RESEARCH REPORT

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An Irrigated Area Map of the World (1999) Derived from Remote Sensing

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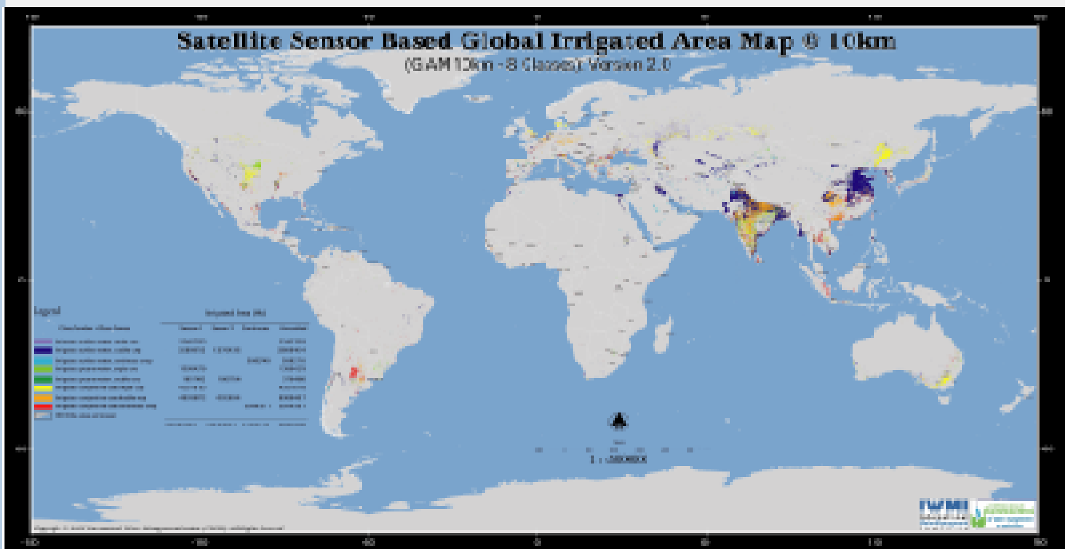

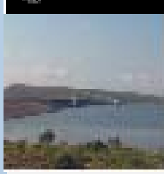

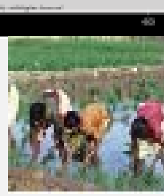

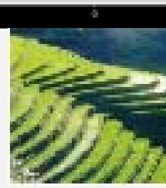

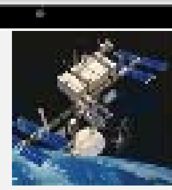

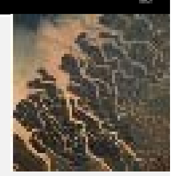

International Water Management Institute

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A Global Irrigated Area Mapping (GIAM) project of this magnitude and complexity can never be done without substantial and persistent support from many places.

We are very grateful to Prof. Frank Rijsberman, Director General of IWMI, for his vision, guidance and financial support; Dr. David Molden, Principal Researcher at IWMI, was instrumental in initial funding and guiding GIAM through the Comprehensive Assessment (CA). Dr. Sarath Abayawardana, former Global Research Director (GRD), was instrumental in laying a strong foundation for the RS\GIS laboratory at IWMI and Julie Van der Bliek, the present GRD head, has continued this support and has steered us towards a spatial data policy at IWMI. All researchers and analysts in the RS\GIS unit have helped in one way or another; we thank Aminul Islam for compiling the excellent groundtruth data of the world and the rainfall data; Wasantha Kulawardana for support when needed; Sarath Gunasinge, and Alankara Ranjith are always there with quiet but strong support in producing maps and flow charts. Jacintha Navaratne provided outstanding secretarial services, most cheerfully.

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The NASA Goddard Space Flight Center (GSFC) made available the AVHRR time series used in this work. Special thanks to Dr. Ron Smith and his group. The Landsat data were downloaded from the University of Maryland's Global Land Cover Facility (GLCF). Several data sets such as the GTOPO30 1-km and SRTM 90 meter elevation data were downloaded from the USGS\EROS. The forest cover data were sourced from Dr. Ruth DeFries of the University of Maryland. Rainfall data were provided by Dr. Tim Mitchell of East Anglica Climate Research Group and the JERS SAR data from Saatchi and the group. The volunteer groundtruth data from degree confluence project were invaluable. The Google Earth data are state of the art and were widely used. Without these great data sets, made available free of charge, the project would not have been completed. So we are very grateful to these agencies and the numerous people behind them.

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Summary

It is necessary to accurately quantify the area and intensity of irrigation in the world in order to properly understand its contribution to food production and security, and to estimate its water use, as competition for water increases with rising urban and industrial needs and the recognition of environmental water requirements. Satellite remote sensing offers a relatively cheap, repeatable and accurate technology to estimate and monitor irrigated areas.

