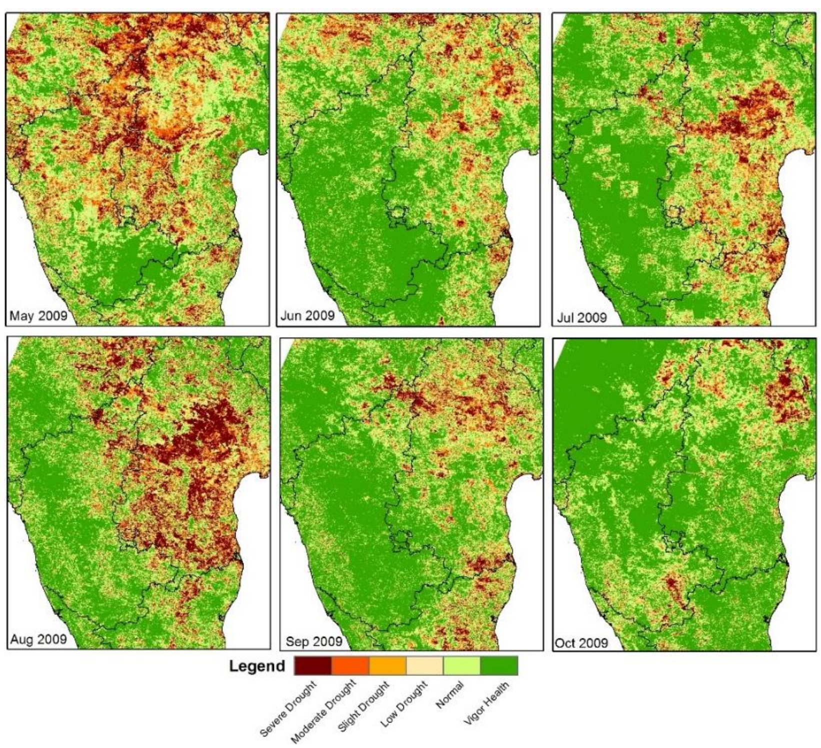


Figure 4: Map showing seasonal variation of drought severity obtained from MODIS time-series for the 2009 drought event. Dark areas represent severe drought and green color highlighting healthy vegetation.

