Environ Monit Assess (2015) 187:4155
DOI 10.1007/s10661-014-4155-1

Temporal change in land use by irrigation source in Tamil Nadu and management implications

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Received: 20 February 2014 / Accepted: 10 November 2014

Abstract Interannual variation in rainfall throughout Tamil Nadu has been causing frequent and noticeable land use changes despite the rapid development in groundwater irrigation. Identifying periodically water-stressed areas is the first and crucial step to minimizing negative effects on crop production. Such analysis must be conducted at the basin level as it is an independent water accounting unit. This paper investigates the temporal variation in irrigated area between 2000–2001 and 2010–2011 due to rainfall variation at the state and sub-basin level by mapping and classifying Moderate Resolution Imaging Spectroradiometer (MODIS) 8-day composite satellite imagery using spectral matching techniques. A land use/land cover map was drawn with an overall classification accuracy of 87.2 %. Area estimates between the MODIS-derived net irrigated area and district-level statistics (2000–2001 to 2007–2008) were in 95 % agreement. A significant decrease in irrigated area (30–40 %) was observed during the water-stressed years of 2002–2003, 2003–2004, and 2009–2010. Major land use changes occurred three times during 2000 to 2010. This study demonstrates how remote sensing can identify areas that are prone to repeated land use changes and pin-point key target areas for the promotion of drought-tolerant varieties, alternative water management practices, and new cropping patterns to ensure sustainable agriculture for food security and livelihoods.

Description The spatial distribution of temporal irrigated agricultural area was derived at high accuracy from MODIS time series data using a combination of methods consisting of spectral matching techniques and intensive field plot information. Results contribute to spatial information about temporal changes in irrigated areas where regulation of water use and remediation measures should be taken up. This may result in suggesting new cropping pattern and alternative water management practices from field level to sub-basin level.

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Keywords Land use change · Irrigated areas · Tamil Nadu · MODIS · Spectral matching techniques · NDVI

Introduction, rationale, and background

Many people, especially those living in rural areas, depend on agriculture for their food and livelihood (OECD 2006). Also, fluctuation in food supply can impact prices and food security. The land used for

Published online: 07 December 2014

agriculture is vulnerable to changes in management practices, cropping system, climatic pattern, and irrigation facilities (FAO 2007). All of these directly affect the people and natural resources; therefore, effective land use monitoring and planning are crucial (Gumma et al. 2011a). In Tamil Nadu, a state located in the southernmost part of India and one of the biggest local producers of rice, it has been observed that some agricultural areas change from year to year because of interannual variability in rainfall. One study demonstrated that net agricultural sown area declined by 17.3 % between 2000 and 2007, resulting in a 19.1 % decrease in food production (Palanisami et al. 2011).

It is important for the achievement of a sustainable agricultural system to monitor cropland changes, and, when such analyses focus on the impacts of rainfall variability, this must be done at the river basin level (Gumma et al. 2011c). This is because the basin is an independent water accounting unit integrating the effect of rainfall over the basin. For example, water demand exceeds actual water supply in many river basins, which is the main cause of cropping pattern changes even for those in command areas under irrigation facilities (Biggs et al. 2010). Cultivable command areas (CCA) or command areas (CA) are the areas which can be irrigated from an irrigation scheme (project) and is fit for cultivation (MOWR 2006). In most Indian irrigation schemes, the release of irrigation water is scheduled for the middle of the cropping season. Rice nurseries for transplanting are sustained prior to this by supplementary irrigation. This means that crops will initially depend on rainfall and then on surface water at the basin level. In line with the emerging attempts on basin- or command-area-level analysis in other countries and regions, we conducted basin-level analysis to monitor crop land changes in Tamil Nadu, Southern India. Mapping irrigated area is an important component of basin characterization to determine a basin's performance and to support planning and hydrological modeling (Biggs et al. 2006). It is important to map command area size, including canal-irrigated area, groundwater-irrigated area, and area irrigated by small reservoirs (Droogers and Allen 2002). The performance of command areas is estimated by using various criteria, such as agricultural productivity, reliability of water supply, and distribution (Bastiaanssen et al. 1999; Bhutta and Van der Velde 1992; Gaur et al. 2008).

Various studies have been conducted on land use change. The main purpose of irrigated agricultural land use change analysis is for monitoring changes in cropping pattern (Singh 1989). Agricultural statistics (e.g., area extent) are heavily relied upon in such studies. However, apart from being reported at administrative unit, typically at the district and state level, there are discrepancies between the statistics reported by agricultural census agencies and irrigation departments. Changes in land use in such large units are insufficient to fully understand its effect on the river basin. On the other hand, satellite imagery can give detailed maps of land use and identify where cropping patterns change significantly in response to variations in rainfall (Badhwar 1984; Thiruvengadachari and Sakthivadivel 1997). Satellite imagery has been used to quantify water use and productivity in irrigation systems (Thiruvengadachari and Sakthivadivel 1997) but has less frequently been used to identify how irrigated area changes in command areas in response to variations in rainfall and water supply. Data from time series of the normalized difference vegetation index (NDVI) have been used for mapping land use changes (Gumma et al. 2011a), and accuracy was 78 %, and they can be used to map irrigated areas, with accuracy of 77 % (Biggs et al. 2006; Thenkabail et al. 2009). Time series data have also been used for detecting changes in irrigated areas in major river basins (Bhutta and Van der Velde 1992; Bastiaanssen et al. 1999; Gaur et al. 2008)

Given the above background, this paper maps the land use changes in major river basins of Tamil Nadu by source of irrigation and identifies water deficit in association with rainfall variations between 2000–2001 and 2010–2011 (agriculture years start from June to May) using NDVI time series data from Moderate Resolution Imaging Spectroradiometer (MODIS) imagery. We estimate the area under each land use for each year and the changes in irrigated cropland area. Both land use and land use change estimates are compared against field data or "ground survey data" and secondary sources such as published statistics on irrigated area. Finally, we identified areas where periodic changes occurred for targeting of new technologies.

The study area

Tamil Nadu is located in the southern part of India, ranging from 76° 13′ 33″ to 80° 20′ 46″ E and 08° 08′ 39″ to 13° 32′ 15″ N (Fig. 1), with a total geographic area of 13 million hectares and population of approximately 62.4 million (Palanisami et al. 2011). Rainfall in Tamil Nadu is dependent on monsoons and low pressure formations in the Bay of Bengal. The mean annual