This research report presents the results of a global analysis of multi-temporal time series at nominal 10 kilometer pixel resolution. Statistics of irrigation at country level are derived from these maps for different seasons and for the entire year (annualized) for the nominal year of 1999. Three methods of area abstraction are used and compared, and three methods of accuracy assessment are applied. The annualized irrigated areas of the world at the end of the last millennium were about 480 Mha of which there were 263 Mha for season 1, 176 Mha for season 2, and 41 Mha for continuous cropping. Of this, Asia alone accounts for 78 percent (375 Mha) with 59 percent from China and India. The country statistics are compared with FAO country-level statistics (see Annex I). The IWMI GIAM 10 km V2.0 map were tested based on 3 sources of independent data resulting in accuracies between 84 and 91 percent with errors of omission not exceeding 16 percent and errors of commission less than 21 percent. The total area available for irrigation (TAAI; the nearest equivalent to FAO's equipped area) was 412 Mha.

The global irrigated area mapping (GIAM) products (e.g., maps, statistics, web maps) are made available through a dedicated web portal (*http://www.iwmigiam.org*). The detailed methodology is also made available through the web portal. The focus of this research report is on the results of the GIAM mapping effort.

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Introduction

This document summarizes the materials and methods used to create a series of maps of irrigated areas of the world using remote sensing approaches. These maps are complementary to existing statistics (FAO-Aquastat) and the GIS-derived maps (FAO/University of Frankfurt Global irrigated area map). The document also provides details of how the estimates of global irrigated areas in one main season (net) and more than one season (intensity or annualized) were derived.

The major products were a) 28 class irrigated area map (GIAM10 km-28 class) comprising *watering method (in this case irrigated), irrigation type (surface water, groundwater, and conjunctive use), irrigation intensity (single, double, or continuous crop) and crop type*; b) 8 class irrigated area map (GIAM10 km-8 class) comprising *watering method, irrigation type and intensity;* and c) 3 class irrigated area map (GIAM10 km-3 class) comprising *surface water, groundwater, and conjunctive use irrigation.* The estimation of seasonal global irrigated areas is based on these products. The simpler GIAM10 km-8 class and GIAM10 km-3 class maps have more "practitioner-friendly" classes and are produced, to allow easier visualization.

The products of the GIAM10 km-28 class, GIAM10 km-8 class, and GIAM10 km-3 class are derived from a generic land use and land cover (LULC) map of the world that has 951 classes; a considerable part of the methodology is concerned with the development of this map and subsequent definition, naming and aggregation of these classes. The work had the explicit intention, as far as possible, to take account of the effect of cropping intensity or irrigated areas from different seasons within a given year. Time-series analysis of remote sensing allows the basic developmental phenology of different crops to be identified, and the number of crop seasons in one year can be determined on aggregate for any pixel. In this study, we have used multiple types of imagery and masking data at different scales.

Although the analysis has been conducted at a nominal scale of 1-km per pixel, the major source of data has been a 20-year time series of 10-km AVHRR data. This has necessitated the use of a classical LULC classification approach that defines LULC classes as a mix of land cover types. Therefore, sub-pixel disaggregation of the component irrigation areas becomes a major objective in trying to accurately assess actual area.

The same processes and data were used to produce the following products:

- Disaggregated 323 class Global Irrigated Area Map (GIAM10 km-323 classes);
- Disaggregated 229 class Global Map of Rain-fed Cropped Areas (GMRCA229);
- Aggregated 22 class map of Global Map of Rain-fed Cropped Areas (GMRCA22);
- Disaggregated 76 class Global Map of LULC Areas (GMLULCA76);
- Aggregated 10 class Global Map of LULC Areas (GMLULCA10).

The work has produced other significant by-products which, along with the main maps, are available via a dedicated website: *http://www.iwmigiam.org*

The website includes maps, images, class characteristics, sub-pixel area (SPA) estimation approaches, digital photos, groundtruth data, animations of time series and accuracy assessments. All the background documentations are also provided.

The website contains a daunting amount of information and data, with substantial improvements and refinements in the presently published version 2.0. Aside from the production of the maps and estimation of the irrigated areas, the intention of this work is to:

- provide repeatable and robust methods and techniques of analysis of irrigated areas
- encourage practitioners and researchers with better local knowledge to improve the definition and detail in their localities and contribute to further refinement of the map

This report continues with a brief background (section 3[1]) to past efforts to assess irrigated areas and the rationale for developing new approaches using remote sensing at a global scale. In section 4 and its subsections, we present the basic remote sensing and other data used to produce the maps. In section 5 and its subsections, we provide details of the analytical methods applied to define and refine the classes. This is followed by section 6 on class aggregation and section 7 on area calculations and sub-pixel decomposition techniques (SP-DCT). The rest are accuracies in section 8, results and discussions in sections 9 and 10, class naming convention in section 11, products in section 12 and conclusions in section 13.