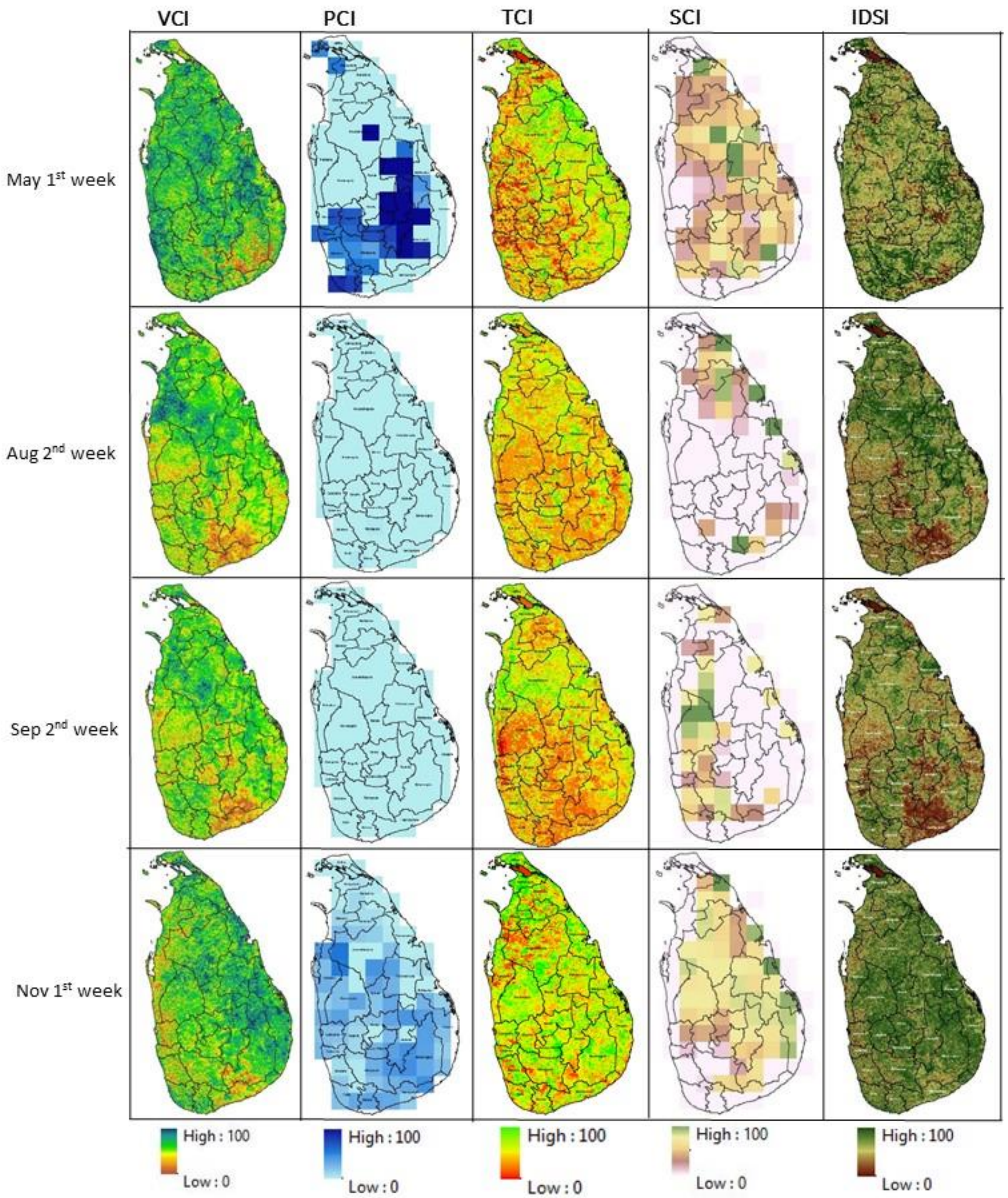


Figure 5: The drought monitoring maps during the period from May to November for Sri Lanka based on IDSI for 2001.

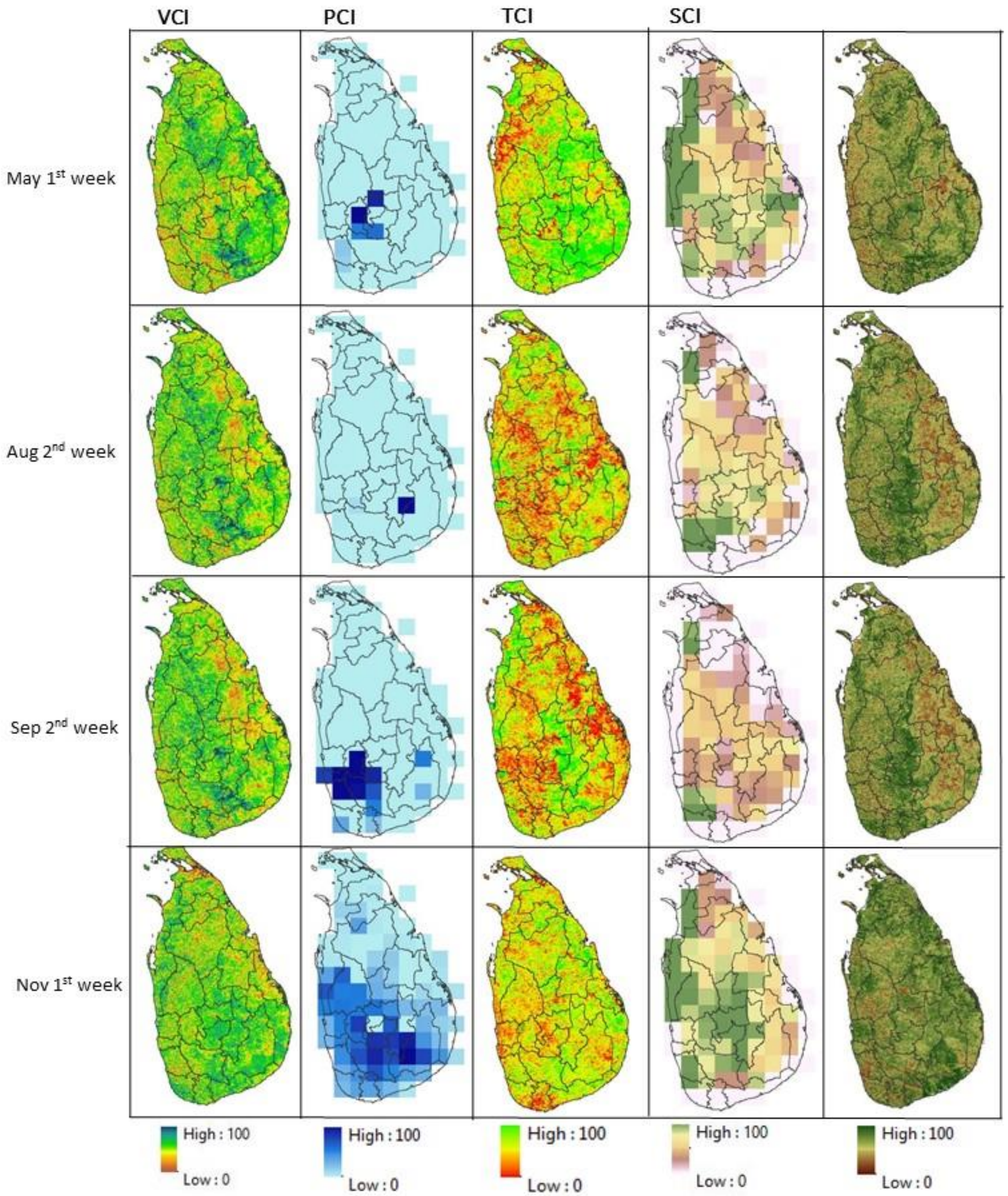


Figure 6: The drought monitoring maps during the period from May to November for Sri Lanka based on IDSI for 2013.