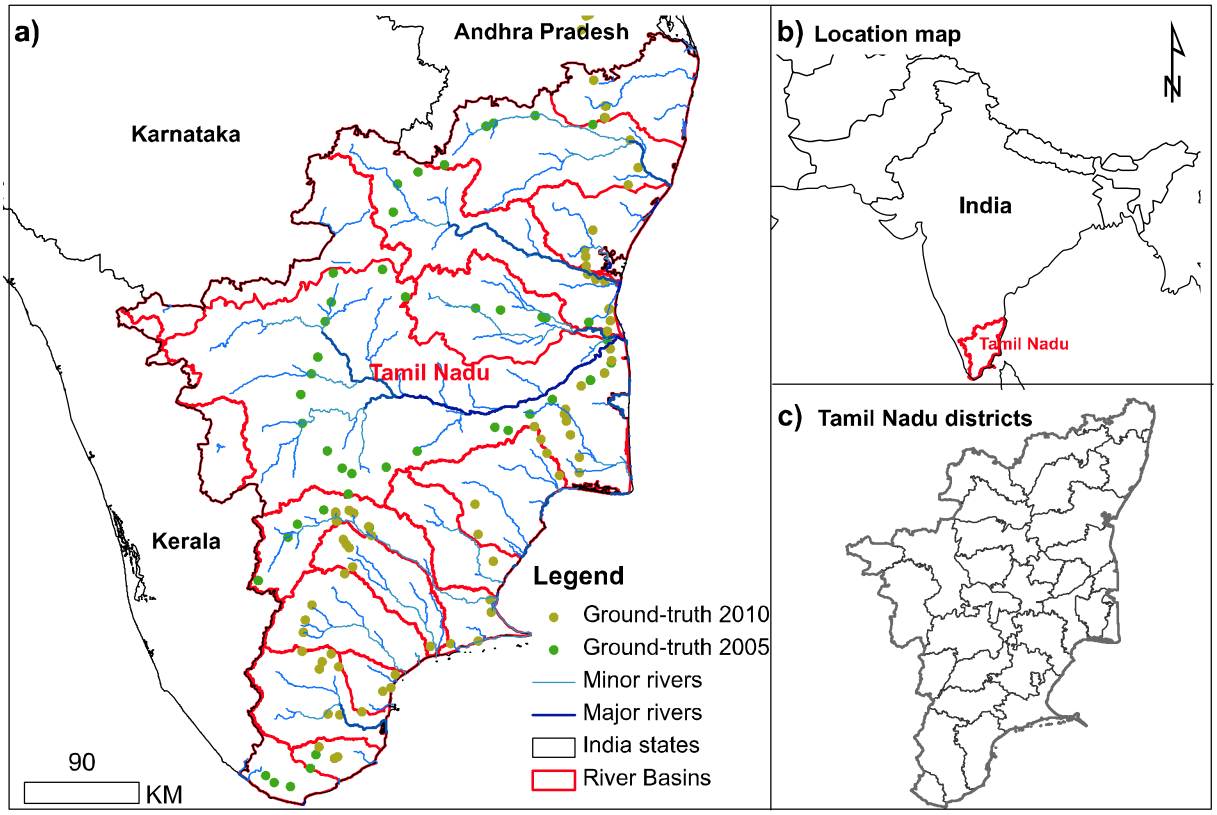

Fig. 1 Study area: **a** map of Tamil Nadu showing major river basins with field plot data, **b** location of the study area in India, and **c** study area showing lowest administrative boundaries. River network delineated from SRTM DEM

rainfall is 945 mm out of which 48 % is contributed by the Northeast Monsoon (October to December) and 32 % by the Southwest Monsoon (June to September). Failure of monsoon leads to water scarcity and drought as it is the main source of recharge of water sources (Indira et al. 2013). The study area contains various physiographic features and consists of 17 river basins (Table 1); for a majority of which the demand exceeds supply for both groundwater and surface water (Palanisami et al. 2011). Therefore, mitigation and remediation of drought is a primary priority of the state agriculture machinery.

Total agricultural land in the state was 13 million hectares according to 2007–2008 agricultural statistics (GTDES 2011), and the major food crops are rice, millets, and pulses. Commercial crops include sugarcane, cotton, sunflower, coconut, cashew, chillies, gingelly, and groundnut. Plantation crops are tea, coffee, cardamom, and rubber. Major forest products are timber, sandalwood, pulp wood, and fuel wood. Annual food grain production in 2005–2006 was 6.1 million tons (GTDES 2011).

Data

Satellite data

MODIS 500-m resolution with 8-day surface reflectance from the Terra platform (MOD09A1) is ideal for monitoring vegetation at a continental scale (Thenkabail et al. 2005). MODIS measures surface reflectance in seven bands with wavelengths that are designed for the study of vegetation and land surfaces: blue (459–479 nm), green (545–565 nm), red (620–670 nm), near-infrared (NIR1, 841–875 nm; NIR2, 1230–1250 nm), and shortwave infrared (SWIR1, 1628–1652 nm; SWIR2, 2105–2155 nm). Each pixel in the MODIS dataset contains the best observation during the 8-day period that it covers (further details are in the Scientific Data Set documentation for MOD09A1 (Thenkabail et al. 2005)). NDVI is a combination of red and NIR bands (Rouse et al. 1973; Tucker 1979) and is extensively used to differentiate vegetation conditions, including vigor and density (Teillet et al. 1997). NDVI values vary from −1 to +1, and high NDVI values indicate high vegetation vigor and vice versa.

Table 1 Characteristics of the major river basins of the study area (average of 30 years, from 1976 to 2005)

Basin ID	Name of basin	Catchment area (ha)	Average annual rainfall (mm)	Number of tanks	Average tank- and canal-irrigated area (ha)
1	Chennai Basin	558,385	1130	1304	133,033
2	Palar River Basin	1,067,737	940	661	202,507
3	Varahanadhi River Basin	469,630	1250	131	80,755
4	Ponnaiyaar River Basin	1,217,599	920	1133	161,364
5	Paravanar River Basin	76,000	NA	2	130,095
6	Vellar Basin	727,472	980	386	742,220
7	Cauvery River Basin	4,709,572	930	NA	120,042
8	Agniyar River Basin	638,190	910	346	110,143
9	Pambar & Kottakaraiyar	417,625	880	160	117,251
10	Vaigai River Basin	775,164	900	521	92,306
11	Gundar River Basin	419,091	770	526	77,505
12	Vaippar Basin	606,359	800	151	16,319
13	Kallar River Basin	146,385	600	15	74,035
14	Thambaraparani River Basin	576,010	1110	NA	25,108
15	Nambiyar River Basin	153,800	950	559	24,681
16	Kodaiyar River Basin	212,790	1720	2	48,208
17	P.A.P. Basin	320,285	610	NA	12,770

Source: http://planningcommission.nic.in/reports/sereport/ser/ser_river1905.pdf

Ground survey data

Field-level surveys were conducted between August 30 and September 28, 2005, across 52 locations, and on September 15–25, 2010, across 80 locations covering the major cropland areas in Tamil Nadu. All location-specific data were collected from 500 to 500 m plots and consisted of GPS locations, land use categories, land cover percentages, cropping pattern during different seasons (through farmer interviews), crop types, and watering method (irrigated, rainfed). Samples were obtained within large contiguous areas of a particular land use/land cover (LULC). The locations were chosen based on the knowledge of local agricultural extension officers to ensure that the same crops were grown during 2000–2001 as were observed during the survey. Local experts also provided information on crop calendars, cropping intensity (single or double crop), irrigation application, and percentage canopy cover for these locations from their recorded data for the previous years. Overall, 132 spatially well-distributed data points (Fig. 1) were collected; of these, 53 data points were used for identification and labeling class names and an additional 80 data points were used for accuracy assessment.

Secondary datasets

The following secondary datasets were also used in the study:

1. SRTM 90-m elevation

Space Shuttle Radar Topography Mission (SRTM) DEM data on a global scale at 90-m horizontal resolution are gap-filled and made available through the Consortium for Spatial Information (CSI) web portal (http://srtm.csi.cgiar.org/). The SRTM DEM data were used to derive slope, stream networks, and catchment boundaries in a geographic information systems (GIS) software ArcGIS v 10.0. The SRTM data were also used to perform image segmentation based on elevation ranges.

2. River basins and their basin-wise irrigated area

The study area consists of 17 river basins. There are 61 major reservoirs, about 40,000 tanks, and about three million wells that heavily use the available surface water (17.5 Billion cubic meters (BCM)). Groundwater irrigation (15.3 BCM) is as important as surface irrigation (EISC 2011; Palanisami et al. 2011). Table 1 summarizes irrigation status by basin, as a mean of 30 years, from 1976 to 2005, and rainfall data covered a 43-year period, from 1961 to 2003 (Palanisami et al. 2011).