Background and Rationale

Irrigation Development and Trends

Following the end of the Second World War, and a period of decolonization, there was a boom in irrigation development which coincided with strongly motivated nation building, particularly in Asia. Irrigated area increased at about 2.6 percent per annum from a modest 95 million hectares (Mha) in the early 1940s to between 250 and 280 Mha in the early 1990s (van Schilfgaarde 1994; Siebert et al. 2002; Seckler 2000 et al.).

In this era, a key developmental agenda for many countries was the construction of large and small dams and river diversions to abstract and store water for agriculture. Over 40,000 large dams (>15 meter in height) irrigate about 30-40 percent of the world's irrigated areas (*www.dams.org*) and are complemented by an estimated 800,000 smaller dams. Since the 1980s, there has been a progressive decline in public and international donor funding for irrigation, which has been replaced in many countries by the private development of groundwater irrigation based on the availability of cheap drilling and pumping technologies. India now has an estimated 20 million tube-well irrigators, accounting for as much as 60 percent of the irrigated area according to some estimates.

This development has allowed food production to keep pace with rapidly growing global populations and an increasingly urban world. Farmers currently produce enough to feed

1The particular sections and subsections can be found by referring to the Contents on p.iii.

the world, although poverty and malnutrition still affect more than a fifth of the global population due to local shortages and inadequate distribution and market systems. Although rates of population increase are now slowing and it is expected that the world will continue to be able to feed itself (Siebert et al. 2002), there will be continued pressure to either expand the irrigated area, or increase crop and livestock productivity or substitute intensive irrigation with better and more extensive rain-fed agriculture.

The population of the world is now approaching six billion and is expected to near 8 billion by 2025. To meet future food demand, some estimate that at least another 2,000 cubic kilometers of water (equivalent to the mean annual flow of 24 additional Nile rivers) will be needed (Postel 1999). Water use for irrigation varies considerably across the globe. It accounts for 2-4 percent of diverted water in Canada, Germany and Poland but is an impressive 90-95 percent in Iraq, Pakistan, Bangladesh, Sudan, Kyrgyzstan and Turkmenistan (Merrett 2002).

Globally, the irrigated landscape remains very dynamic. Although the annual rate of increase of irrigated areas has slowed to about 1 percent, this still represents an increase of between 2 Mha and 3 Mha each year. There is a smaller corresponding annual loss of irrigated area to salinity and waterlogging as well as to abandonment of uneconomic projects. Countries such as China and India continue to build large multipurpose dam projects that also supply water for irrigation. In sub-Saharan Africa, irrigation is perennially seen as having an unfulfilled potential. Elsewhere in the world, there are moratoria on dam building and even the decommissioning of dams in the western USA.

Better technology, advances in agronomy and crop breeding (including genetically modified crops) are expected to contribute to increasing cropland and water productivity. However, both extensification and intensification are increasingly questioned by environmental activists and more ecologically sensitive governments. A key challenge for the irrigation sector lies in using less water to produce more food, whilst mitigating negative impacts on the environment, particularly on aquatic ecosystems.

The irrigated landscape of the world will be shaped increasingly by the effects of competition for water from other sectors, notably urban and rural domestic water supply and industrial needs. It is becoming increasingly common for river basins to be over-allocated, with negative downstream effects of competitive upstream development, such as in the Krishna basin in India (Biggs et al. 2006). Similarly, groundwater is being mined in many places, notably in significant parts of India and in the Olgalala aquifer in the mid-west of the USA. Reservation and reallocation of flows for environmental purposes will, in the end, place even greater competing demands in terms of water volumes. Climatic change will impose additional challenges that will reshape the irrigated landscape through changes in snowmelt and rainfall.

In summary, irrigation is widely thought to provide 40 percent of the world's food from around 17 percent of the cultivated area. Key questions concerning the sector include:

- How much irrigation do we have now?
- How much do we need in the future?
- How much do we want in the future to achieve a sustainable balance with the environment?
- How much water does it require and will this be available?

Estimates of Irrigated Area

There remains considerable uncertainty about the exact extent, area and cropping intensity of irrigation in different parts of the world, due to the dynamics referred to above and systematic problems of underreporting and overreporting of irrigation in different contexts (e.g., groundwater) and countries.