7. Drought Product Validation using standardized precipitation index (SPI) and Ground Verification

Wide range of precipitation data was collected from various sources including Global Hydrological Climate Network, Spatially Gridded 0.25 degree rainfall data from Indian Meteorological Department (IMD), Satellite rainfall estimates from Aphrodite, TRMM were collected for its use in calculation of SPI and validation of IDSI (Figure 7 – 9).

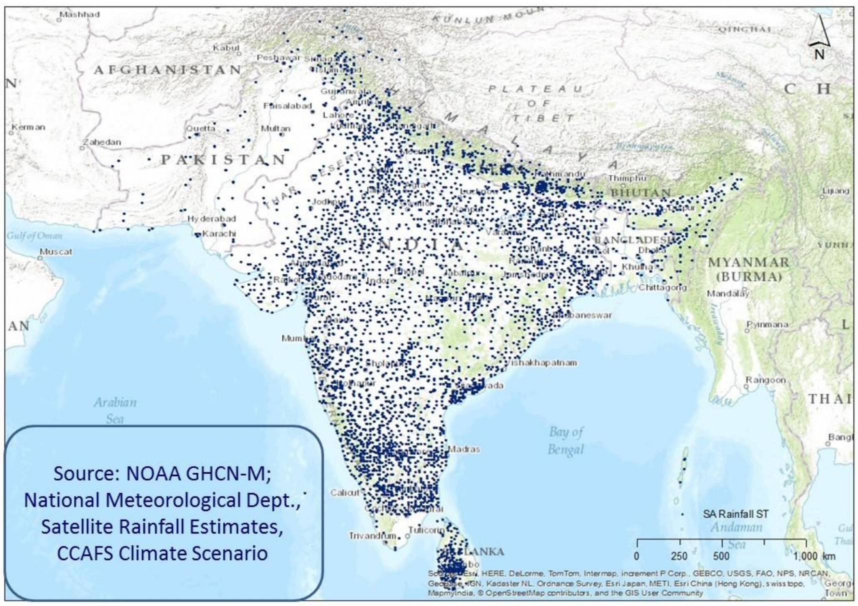


Figure 7: Spatial distribution of rainfall stations from various global sources for tis use in Standardized Precipitation Index (SPI)

The SPI, developed by McKee et al. (1993, 1995) is only based on precipitation data. The index has an advantage of being easily calculated, having modest data requirements, and being independent of the magnitude of mean precipitation and hence it is comparable over a range of climatic zones. It is calculated by fitting historical precipitation data to a Gamma probability distribution function for a specific time period and location, and transforming the Gamma distribution to a normal distribution with a mean of zero and standard deviation of one. One of the significant advantages of the SPI is that it can be calculated for different timescales to monitor meteorological droughts with respect to severity, duration, onset, extent and end. A time series SPI dataset of more than 200 weather stations during 1950 - 2013 was calculated using in situ daily/monthly total precipitation data for a higher statistical precision and only the SPI during 2000–2010 were used to validate SDI. Since the influence of drought on vegetation having about 3 months lag in sub-humid and semi-arid areas (Udelhoven et al., 2009), a 3-month scale SPI (SP3) was calculated in this study. SP3 reflects medium term moisture conditions and provides a seasonal estimation of precipitation.