3. District-wise census data for irrigated areas

Irrigated area statistics were obtained at the sub-national level (district) and represent the net irrigated cropland area. Irrigated area statistics were supplied by the Department of Economics and Statistics, Government of Tamil Nadu.

Daily rainfall data were downloaded from Hydromet Division, India Meteorological Department (IMD), for 2000 to 2010 (Table 2) (http://imd.gov.in). Even though data was available over the years and analyzed for all seasons (*kharif*/*rabi*/*summer*) this paper presents results for kharif season only, which is also the main agricultural season of the state.

Methods

The methodology for the identification of land use changes and targeting of new technologies is shown in Fig. 2 and is described in the following sections.

Remote sensing methodology for historical irrigated area mapping

Temporal MODIS (MOD09A1) data was used to map irrigated areas from 2000 to 2010 (Gumma et al. 2011a; Thenkabail et al. 2005). The process begins with downloading of 8-day composites of MOD09A1 with 500-m resolution and then stacking them into a single dataset for crop years: June 2000 to May 2001 (46 images), June 2001 to May 2002 (46 images), June 2002 to May 2003 (46 images), June 2003 to May 2004 (46 images), June 2004 to May 2005 (46 images), June 2005 to May 2006 (46 images), June 2006 to May 2007 (46 images), June 2007 to May 2008 (46 images), June 2008 to May 2009 (46 images), June 2009 to May 2010 (46 images), and June 2010 to May 2011 (46 images). The MODIS mega-file was segmented into three distinct zones: one was major irrigation command areas delineated by the Central Board of Irrigation and Power (CBIP 2007) and the other two segments derived from slope. The idea behind the segmentation process was to focus more on the segments having a higher amount of informal and fragmented irrigated classes such as the command areas which include uplands, conjunctive irrigated areas, etc. Such segments would be classified into finer classes of different types (irrigated single crop, irrigated double crop, irrigated-conjunctive use, etc.) using the protocols explained by Thenkabail et al. (2005)). The next step in the process was delineating the slope zones. Slope is also a limiting

Table 2 Normal monthly rainfall, 2000–2010

Month	Normal rainfall per season[a] (mm)	Average rainfall (mm)										
		Year 2000	Year 2001	Year 2002	Year 2003	Year 2004	Year 2005	Year 2006	Year 2007	Year 2008	Year 2009	Year 2010
May	317.6 (monsoon)	98.1	110.9	106	34	234	70	59	41	48	57	108
June		256.4	238.9	151	166	42	27	51	62	47	33	79
July		183.7	230.5	86	172	60	76	124	78	72	58	90
August		269.9	165.7	130	131	34	79	167	135	125	93	119
September		163.5	177.1	56	51	211	108	114	78	66	110	121
October	438.2 (post-monsoon)	157.4	224.8	104	159	262	278	271	224	243	61	160
November		99.1	102.7	18	53	173	364	211	81	298	0	330
December		60.9	46.9	11	11	15	162	27	216	53	0	146
Total	796.3	1289	1298	663	779	1031	1165	1024	916	952	412	1152

Source:http://imd.gov.in/section/hydro/distrainfall/districtrain.html, accessed 25 Feb 2011

[a] Normal rainfall (mm) represents the long period (1951–2000) averages of rainfall for Tamil Nadu

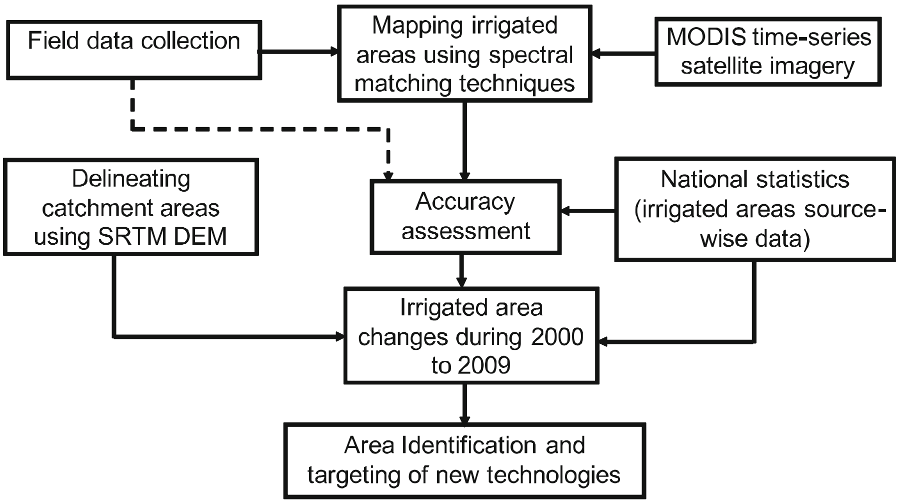

Fig. 2 Overview of the methodology for estimating irrigated area and cropping pattern in command areas

factor in crop cultivation, even though upland agriculture operates on more than 15 % slopes. Series of thresholds were used to classify the terrain into flood plains and lower valley slopes with ≤2 % gradient as one segment and >2 % gradient as another segment. Such segmentation allows for easier class spectrum separation and the identification of upland rainfed agriculture areas (informal irrigated areas) other than command areas and deltas having low and high elevated areas with forest vegetation.

Each year's dataset was classified using unsupervised ISOCLASS cluster *k*-means. At the regional scale, when the NDVI signatures of all potential classes are not known, unsupervised classification captures the range of phenological variability. The classification was performed by setting a maximum of 100 iterations and convergence threshold of 0.99. In all, 100 classes were obtained for each individual year. Class identification and labeling were based on NDVI time series plots, ground survey data, and very high resolution images (Google Earth). The grouping of class spectra was accomplished based on individual class spectral signatures acquired during ground survey; additionally, rigorous protocols were employed to identify and label classes using large volumes of ground survey data and very high resolution imagery. The misclassified classes were identified and reclassified by integrating elevation and rainfall data using GIS techniques in conjunction with other methods used for irrigated area calculations and accuracy assessments (Gumma et al. 2011b).

The classes generated from the unsupervised classification were aggregated into ten classes and named based on spectral similarity with magnitude/direction of vegetation index, intensive field plot information, and Google Earth imagery. Spectral matching techniques (SMTs) were used to relate the classes for all the years. These processes are described in detail by Gumma et al. (2011b) and Thenkabail et al. (2007). It is important to note that, because of the coarse spatial resolution of MODIS (each pixel is 500 m on each side and larger than many agricultural fields in the study area), many pixels can have overlapping land cover types. Each pixel covers an area of 21.5 ha, which is larger than typical farm of small holder farmers and different land use classes. To overcome this issue, an area fraction that was determined is used to estimate the area under corresponding land cover type as explained by Thenkabail et al. (2007) and Thenkabail et al. (2005). The irrigated area fractions were determined using intensive ground survey data, and area fraction varies interannually. Cropped fractions are assumed as irrigated fraction in irrigated classes (Biggs et al. 2006; Gumma et al. 2011b; Thenkabail et al. 2005).