Currently, there is one irrigated area map of the world produced by FAO/University of, Frankfurt (*http://www.fao.org/ag/agl/aglw/aquastat/irrigationmap/index.stm*). This map presents areas that are “equipped for irrigation” but not necessarily irrigated (Siebert et al. 2005; Siebert et al. 2002; Siebert and Döll 2001; Döll and Siebert 1999, 2000). The map is produced using irrigated area statistics from various nations. GIS and national statistics based irrigated area maps are also available for individual nations such as India’s CBIP maps which may have following limitations. First, extrapolating the statistical numbers to the spatial domain can be a rough approximation of the actual location of the irrigated areas. As a result, we may have an entire state such as Washington in the USA having <5 percent irrigation with no indication on which specific areas this irrigation takes place. Second, irrigated area statistics provided by different countries have various inconsistencies. There is a tendency to believe in “official” statistics as the right one. However, a cursory look at these data often highlights numerous inconsistencies. For example, the irrigated areas of the 29 Indian states had a 99 percent correlation between areas of 1995-96 and 2000-01. This simply implies that the same numbers from previous years have been copied in subsequent years. Third, it does not account for the intensity (gross area) of irrigation. Irrigated area maps and statistics from various nations have their own limitations. For example, the Central Board of Irrigation and Power (CBIP) of India calculates irrigated areas based on the irrigated command area. Our studies at 500-m resolution, currently in progress and within the scope of the GIAM project, showed that a very significant proportion of the command area is left fallow at any given period of time. Further, within the command area boundaries, there are other classes: groundwater irrigation, rain-fed croplands and other land use/land cover. The command area maps help establish “equipped area” but not actual area. The gap between “actual” versus “equipped”can be significant. Another source of inconsistency concerns the cropping intensity which varies from year to year and among systems and regions.

The FAO/University of Frankfurt (FAO/UF) study estimates area equipped for irrigation to be 274 Mha or about 16 percent of the total croplands (1.5 billion ha). The pixel resolution presented by FAO/UF is based on sub-national statistics and variable scale maps and administrative units (Siebert et al., 2005).

Irrigated area is also estimated, rather coarsely, in global land use classifications derived from remote sensing, which have usually focused on other objectives, such as forestry, rangelands and rain-fed croplands. Examples include USGS 1993 (Loveland et al. 2000), GLC 2000 (Bartholome´ and Belward 2005), and Global Forest Cover (DeFries et al. 2000a, b; DeFries et al. 1995, 1998).

Settled agriculture began about 10,000 years ago. There are many examples of irrigation dating back to at least 4000 B.C. in great ancient civilizations in the Nile, Euphrates, Indus and the Ganges (Postel 1999). Irrigation was practiced extensively in the ancient world in the Tigris and Euphrates by Sumerians, Babylonians and Mesopotamians about 2000 to 6000 over years ago, and by the Harappa and Mohenjo-Daro civilizations in the Indus valley about 4000 years ago. In the Nile delta, there has been a nearcontinuous practice of irrigation over 6000 years ago and large-scale systems have been continually expanded in China for up to 4000 years, for example in Dujiyangyan, in Szechuan, which now covers a near-contiguous area of nearly a million hectares.

Historical estimates of global irrigated area begin with 8 Mha in 1800, rising to 95 Mha in 1940, to the current ones. About 60 percent irrigation is found in six countries: India (21.7 % of the world’s total irrigated area), China (19.4%), USA (7.9%), Pakistan (6.6%), Iran (2.8 %) and Mexico (2.4%) (Droogers 2002). These countries also have the highest proportions of irrigation relative to total cultivated area, for example: 50.1 percent for India, 49.8 percent for China, 21.4 percent for USA, 17.2 percent for Pakistan and 7.3 percent for Iran (Postel 1999).

Satellite sensors potentially offer a consistent, continuously updated, timely and increasingly free resource that meets high scientific standards, such as MODIS and SPOT Vegetation which respectively have 250 meter to 1-kilometer spatial resolutions with global coverage every day (see Thenkabail et al. 2005d, e). These data are backed by numerous high-quality secondary spatial data such as SRTM digital elevation models, Landsat, SPOT and ASTER high-resolution data and global time series of precipitation and other climatic variables.

The International Water Management Institute (IWMI) initiated a GIAM project in 2002 (see Droogers 2002; Turral 2002) supported by the Comprehensive Assessment of Water Management in Agriculture.

The main motivation to develop the IWMI map lies in the potential for a wide range of increasingly sophisticated remote sensed images and techniques to reveal vegetation dynamics that:

- define more precisely the actual area and spatial distribution of irrigation in the world
- elaborate the extent of multiple cropping over a year, particularly in Asia, where two or three crops may be planted in a year, but cropping intensities are not accurately known or recorded in secondary statistics
- develop methods and techniques for consistent and unbiased estimates of irrigation over space and time for the entire world

Data Used in Creating IWMI's Global Irrigated Area Map

In this analysis, we make use of as much freely available data as possible. AVHRR and MODIS data are of a relatively coarse scale, with resolutions from 10-km down to 250-m. Compiling a MODIS data set for the world at 500-m or 1-km over time (e.g., 8-day or monthly for several years) requires enormous computer storage and extremely high end processors that are expensive. The longest multi-temporal series of remote sensing data with global coverage is AVHRR 8-km (re-projected to 10-km). However, since this resolution is coarse, we have combined a 3-year monthly time series of AVHRR 10-km from 1997 to 1999 with a 1-km SPOT Végétation mosaic of the world for 1999. A summary of the data used, and its main processing chain are summarized in figure 1.