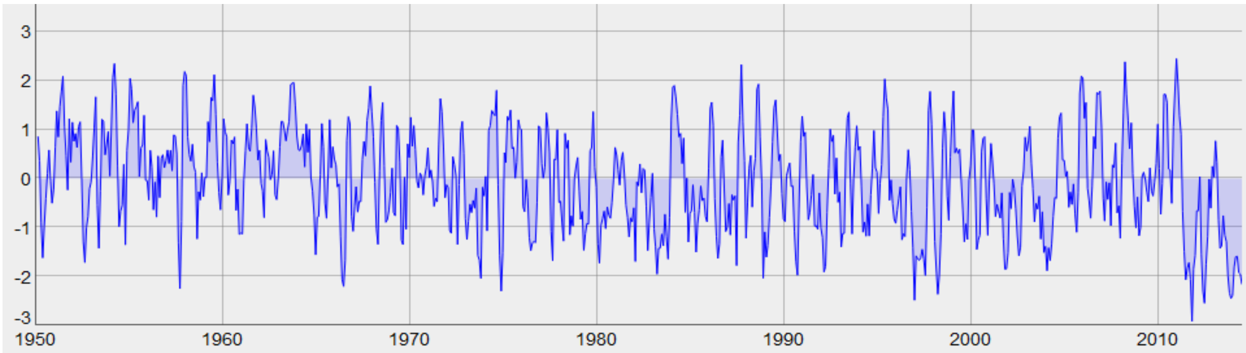


Figure 8: Example of SPI calculation for Kurnnegala district, Sri Lanka

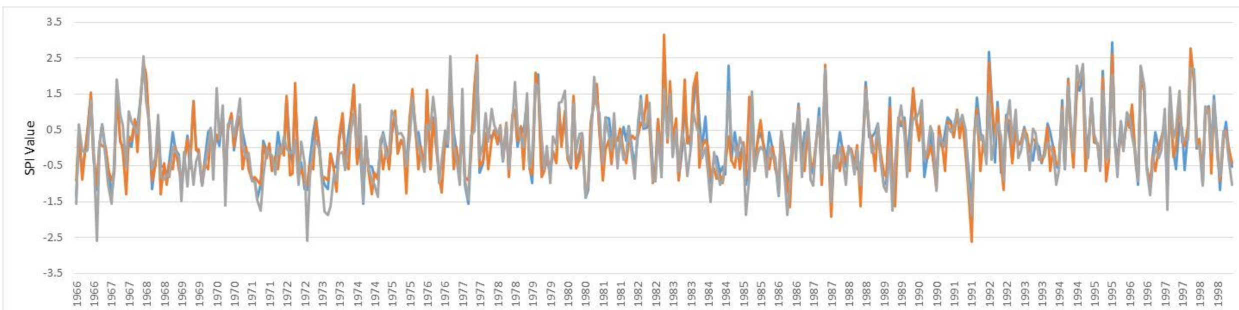


Figure 9: Comparison of SPI derived from in-situ observations and Satellite based rainfall estimates for the Khuzdar, Balochistan province, Pakistan

Comparison of IDSI and SPI Drought Index

For assessing the accuracy of IDSI, a validation experiment was carried out using in situ meteorological drought index. The results showed that IDSI and SPI3 are highly correlated during the crops (Rice and wheat) growing period (Fig. 10) and all of them passed the significant test (p-value < 0.01). This proves that the new drought index, IDSI can monitor meteorological drought favorably and it can reveal the regional climatic drought in space rather than in point.

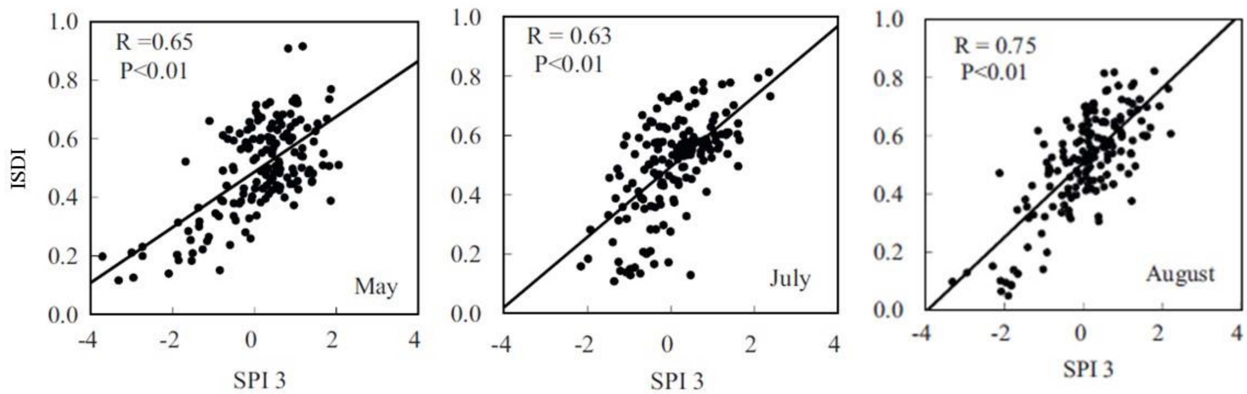


Figure 10: Comparison of IDSI and SPI derived from in-situ observations for the Maharashtra State, India

Comparison of IDSI and Crop yield data

Compared with crop yield variation, the drought affected crop area is more appropriate to validate drought index since it is directly related to drought. Here, the drought affected crop area of Maharashtra State was used to do a correlation analysis with IDSI. The result showed IDSI, like VCI and TCI, has a statistically significant correlation (p-value < 0.01) with drought affected crop area and the correlation coefficient is −0.86, it is only slightly lower than the VCI, although there are only small number of samples (11 years) (Table 2). VCI is an important index that can be used to evaluate the influence of drought on agriculture and be widely accepted in regional (Kogan et al., 2005). This validation was proved that IDSI still keeps the function of vegetation drought monitoring of VCI and can be used to monitor agricultural drought.