Class naming was given based on a standardized hierarchical classification scheme (Thenkabail et al. 2009). These classes represent different land use classes at different levels and these can be "cross-walked" (Torbick et al. 2006). The "cross-walk" procedure shows how the classes are aggregated or disaggregated. In this way, an aggregated class can be tracked to determine which disaggregated classes were combined to form it or vice versa. The irrigated area fractions obtained from coarse-resolution imagery were estimated at the sub-pixel level by multiplying full-pixel area by cropped area fraction as discussed by Gumma et al. (2011a, b) and Thenkabail et al. 2007). Sub-pixel LULC areas for each class were computed based on ground survey data. Ground survey data includes observing a 500 m × 500-m area that surrounds the observation point under different LULC and noting down the % area of a class in the irrigated pixel. The sub-pixel % is also added up while estimating the area under that class. Area estimation of various land use and land cover types is done by multiplying the full-pixel area of the class by the crop fraction (%) of the class, and the results are reported in Table 3. Furthermore, the accuracy assessment of irrigated areas was based on the standard method employed by Biggs et al. (2006), Gumma et al. (2011b), and Thenkabail et al. (2005).

Identifying changes in irrigated area using NDVI, spectral matching techniques

The change in irrigated area is said to have occurred when the NDVI value of a irrigated pixel in any year is less than the NDVI value of that pixel which is the maximum observed during one of the years out of all the years. The maximum NDVI was observed in 2000–2001. This change in irrigated area when the irrigated class for a year was identified as "any other class" during another year, using spectral matching techniques (Gumma et al. 2011a, b, c; Thenkabail et al. 2007). The change was identified by taking into consideration the duration, magnitude, and peak of NDVI curve. A higher value of NDVI has been noticed during the kharif season (with the peak of NDVI observed during October/November) when compared with the rabi season. In Tamil Nadu, the highest value of maximum mean NDVI was 0.75 during the kharif season, but the value of NDVI was never above 0.4 in any of the months during years with land use change.

Assessment using ground survey data

Accuracy assessment was performed based on two approaches: (a) correlation between national statistics and MODIS-derived irrigated area and (b) MODIS-derived irrigated area evaluated with ground survey information. Accuracy assessment was performed against field plot data. Qualitative accuracy assessment was performed to check whether the irrigated area (by source) was classified as irrigated or not, without checking for crop type or duration of irrigation. The accuracy assessment was performed using ground survey data to derive robust understanding of the accuracies of the datasets used in this study.

The assessment determines the probability that the class assigned to a given pixel matches the class as determined by ground-level data at the same location. The ground survey data were based on an extensive field campaign conducted throughout the study area during the kharif season of 2010–2011. Accuracy assessment provides realistic class accuracies where land cover is heterogeneous and pixel sizes exceed the size of

Table 3 Distribution of agricultural area for each land use providing an understanding of sub-pixel fractions for the ten final classes in Tamil Nadu during a water-surplus year (2010–2011)

Land use/land cover	Full pixel areas (ha)	Fraction of vegetation cover (%)					Crop fraction (CF)	Agricultural area (ha)*
		Sample size	Trees	Shrubs	Grass	Others		
Class 01: Rainfed mixed crops	2,595,669	11	1.5	6.2	2.7	1.6	88.0	2,284,189
Class 02: Irrigated tank mixed crops	610,425	12	2.1	1.9	1.0	10.5	84.5	515,520
Class 03: Irrigated GW mixed crops	1,864,506	18	2.2	5.9	2.7	17.6	71.6	1,334,184
Class 04: Irrigated SW mixed crops	870,450	22	0.5	2.1	1.8	6.1	89.5	779,336
Class 05: Shrublands	445,663	5	16.8	64.9	7.3	2.9	8.1	36,099
Class 06: Barrenlands mix with rangelands	822,363	3	8.1	56.4	28.5	5.5	1.5	11,924
Class 07: Rangelands mix with fallows	3,959,357	8	11.9	21.5	48.7	6.7	11.2	443,448
Class 08: Forests shrublands	1,594,706	4	63.4	27.1	5.3	1.8	2.3	36,678
Class 09: Urban areas	218,275	2	15.1	1.7	0.0	83.2	NA	218,275
Class 10: Water bodies	147,200	5	0.0	0.0	0.0	100.0	NA	147,200

* Cropped fractions are assumed irrigated fraction in irrigated classes

uniform land cover units (Biggs et al. 2006; Congalton and Green 1999; Gumma et al. 2011c; Thenkabail et al. 2005). For this study, we had assigned the 3×3 cells of MODIS pixels around each of the field plot points to one of six categories: absolutely correct (100 % correct), largely correct (75 % or more correct), correct (50 % or more correct), incorrect (50 % or more incorrect), mostly incorrect (75 % or more incorrect), and absolutely incorrect (100 % incorrect). Class areas were tabulated for a 3×3-pixel (9-pixel) window around each field plot point. The fuzzy classification accuracy varied from 82 to 90 % across agriculture classes, with an overall accuracy of 87.2 % (Table 7).

Results and discussion

In this section, we discuss changes in land use and land cover area, temporal irrigated area changes, variations in irrigated area, and accuracy assessment based on ground survey data and comparison between irrigated area from the present study and national statistics. In addition, we identified the areas suffering from periodic changes that happened due to water deficit for identifying stress-prone areas. This study focused on 16 major river basins, because the P.A.P. basin has very small catchments and irrigated areas. The accuracy of the results is explained.

Irrigated area map and area statistics

The 8-day time series NDVI successfully distinguished canal-irrigated, groundwater-irrigated, tank-irrigated, and rainfed agricultural areas, as well as other land cover classes in the study area. Ten classes were identified from MODIS 500-m time series data (Fig. 3) using spectral matching techniques. Almost 6.5 million hectares of agricultural land was labeled as containing some degree of irrigated cultivation based on full-pixel areas (FPAs). However, when irrigated area fractions were used, the actual (sub-pixel) area was 5.8 million hectares for 2000–2001. The final land use class name or label