The process starts with a number of publicly available data sets, which are processed into one large 159-layer time series file, known as a mega-file. The time series analysis is conducted on the mega-file and is described in sections 4 and 5. DEM, temperature and rainfall data are combined into the mega-file to allow segmentation of a set of masks (figure 1) of different characteristic regions of the world which are analyzed separately and then combined into the class naming and area calculation steps. A number of other data sets (figure 1) are used to provide contextual and detailed information to assist in identifying, separating and aggregating classes.

The mega-file used for the IWMI global irrigated area map (GIAM) consisted of 159 data layers (figure 1). This consisted of 144 AVHRR 10-km layers for 3 years (12 layers from 1 band per year * 4 bands including an NDVI band * 3 years), 12 SPOT vegetation 1-km layers for 1 year, and single layers of digital elevation model (DEM) 1-km, mean rainfall for 40 years at 50-km, and AVHRR-derived forest cover at 1 km. The 159-band mega-file data layers were all retained at a common resolution of 1 km by resampling the coarser resolution to 1 km.

Figures 2 and 3 illustrate various types of data present in the mega-file. The drop-down menu of bands shows how the layers are ordered. The following sections provide a brief description of each of the data sets, which are summarized in detail in tables 1 and 2.

Figure 1.

Processing chain for the global irrigated area map (GIAM).

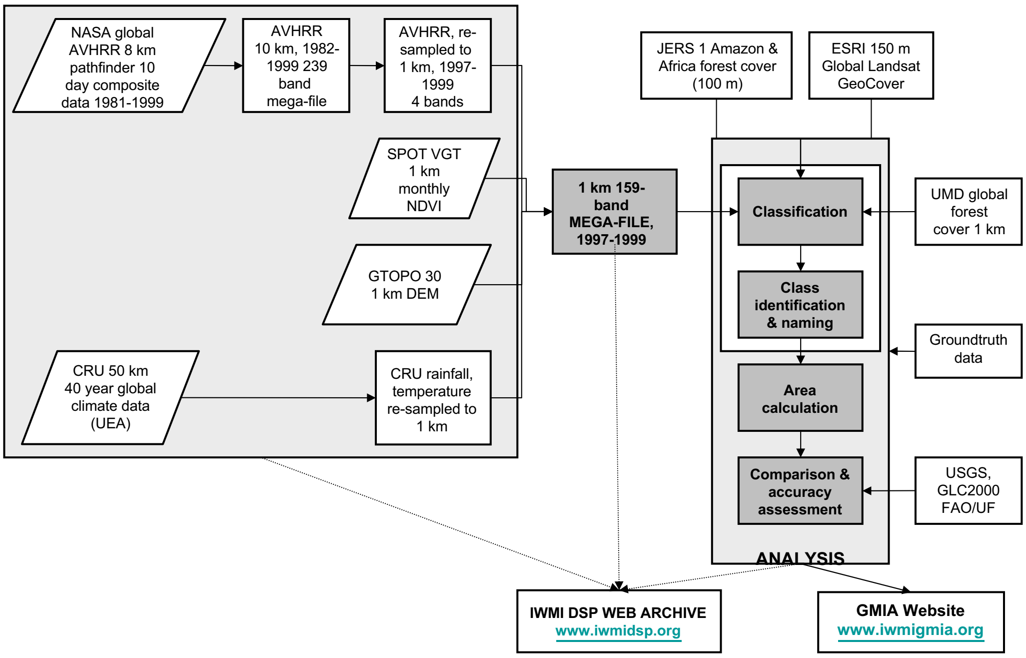


Figure 2.

Mega-file used in GIAM. The mega-file of 159 layers of data which consist of 144 AVHRR 10-km monthly layers from 3 years, 12 SPOT monthly layers from year 1999, single layer of DEM, mean annual rainfall for 40 years, and forest cover.