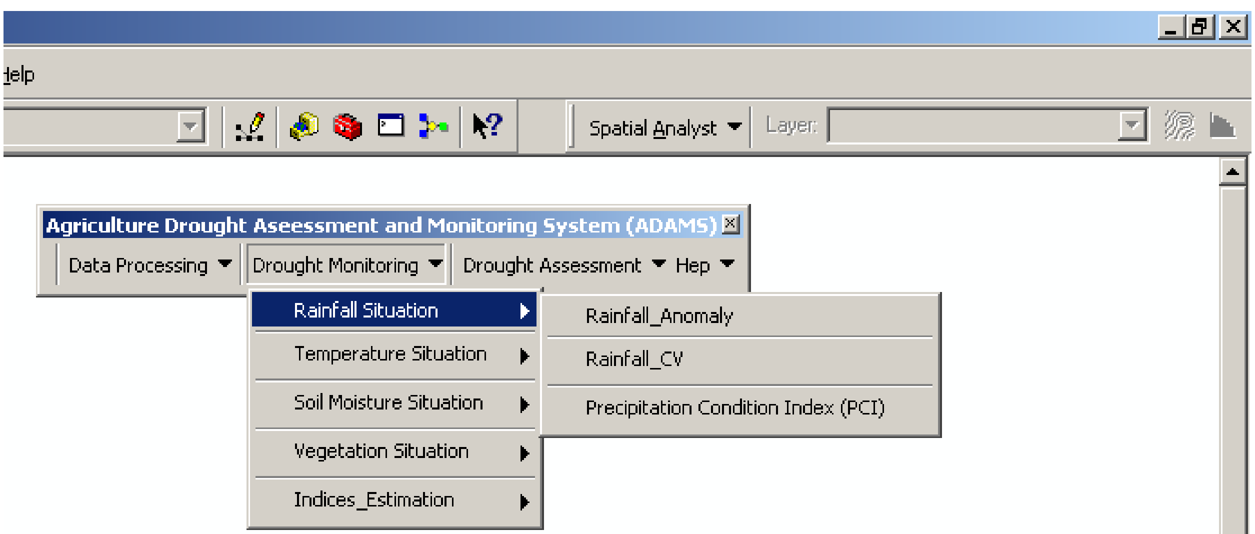
Table 2: Correlation of crop yield data with the IDSI products for major drought years in Maharashtra State, India

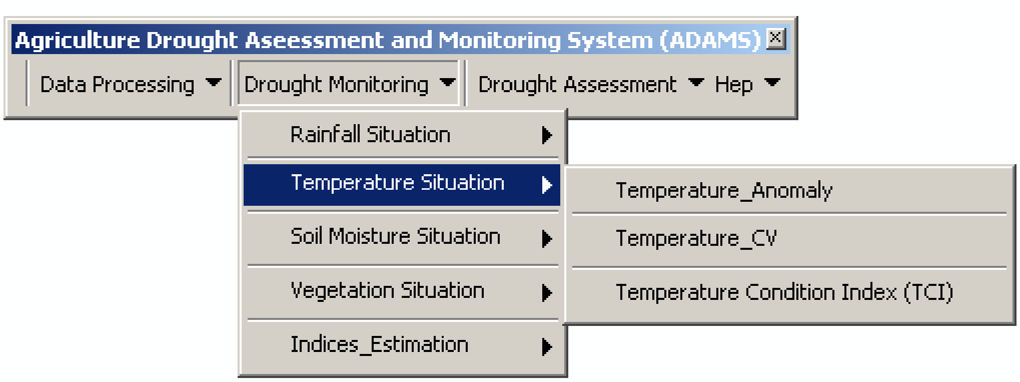
MAHARASHTRA (INDIA)					
BEED		**Integrated Drought Severity Index**			
Year	**Production Tonnes**	Severe	Moderate	Abnormally Dry	Healthy
1998	1400				
1999	1700				
2000	2000			3	8
2001	1500				
2002	600				
2003	1000				

2004	600	7	3	1	
2005	900				
2006	1500				
2007	7	9	2		
2008	400	8	2	1	
2009	200	5	3	2	1
2010	300				

8. IDSI product implemented using DMS tool

DMS is being developed using Visual Basic .NET programing language and ArcObjects 10.x. DMS requires ArcGIS 10.x with the spatial analysis extension, and the NET framework to work properly, with minimum hardware requirements of a Pentium 4.2.2 Ghz processor and 2 GB RAM. The installation is simple and straight forward. The DMS Main menu allows one to choose four options (Figure 11). This contain Pre-processing of satellite images, Drought Monitoring, Drought Assessment and Help menu.