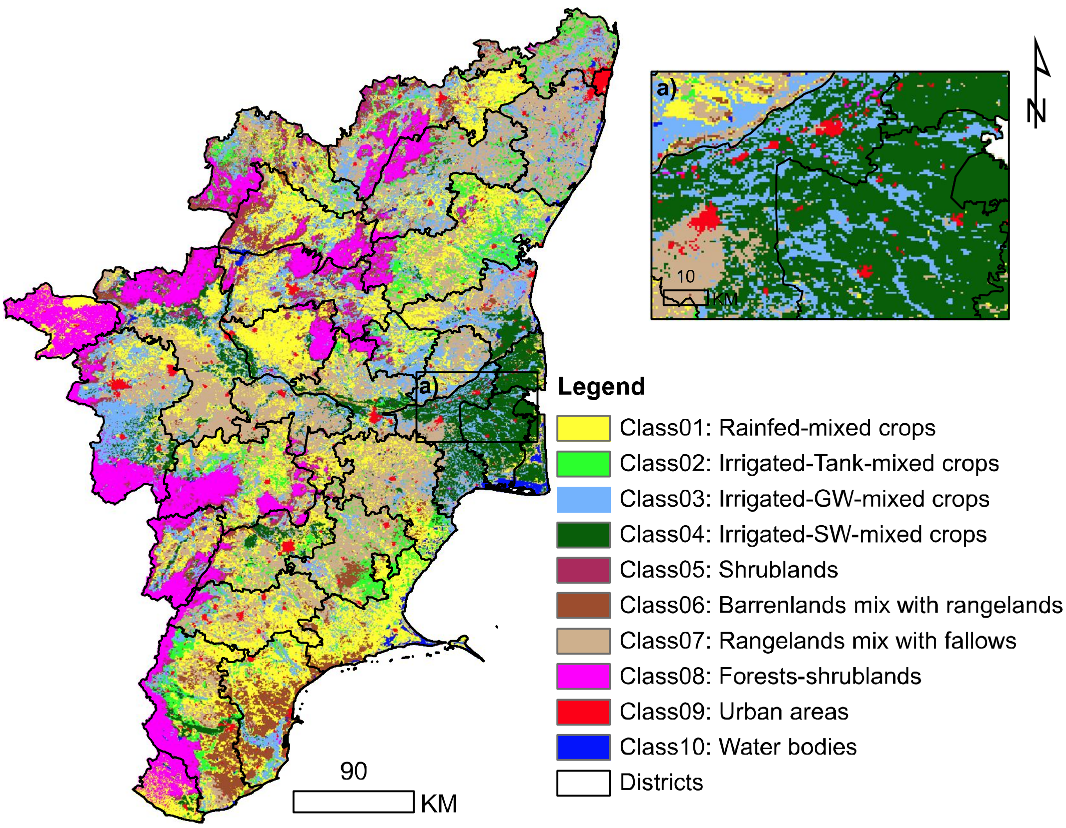

Fig. 3 The final ten agricultural cropland classes and other land use/land cover (LULC) classes for the normal year of 2010–2011

Table 4 Average source-wise net irrigated area and its percent of total study area from 2000 to 2009 in major river basins

River basin	Irrigated area by source (ha)			Irrigated area by source (%)[a]		
	Canal	Tank	GW	Canal	Tank	GW
Chennai	3,895	49,511	59,920	0.5	9.0	4.3
Palar	7,558	58,644	136,142	0.9	10.7	9.7
Varaha	571	71,893	63,239	0.1	13.1	4.5
Ponnaiar	18,306	56,095	186,733	2.3	10.2	13.3
Vellar	23,378	39,964	101,731	2.9	7.3	7.2
Cauvery	597,914	61,988	528,182	74.2	11.3	37.5
Agniar	57,553	30,983	44,054	7.1	5.6	3.1
Pambar	4,229	48,977	16,025	0.5	8.9	1.1
Vaigai	33,662	22,051	65,522	4.2	4.0	4.7
Gundar	10,237	17,482	30,710	1.3	3.2	2.2
Vaippar	1,166	34,130	45,121	0.1	6.2	3.2
Kallar	0	2,855	2,762	0.0	0.5	0.2
Tambrapam	26,119	42,597	36,371	3.2	7.8	2.6
Nambiar	204	8,560	8,254	0.0	1.6	0.6
Kodaiyar	7,068	3,801	4,617	0.9	0.7	0.3
Pollachi	13,410	0	77,942	1.7	0.0	5.5

Sub-pixel areas and irrigated area fractions are shown in Table 3

[a] Irrigated area by source as percent of total irrigated source-wise across all river basins

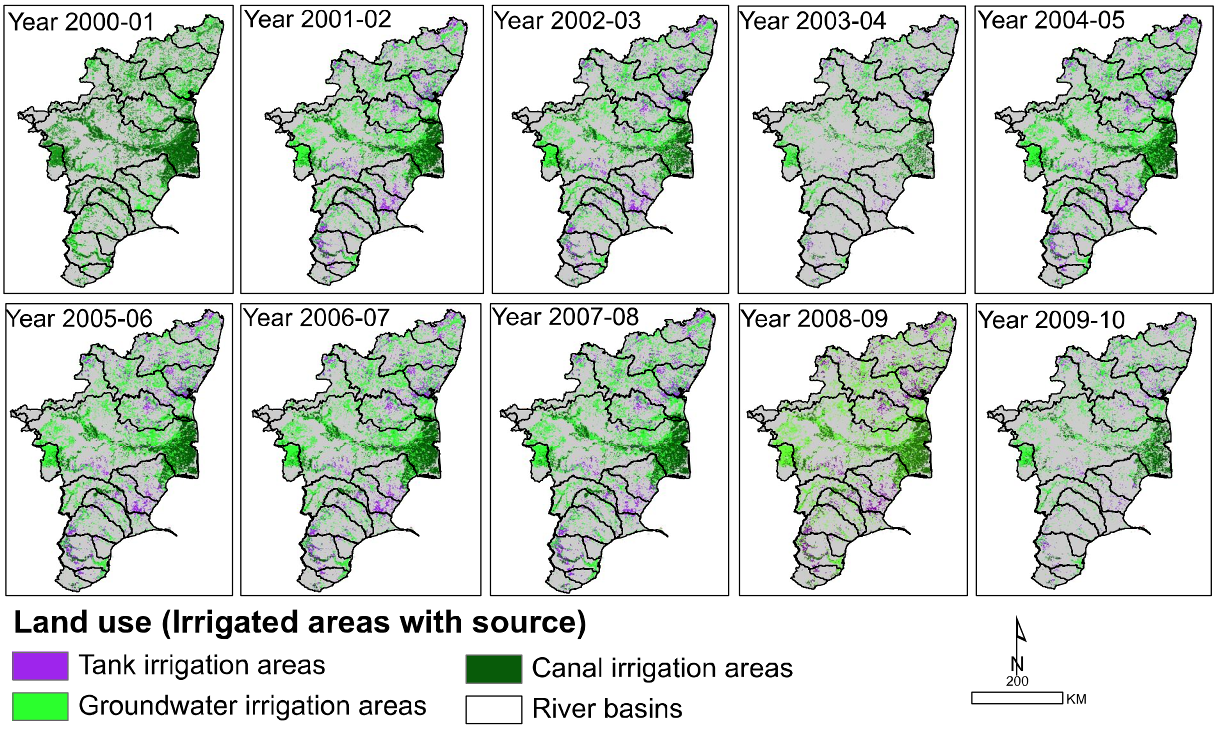

Fig. 4 Agricultural (land use) classification, by source, across Tamil Nadu from 2000–2001 to 2009–2010 with major river basins

Table 5 Irrigated area derived from MODIS time series data and area from national statistics with % difference with 7-year normal irrigated area

Year	Irrigated areas from MODIS 500 m (ha)			Irrigated areas from national statistics (ha)			% Change in irrigated area by source compared to average over 2000–2009 (MODIS)		
	Canal	Tank	GW	Canal	Tank	GW	Canal	Tank	GW
Year 2000–2001	842,439	573,893	1,468,192	833,147	588,633	1,465,805	15	2	1
Year 2001–2002	788,322	590,859	1,228,293	801,303	536,706	1,462,948	8	5	−16
Year 2002–2003	618,955	496,556	1,150,390	614,143	422,313	1,273,434	−15	−12	−21
Year 2003–2004	541,243	292,569	1,170,671	491,364	384,960	1,312,770	−26	−48	−20
Year 2004–2005	684,230	524,436	1,610,744	753,819	465,355	1,418,024	−7	−7	11
Year 2005–2006	739,018	590,261	1,650,144	800,161	575,352	1,544,032	1	5	13
Year 2006–2007	716,825	589,990	1,632,369	781,993	531,376	1,566,207	−2	5	12
Year 2007–2008	730,283	578,602	1,435,383	752,654	506,070	1,605,099	0	3	−1
Year 2008–2009	737,633	564,377	1,479,043	680,000	NA	NA	1	0	2
Year 2009–2010	698,987	436,933	1,163,961	706,864	NA	NA	−5	−22	−20

NA not available

was based on the predominance of a land use class and the dominant water source (e.g., irrigated surface water mixed crops) (Fig. 3). Each class was a combination of several land use/cover types (see Table 3). For example, class 3 was described as irrigated groundwater mixed crops. Within this class, various other land use/land cover areas existed and cultivable areas (84.5 %) dominated but there were other land cover types with 1.2 % trees, 0.9 % shrubs, 2.7 % grass, and 1.6 % for fallows, weeds, rocks, and built-up lands. In these cultivable areas, rice was the predominant crop, whereas maize and grains were the next dominant crops.