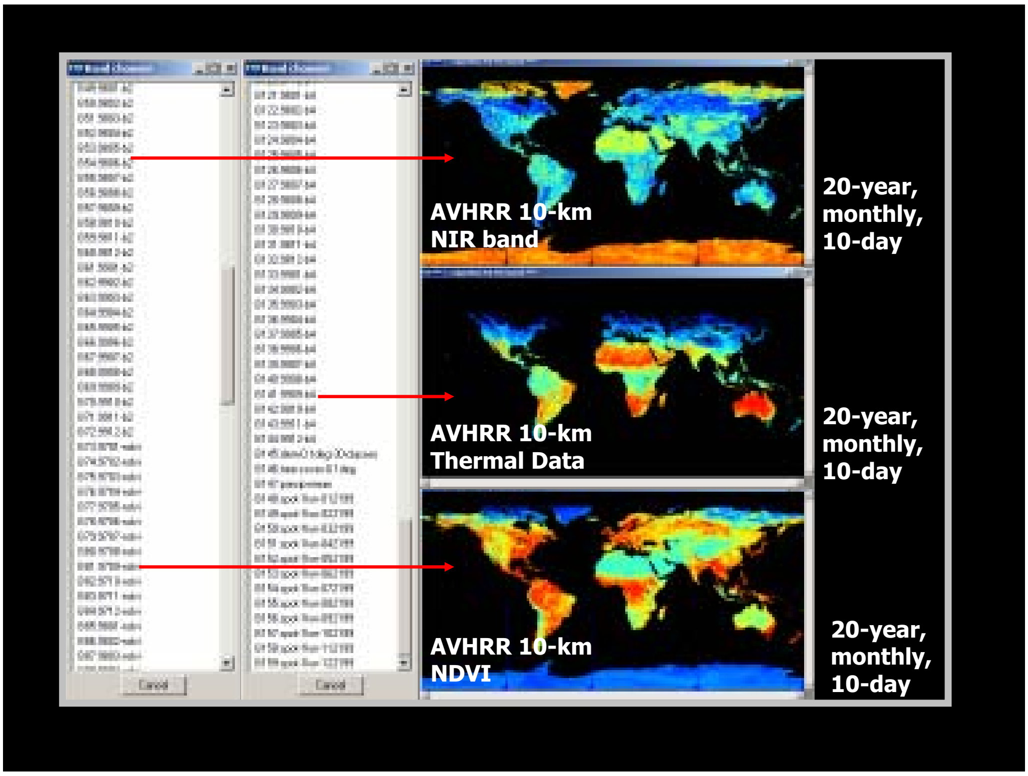
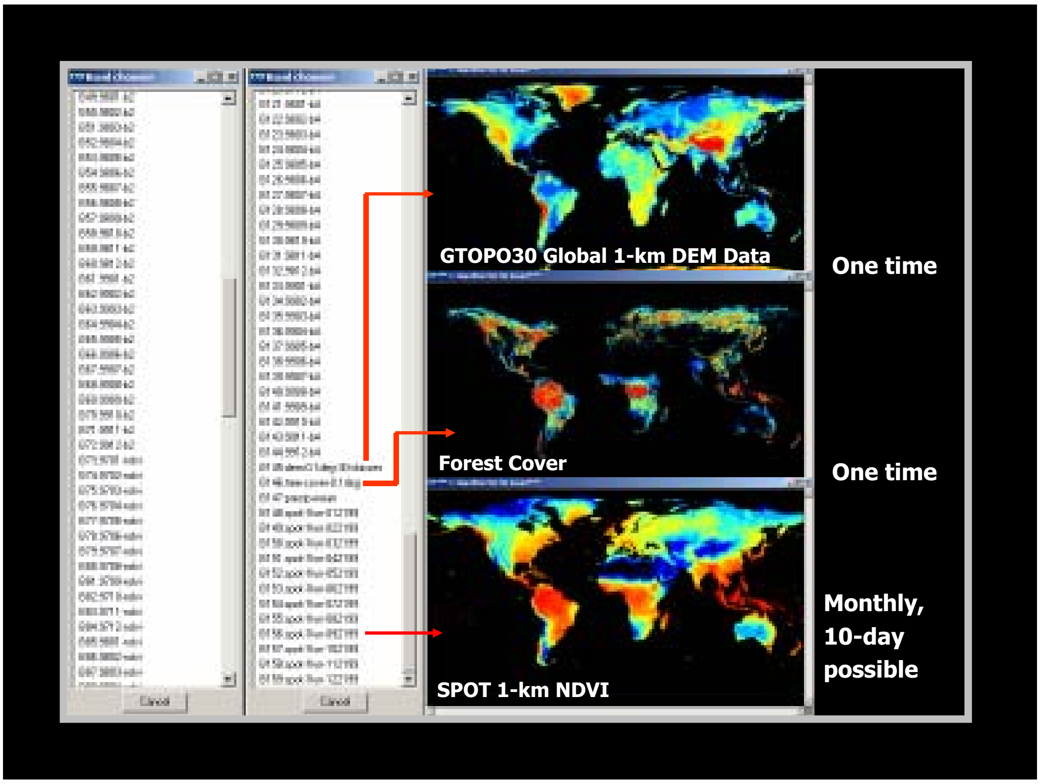


Figure 3.

Primary and secondary data sets used in the mega-file.