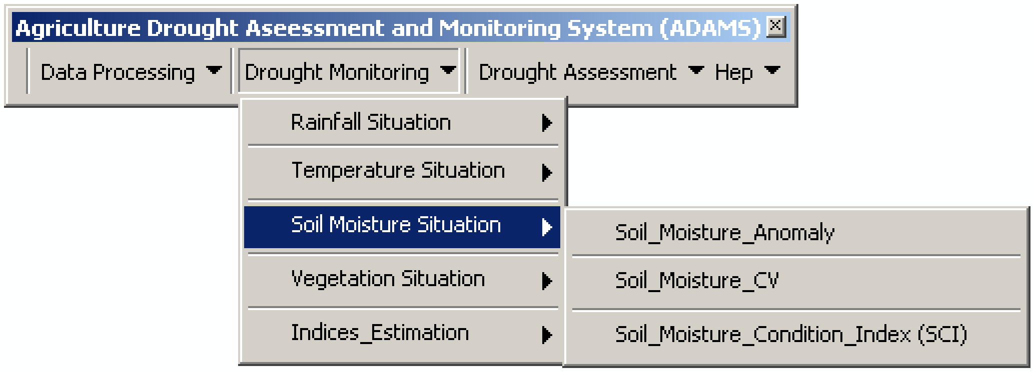


Figure 11: Snapshot of drought monitoring system tool using ArcGIS platform

9. Reconnaissance survey for the 2014 droughts in Sri Lanka and India

With the beginning of the drought project, 2 major field study was carried out in drought affected areas in Maharashtra (India) and Kurunegala and Polonnaruwa districts in Sri Lanka. The main objectives is to assess the accuracy of the drought severity products and aspect to drought watch category e.g. extreme and moderate levels. In addition the project had consultative discussion with various decision makers in the field of agriculture, irrigation and water resource authorities to promote the new drought monitoring information in terms of new knowledge and information and operational platform that can be used in decision making process and mitigate the extreme drought situation in South Asia.

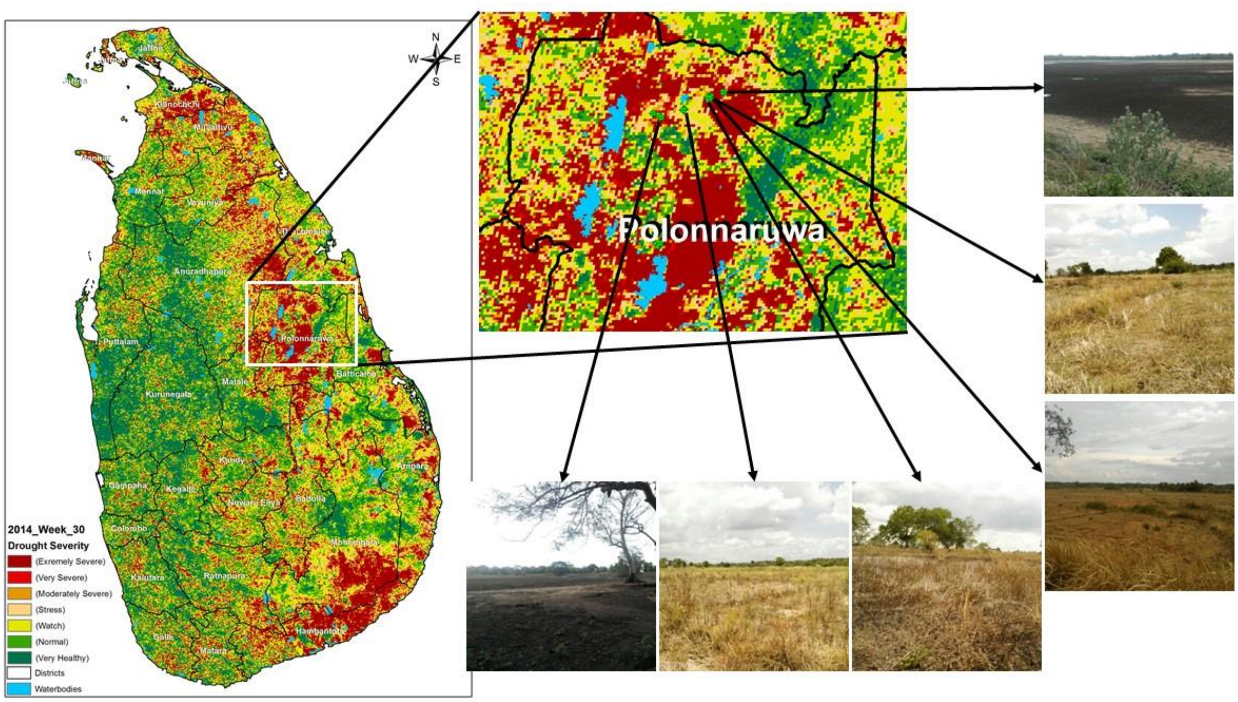


Figure 12: 2014 Drought product evaluation for Polonnaruwa district in Sri Lanka. Green points in the image box are the locations were field survey was carried out and interpretation of drought product was analyzed to improve the modeling performance.