The total irrigated area was estimated to be 2,861,829 ha, which includes irrigation by tank (573,893 ha), irrigation by groundwater (1,444,768 ha), and irrigation by canal (843,168 ha) in the year 2000–2001. Surface irrigation was mainly located in the districts adjacent to the River Kaveri (Thiruvur, Thanjavur, Nagapattanam, and Erode), and tank-irrigated areas are predominant in Tirunelveli and Pudukkottai. Groundwater-irrigated areas were spread across the study area, mainly in Coimbatore, Salem, Villupuram, and Thiruvannamali (Fig. 3). Average irrigated area by source in each river basin is shown in Table 4.

Land use changes in the river basin

The temporal changes in irrigated area of Tamil Nadu over 10 years from 2000–2001 to 2009–2010 within all catchment areas are shown in Fig. 4 and Table 5. The 16 river basins showed widely different changes in cropping pattern during the low-rainfall years 2002–2003, 2003–2004, 2006–2007, and 2009–2010. The major command area (Kaveri delta) has some irrigated agriculture, where surplus flows occur even in low-rainfall years. In the last decade, 2002–2003 and 2003–2004 had the lowest irrigated area when compared to normal years, with an estimated decrease of 15 and 26 % in canal-irrigated area, 12 and 48 % of tank-irrigated area, and 21 and 20 % of groundwater-irrigated area, respectively (Table 5). Recently, severe drought occurred in 2009–2010; rainfall was noted at 412 mm during the monsoon season compared with normal rainfall of 796.3 mm. In 2009–2010, irrigated area decreased by 5 % under canal irrigation, 22 % under tank irrigation, and 20 % under groundwater irrigation.

Irrigated area changes

Figure 5a shows state-level periodic changes during the last decade, in agricultural area by irrigation source and corresponding annual rainfall. Figure 5b shows source-wise irrigated area of the16 individual basins. An important finding was that, in all the basins except a few small ones, groundwater-irrigated area was the most severely affected by drought in 2002–2003 and 2009–2010. Tank-irrigated area was the most severely affected

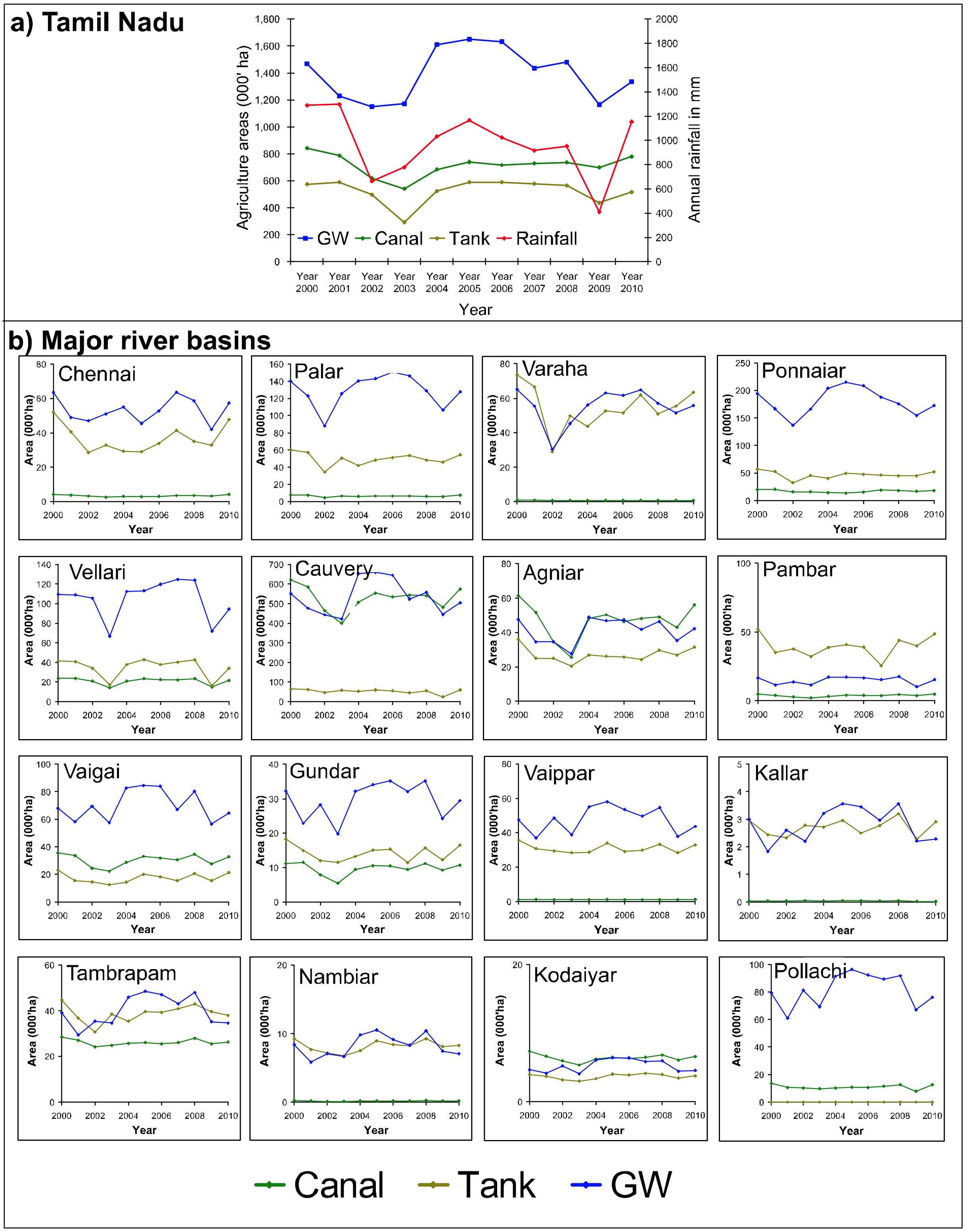

Fig. 5 Temporal variations in various irrigated agricultural areas across Tamil Nadu with rainfall

Table 6 Frequency of land use change in canal-, groundwater-, and tank-irrigated area and its percent of total irrigated area during 2000–2009

Frequency of land use change from 2000 to 2009	Irrigated area change			% Change from average over 2000–2009		
	Canal area (ha)	Groundwater (ha)	Tank area (ha)	Canal area (%)	Groundwater (%)	Tank area (%)
Once	303,357	435,439	178,968	38	31	33
2–3 times	314,821	477,363	200,910	39	34	37
4–5 times	117,915	241,210	113,131	15	17	21

by drought in 2003–2004 and 2009–2010. Tank-irrigated areas were seriously affected (48 % area decreased) by drought in 2003–2004 (Table 5). This indicates that groundwater in Tamil Nadu cannot serve as a secure water source in the case of scarcity of surface water and rainfall. This feature can be attributed to Tamil