Primary Remote Sensing Data Sets and Masks

AVHRR Data Characteristics

The monthly time-composite NOAA AVHRR 0.1 degree data that included bands 1, 2, 4 and NDVI are obtained from the NASA Goddard DAAC (*www.daac.gsfc.gov/data/data set/AVHRR*) (Smith et al. 1997; Rao 1993a, b; Kidwell 1991; Campbell 1987; Flieg et al. 1984; Foddy et al. 1996; Hallant et al. 2001; IGBP 1990; Kogan and Zhu 2001). The monthly maximum value composite (MVC) data from 1981 to 1999 are stored in a single mega-file of 239 bands. A subset of 3 years of these data (1997-1999) was incorporated into the irrigation mapping mega-file.

SPOT Data Characteristics

The SPOT Végétation (SPOT VGT) 1-km data have 4 wavebands: blue (0.43-0.47 µm); green (0.61-0.68 µm); near-infrared (NIR) (0.78-0.89 µm); and shortwave infrared (SWIR) (1.58-1.75 µm). There is a 10-day synthesis of SPOT VGT data that can be downloaded free of cost for the entire world (*http://free.vgt.vito.be/*). A single year monthly SPOT VGT NDVI data for 1999 were used in this study.

Mask Data

Secondary data sets in the mega-file are used to segment the world into characteristic regions, based on rainfall, elevation, temperature and known forest cover. For example, in areas where temperatures are less than 280 K, it is unlikely that there is any vegetation and little chance of any irrigation.

GTOPO 30 1-km DEM

The GTOPO30 is derived from eight sources consisting of digital terrain elevation data or

Table 1.

Characteristics of the satellite sensor and secondary data sets used in mapping global irrigated areas. These data sets were compiled into a 159-band layer stack.

Band number[3] or primary source (#)	Wavelength range (µm)	Duration[4] (years)	Number of bands and radiometry (#; one per month)[1]	Data final format Z-scale (percent: for reflectance)	Range (percent)
Satellite sensor data					
AVHRR 10-km					
Band 1 (B1)	0.58 - 0.68	1997-1999	36	reflectance @ ground, 8-bit	0-100
Band 2 (B2)	0.73-1.1	1997-1999	36	reflectance @ ground, 8-bit	0-100
Band 4 (B4) (top-of-atmosphere)	10.3-11.3	1997-1999	36	brightness temperature	160-340
NDVI	(B2-B1)/(B2+B1)	1982-2000	36	unitless, 8-bit scaled NDVI	-1 to +1
Secondary data					
GTOPO30 1-km one-band	DCW, DTM, and others	1 time	1	meters, 16-bit	-1 to + 1
Rainfall 1-km one-band	Mean of monthly 40-years	1961-01	1	mm, 16-bit	0-65536
Forest cover 1-km one-band	None	1992-93	1	class names, 8-bit	0-256

Table 2.

Other data used in conjunction with the megafile

1. Band 1, 2, NDVI	same as above	1981-2001	239[1]		
2. SPOT 1-km[2] NDVI	(B3-B2)/(B3+B2)	1999	12	unitless, 8-bit scaled NDVI	-1 to +1
3. JERS SAR 100-m one-band	L-band;24.5 cm	Jan.-Mar 1996	1	unitless, 8-bit	0-256
		Oct-Nov 1996	1	unitless, 8-bit	0-256

Note:

1 = animations of the irrigated area classes were run for the entire AVHRR time series to help understand the change history of the class. There were data for 239 months in 19 years (July 1981-September 2001). September-December 1994 data were not acquired due to failure of the satellite.

DTED (50% of global coverage), digital chart of the world or DCW (29.9%), USGS 1-degree digital elevation models (6.7%), army service maps (ASM maps) at 1:1,000,000 scale (1.1%), international maps of the world (IMW maps) at 1:1,100,000 scale (4.7%), Peru map at 1:1,000,000 scale (0.1%), New Zealand DEM (0.2%), and Antarctic digital database (8.3%) (Tucker et al. 2005; Verdin and Greenlee 1996; Verdin and Jenson 1996; NGDC 1994).

CRU Precipitation and Temperature Data

The 40-year (1961-2000) monthly, 0.5 degree, interpolated rainfall and temperature data were obtained from Dr. Tim Mitchell of the Climate Research Unit (CRU), University of East Anglia, UK (Mitchell et al. 2003) (http://www.cru.uea.ac.uk/~timm/index.html). The data have been converted to ESRI GRID format at IWMI and mean monthly precipitation and temperature for 40 years were computed for each pixel and added to the mega-file.

Forest Cover Data

Forest cover was derived from the 1992 AVHRR 1-km data by the University of Maryland that used a continuous fields approach (rather than discrete number of classes) using a linear mixture model approach (see DeFries et al. 2000a, b). This data set was used to mask areas of very high forest cover, which implies the land is not available for cultivation or irrigation.