We developed reconnaissance survey and discussed with key informants and farmers unions to identify major issues during the drought event and identify areas of prioritizations including early warning information as drought progression, crop management practices and efficient ways to quantify the impact for compensation and relief process. 2014 Drought product evaluation for districts in Sri Lanka, sample questionnaire and field photos can be referred from figure 12-18.

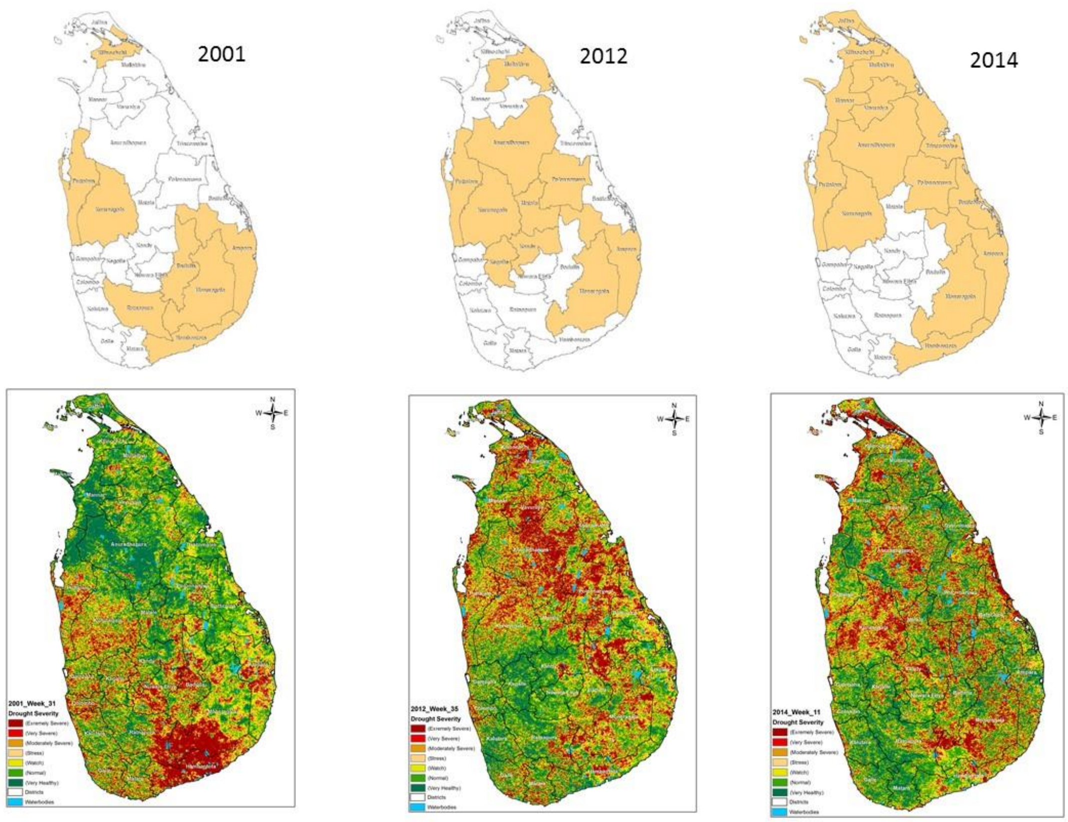


Figure 13: Comparison of Drought assessment at field level from Disaster Management Centre (DMC), Sri Lanka and IDSI product

An assessment of the response to the 2014 drought in Kurunagala (Sri Lanka)

The questionnaires for reconnaissance survey in selected drought affected districts of Kurunagala. Below are the checklists and questionnaires that will be used to collect the information while visiting various farmers/stakeholders at district level.

Respondent: Mr. W Ariyaratne

GENERAL INFORMATION:

Site Specific Details			
District	Kurunagala		
G S Division	48 Jayabima		
Village Name	Track 6		
Latitude / Longitude / Elevation	7.493088	80.320102	353ft
Major crops	Paddy & Cash Crops		
Soil type			
Note: Take picture in High resolution quality and tag the Photo ID No	12		

Drought Information

1. Ask the community/Stakeholders to explain the current drought situation and its impact?	In this "Yala Season", rain started on 10 April and lasted for 20 days until 10 May. But generally rain in "Yala Season" starts on 15 March & last until April end. Therefore, due to drought, there were not much fields cultivated in this "mass kanna". Farmer thinks this unusual weather pattern is due to climate change.
2. a) How and when do you notice the drought progress in your farm field? (example month, particular week). b) Do you also get any climate information services from agencies?	a) Delayed rain setting is an indication of less rain in this season. In addition to that, there are indigenous concepts of predicting the drought by examining the fruiting pattern of some trees in the area. b) [1]Business Committee meets every month and weather data are shared by officials with farmers.

[1] BC is a statutory committee comprises of Farmer Leaders, officials from Agriculture Department, Govi Jana Seva & Irrigation Department and exchange technical details & take decision on releasing water to farm lands.