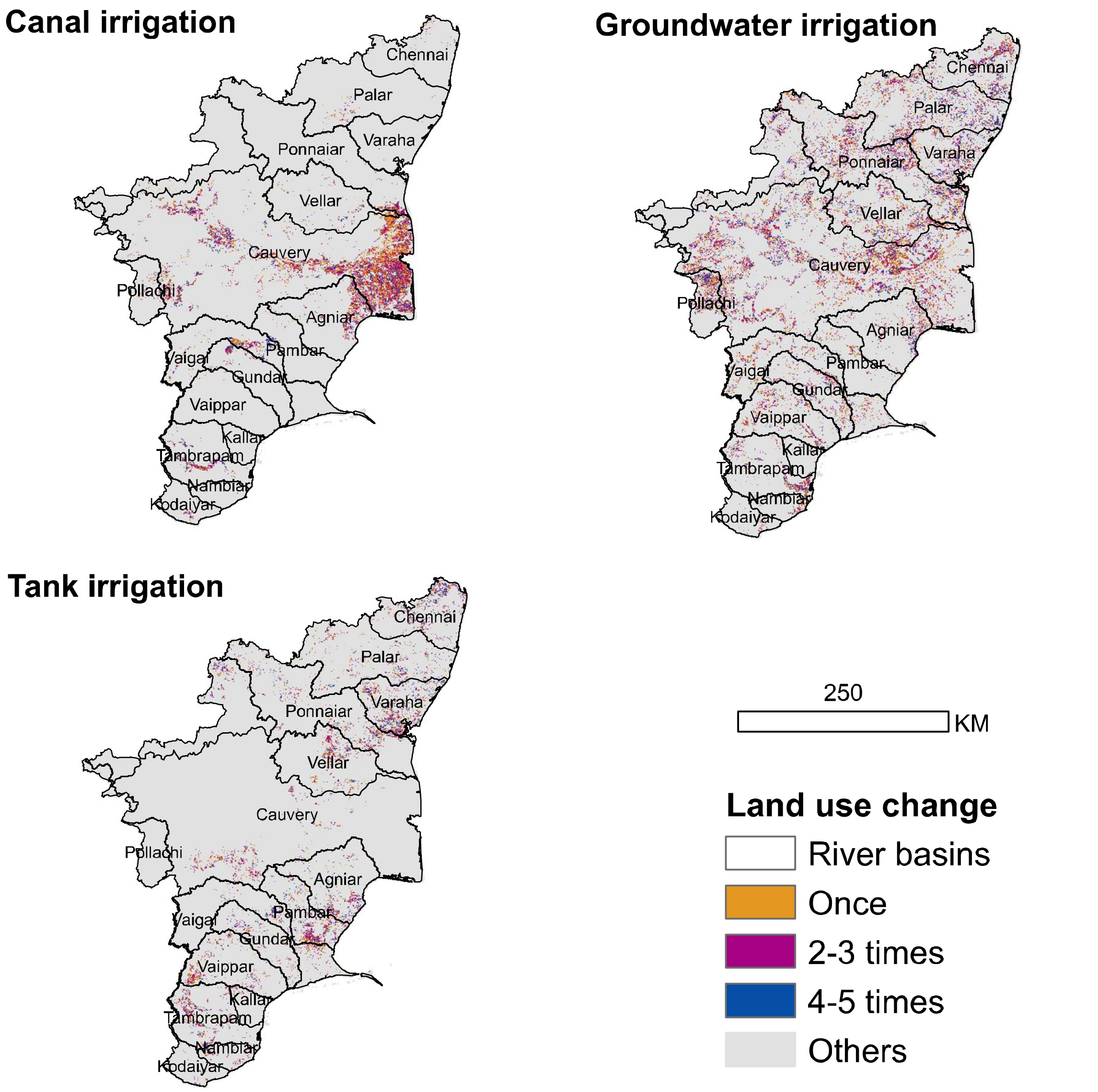

Fig. 6 Irrigated area changes during 2000 to 2009

Nadu's hard rock geologic structure in which storage capacity of the aquifer is limited. However, the southern basins of Tamil Nadu (basins shown in third and fourth rows in Fig. 5b) are less affected by drought because the catchment area is bigger and there is a continuous water flow from the river (Palanisami et al. 2011). This finding is consistent with an example from a hard rock aquifer area in Telengana, Andhra Pradesh, studied by Fishman et al. (2011), which shows that groundwater provides buffer, but it is susceptible to interannual rainfall fluctuation. In addition, as a typical example of tragedy of commons, the overexploitation of groundwater is rampant over the country (Shah 2010). Unless some counter actions were taken, the reliability of groundwater would decline further. Shah (2012) documents spontaneous initiatives for coping with or countering water depletion in many hard rock aquifer areas in India. Although Tamil Nadu is not included in Shah's examples, such a movement could have a potential to reverse the current trend in our study area.

The similar drought impacts among irrigation sources can be confirmed from Table 6 statistics, which show three classes based on the number of times land use changed in the last 10 years. Note that, in all irrigation sources, the percentage change from the normal year was 30–40 % and the frequency of land use changes was observed to be one or two to three times from 2000 to 2010. The magnitude of these changes is much higher than that of neighboring states such as Karnataka or Andhra Pradesh, where the corresponding figures are 10–15 % (Gumma et al. 2011c). This can be attributed to the fact that Tamil Nadu has fewer interstate rivers and thus a more closed water system than the other states. Therefore, we can observe that Tamil Nadu's agriculture in a particular season depends predominantly on the corresponding season's rainfall.

Corresponding to Table 6, Fig. 6 shows the geographic pattern of land use change by irrigation source. It indicates that, for groundwater, the changes in land use spread over the state with a few exceptions, such as Agniar, Tambrapam, and Kodaiyar. Meanwhile, it shows that the impact of drought was very area specific regarding canal or tank irrigation. The impact on canals was concentrated in the downstream of the Cauvery basin, and the impact on tanks was observed mainly in the northern and southern part of the state. Accuracy assessment was performed through fuzzy classification, and classification accuracy varied from 82 to 90 % across agriculture classes, with an overall accuracy of 87.2 % (Table 7).

Table 7 Fuzzy accuracy assessment from ground survey data

Fuzzy classification accuracy									
Land use/land cover	Sample size	Total correct (51–100 %)	Total incorrect (0–50 %)	Absolute correct (100 %)	Mostly correct (76–99 %)	Partly correct (51–75 %)	Partly incorrect (26–50 %)	Mostly incorrect (1–26 %)	Absolute incorrect (0 %)
Class01: Rainfed mixed crops	11	81.82	18.18	72.73	0.00	9.09	9.09	0.00	9.09
Class02: Irrigated tank mixed crops	14	88.24	11.76	76.47	11.76	0.00	11.76	0.00	0.00
Class03: Irrigated GW mixed crops	25	90.00	10.00	80.00	0.00	10.00	0.00	10.00	0.00
Class04: Irrigated SW mixed crops	18	88.89	11.11	77.78	0.00	11.11	0.00	11.11	0.00
Other LULC	12	87.20	12.80	0.00	11.11	77.78	0.00	0.00	11.11
Total	80	87.2	12.8	76.7	2.9	7.6	4.2	4.2	2.3

Identification and targeting of new technologies

Figures 5 and 6 provide a means to assess the impact of drought by water source and location, which can serve as basic information for targeting new cropping patterns, alternative management practices, and new seed varieties. This subsection demonstrates how we can use this information for targeting.