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Figure 14: Reconnaissance survey form prepared for discussion with key informants and discussion with farmers

Figure 15: Irrigation canal that is completely dried in Kurnnegala district in Sri Lanka

Figure 16: Paddy crop that is completely affected during the 2014 drought in Kurnnegala district in Sri Lanka

Figure 17: Groundnut and other crops impacted due to lack of water supply in Osmanabad District, Maharashtra State, India

Figure 18: Grape fields affected by drought in Osmanabad District, Maharashtra State, India

10. Conclusions

(1) The project has successfully developed drought monitoring algorithm using multisource remote sensing data covering South Asia. Primary data source MODIS Terra and Aqua was used to calculate VCI, TCI and precipitation for PCI and soil moisture for SCI index. The principal component integrates VCI, TCI and PCI to define integrated drought severity index (IDSI) that can monitor the onset, duration, extent and severity of drought. The IDSI synthesizes the precipitation deficits, soil thermal

stress and vegetation growth status in drought process and it is favorable to monitor the comprehensive drought. As an example, the historical drought from 2000 to 2014 was monitored by this method to test the product performance in selected sites including Sri Lanka, Southern Indian states and its results was consistent with actuality of drought occurred in past decades.

(2) For validating the accuracy of IDSI, a 3-month scales standardized precipitation index, SPI3 was calculated from precipitation data of meteorological stations, the variation of crop yield which was standardized from the annual crop yield of each prefecture city and the drought affected crop area of whole Maharashtra State was used to do correlation analysis with IDSI. The IDSI is not only well correlated with SPI3, but also has a correlation with the crop yield variation and the drought affected crop area. This result proves that the new drought monitoring method integrating multi-source remote sensing data is a comprehensive drought monitoring indicator, and it could not only contain the meteorological drought information but it can reflect the drought influence on agriculture as well.

(3) The extension of Phase-II activities of this project includes seamless drought monitoring product for complete South Asia, finalizing the DMS tool that uses ArcGIS interface, close coordination with national partners in evaluation of drought product, drought product dissemination in web interface and finally provide capacity development to relevant stakeholders on the use of remote sensing data for drought monitoring.

Acknowledgement

This research was funded by the Global Water Partnership (GWP) and World Meteorological Organization (WMO) as part of the *Integrated Drought Management Programme (IDMP)*, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) and the International Water Management Institute (IWMI). We would like to thank various agencies including Indian Meteorological Agency (IMD), Departments of Meteorology, Irrigation Department, Agrarian in Sri Lanka, Disaster Management Centre (DMC) of Sri Lanka for data sharing and their inspiring guidance and encouragement.

11. References

Kogan, F.N., Yang, B., Wei, G., Zhiyuan, P., Xianfeng, J., 2005. Modelling corn production in China using AVHRR-based vegetation health indices. International Journal of Remote Sensing 26 (11), 2325–2336.

Kogan, F.N., 1995a. Application of vegetation index and brightness temperature for drought detection. Advances in Space Research 15 (11), 91–100.

Kogan, F.N., 1995b. Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. Bulletin of the American Meteorological Society 76 (5), 655–668.

Kogan, F.N., 1997. Global drought watch from space. Bulletin of the American Meteorological Society 78 (4), 621–636.

Vicente-Serrano, S.M., 2007. Evaluating the impact of drought using remote sensing in a Mediterranean, semi-arid region. Natural Hazards 40 (1), 173–208.

Karnieli, A., Bayasgalan, M., Bayarjargal, Y., Agam, N., Khudulmur, S., Tucker, C.J., 2006. Comments on the use of the vegetation health index over Mongolia. International Journal of Remote Sensing 27 (10),

Lasaponara, R., 2006. On the use of principal component analysis (PCA) for evaluating interannual vegetation anomalies from SPOT/VEGETATION NDVI temporal series. Ecological Modelling 194 (4), 429‑434.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. In: Proceedings of Eighth Conference on Applied Climatology, Anaheim, CA. American Meteorological Society, Boston, MA, pp.179‑184.

Salazar, L., Kogan, F., Roytman, L., 2007. Use of remote sensing data for estimation of winter wheat yield in the United States. International Journal of Remote Sensing 28 (17), 3795‑3811.

Salazar, L., Kogan, F., Roytman, L., 2008. Using vegetation health indices and partial least squares method for estimation of corn yield. International Journal of Remote Sensing 29 (1), 175‑189.

Singh, R.P., Roy, S., Kogan, F., 2003. Vegetation and temperature condition indices from NOAA AVHRR data for drought monitoring over India. International Journal of Remote Sensing 24 (22), 4393‑4402.

Disclaimer: The technical report on the South Asia Drought Monitoring System mainly uses multisource remote sensing data with limited field observations. This is currently being improved with more validation and stakeholder's discussion for finalization of drought product.