For the areas that suffer severe droughts frequently, rice cultivation (the dominant crop of the state) is risky (for example, blue-dot areas in Fig. 6); therefore, a better agricultural system may be to grow less water-demanding crops. On the other hand, if the water stress

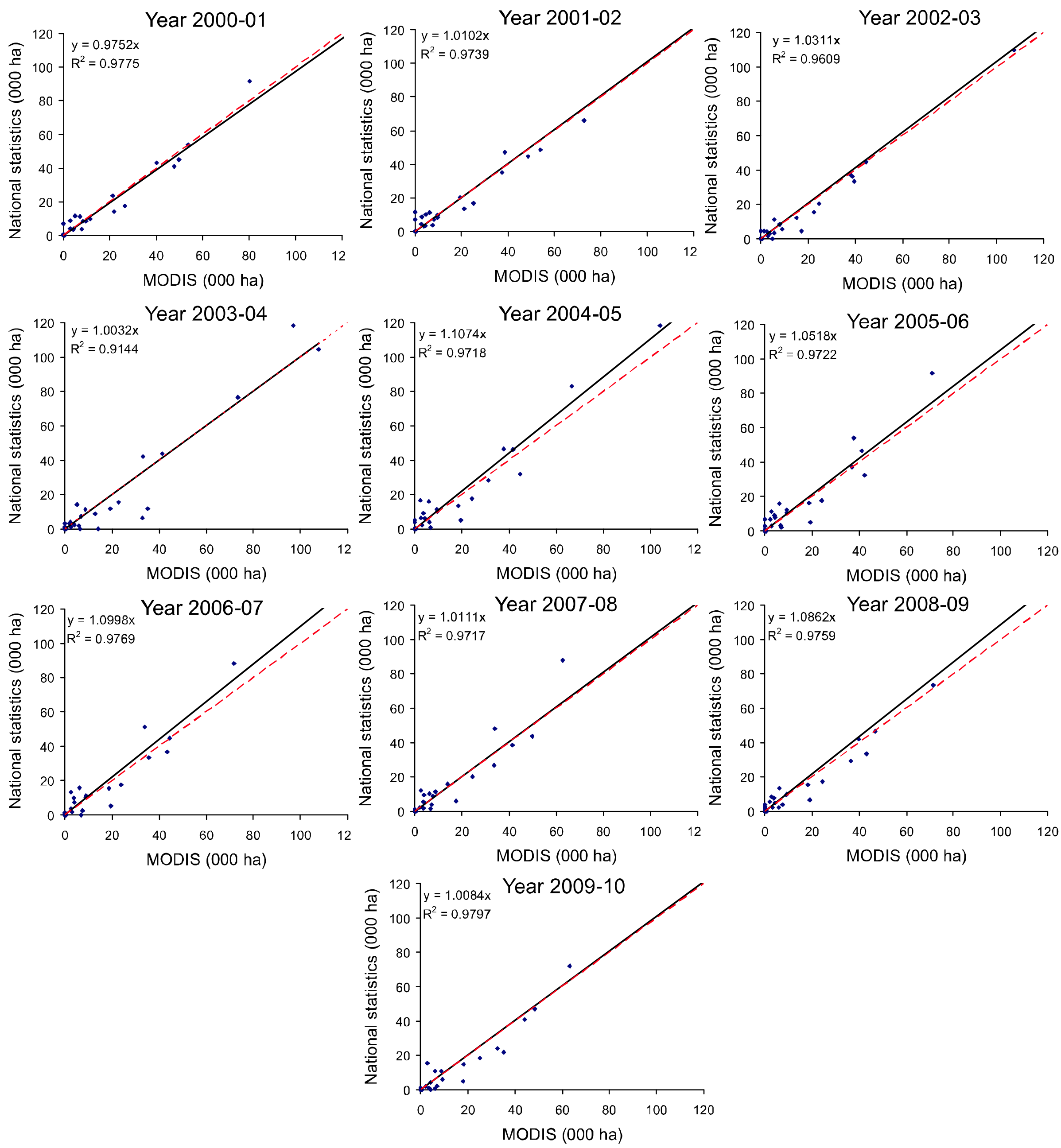

Fig. 7 District-level canal-irrigated areas derived using MODIS 500-m time series data compared with census data by agricultural year from 2000–2001 to 2009–2010

is not that severe, an introduction of water-saving technologies for rice cultivation would be useful. Examples include alternate wetting and drying (AWD) practice for irrigation and the direct-seeding method.[1] Among these, AWD requires strict water control because the soil should not be dried long enough to penalize yield. Hence, the practice of AWD may be difficult under tank or canal irrigation unless strict collective management is possible. Therefore, it may be better to prioritize the introduction of AWD to groundwater-irrigated areas. Nevertheless, note that, as long as the state government persists in a free electricity policy, the incentive of electric pump users to adopt AWD may not be large unless a water shortage is really severe. The introduction of drought-tolerant or short-maturity varieties would be useful to circumvent drought shock. However, note that even such varieties require water at the critical stage of growth. Therefore, this strategy may not be effective if drought is prolonged over the entire cropping season. Identification of the type of drought is beyond the scope of this manuscript, which we leave for our future research agenda.

Our analysis found that most of the basins show similar patterns of drought impacts. Hence, the hedging of shocks within the state may be difficult. Further examination of the geographic patterns of drought shocks is crucial, and the progress of our kind of analysis would contribute toward this end. Results will also be useful as a guide to increase irrigated area using advanced irrigation techniques such as small river banking (Karimov et al. 2012; Karimov et al. 2010).

Comparisons with census data

The irrigated area statistics of Tamil Nadu districts were obtained from the Directorate of Economics and Statistics Bureau of Economics and Statistics, Tamil Nadu. The canal irrigation area statistics were collected at the *district* level from the respective districts for a comparative study with the MODIS data. District-wise statistical data were compared with the MODIS data for 2000–2001 to 2007–2008 (available data) (Fig. 7). Most of the district data are in agreement with the MODIS results for each year from 2000–2001 to 2009–2010. A few districts show a ±10 % difference between the statistical data and MODIS data (Fig. 7). Root mean square error (RMSE) was calculated for 29 districts, and it is 7165 ha for 10 years.

[1] AWD is an irrigation practice to reduce irrigation water from 15 to 35 % without any yield penalty by letting the rice field dry intermittently at the stage when the crop is not so sensitive to water stress.

Conclusions

This paper provides a comprehensive and detailed mapping of land use changes in irrigated area in Tamil Nadu using spectral matching techniques on remotely sensed data. The analyses were conducted at the state and subbasin level. Spatial-temporal land use changes and statistical tabular data are essential for developing sustainable agriculture, including monitoring, planning, and management at the basin level. MODIS NDVI time series data were combined with field plot data and spectral matching techniques to classify canal irrigation, tank irrigation, groundwater irrigation, and rainfed ecosystems in the region.

The outcome of this study highlights the importance of using MODIS time series data and advanced methods such as spectral matching techniques in studying agricultural cropland changes in large river basins. Key findings include the severe negative impact of drought not only in canal and tank irrigation area but also in groundwater irrigated area, the geographic pattern of differential impacts (the concentration of tank- and canal-irrigated area vs the spread of groundwater-irrigated area), and the relatively lighter drought impact in southern basins.

In this manner, mapping temporal land use changes contributes to identifying water stress areas due to interannual variability in rainfall, water management, upstream irrigation, and crop prices at the basin level. This attempt is important for basin characterization, planning, hydrological modeling, adopting new cropping patterns, alternative management practices, and the adoption of new stress-tolerant varieties for sustainable agricultural development.

Acknowledgments This research was supported by the "Green Super Rice" (GSR) and CGIAR Research Program: Water Land Ecosystems (WLE). The authors thank Dr. Amit Chakravarty, science editor/publisher, ICRISAT, for editing this article. We would like to thank three anonymous reviewers who helped in substantially improving the quality of this paper.

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