Secondary Data Sets

JERS-1 SAR-Derived Forest Cover

The Japanese Earth Resources Satellite-1 (JERS-1) Synthetic Aperture Radar is an L-band (24.5-cm wavelength) imaging radar with initial full resolution of 18-m that is processed to 100-m, mosaicked and made available for the entire contiguous rain forests of Amazonia and Central Africa (Saatchi et al. 2001; Saatchi and McDonald 1997; Saatchi and Rignot 1997; Saatchi et al. 2000; and Saatchi et al. 1997). We obtained 100-m resolution JERS-1 SAR tiles (http://southport.jpl.nasa.gov/GRFM/**)** for South America and Africa to assist in mapping major rain-forest areas at higher resolution. Unfortunately, well-processed JERS SAR images are not readily available for Asia and hence could not be used.

ESRI Landsat 150-m GeoCover

ESRI resampled the 8,500 ortho-rectified Landsat ETM+ "GeoCover" tiles that had been produced by the EarthSat Corporation (*http://www.earthsat.com*), funded by NASA (Tucker et al. 2005). The original images are free from the USGS EROS data center and the University of Maryland (*http://glcf.umiacs.umd.edu/index.shtml*). The resampled images have a pixel resolution of 150 m compared with the original pan-sharpened size of 15 m. GeoCover is the most positionally accurate image set covering the entire globe and shows maximum greenness and offers a detailed "zoom-in" view of any part of the world, which is used to provide contextual information and pseudo "groundtruth" by geo-linking to the class maps to identify and label classes.

Google Earth Data Set

Google Earth (*http://earth.google.com/*) contains increasingly comprehensive image coverage of the globe at very high resolution of 0.61-4 m, allowing the user to zoom into specific areas in great detail, from a base of 30 m resolution data, based on GeoCover 2000. This assists:

- identification and labeling the GIAM classes
- area calculations (section 7)
- accuracy assessment of the classes (section 8)

For every identified class, 20-50 sample locations were cross-checked using Google Earth. Google Earth data were used as a substitute for groundtruth and, at times, they were better than groundtruth data.

Groundtruth Data

There are two global archives of GT data, one collected by IWMI and its staff and the other using public domain data from the degree confluence project (http://www.confluence .org/).

Groundtruth at IWMI: Data Collected in Field Campaigns

Detailed groundtruth data were collected by IWMI, specifically for irrigated area mapping (see for example, *http://www.iwmidsp.org* and also Thenkabail et al. 2005a, b; Biggs et al. 2006). At each location the following data were recorded (Thenkabail et al. 2005a):

- LULC classes: levels I, II and III of the Anderson approach
- land cover types (percentage): trees, shrubs, grasses, built-up area, water, fallow lands, weeds, different crops, sand, snow, rock and fallow farms
- crop types, cropping pattern and cropping calendar for *kharif* or *rabi* (winter or dry season cropping period from November to March) and interim seasons
- water source: rain-fed, full or supplemental irrigation; surface water or groundwater
- digital photos "hot linked" to each groundtruth location

Public-Domain Groundtruth: The Degree Confluence Project

The Degree Confluence Project (DCP) (*http://www.confluence.org/*) is an organized sampling of the entire world at every 1 degree latitude and longitude intersection. It is a voluntary effort and close to 4,000 confluence locations have already been contributed. The confluence points include precise latitude, longitude and a digital photo of land cover. These were converted to proprietary GIS formats and added to the DSP in a separate archive to preserve their identity.

Other Data Sets for Comparison Purposes

A number of existing global LULC products were used in the preliminary class identification and labeling process. These included USGS LULC (Loveland et al. 2000), USGS seasonal LULC (Loveland et al. 2000), GLC2000 (Bartholome´ and Belward 2005), IGBP (IGBP 1990) and Olson eco-regions of the world (Olson 1994a, b). These data supplemented/complemented the groundtruth data during the preliminary class identification and labeling processes. The characteristics of these LULC classes are briefly mentioned here and for further detail the reader is referred to peer-reviewed publications.

The Global Land Cover 2000 (GLC2000, Agrawal et al. 2004) data set was derived using data from SPOT 1-km resolution Végétation Instrument (Bartholome´ and Belward 2005; Agrawal et al. 2004). The 10-day synthesis data from November 1, 1999 through December 31, 2000 were used for the classification (*http://www.gvm.sai.jrc.it/ glc2000/ Products/*). The Global Land Cover characteristics database was developed on a continent-by-continent basis using 1-km, 10-day AVHRR data spanning April 1992 through March 1993 (Loveland et al. 2000). The same primary data were used in the Global USGS LULC, seasonal USGS LULC and IGBP LULC (*http://edcdaac.usgs.gov/ glcc/ globe_int.html*).

Olson data provided global 94 unique ecosystem classes for the globe (Olson 1994a, b) (*http://edcdaac.usgs.gov/glcc/globe_int.html*). This approach was developed in the mid-1980s and did not use any remote sensing information. For convenience, all these land cover products are made available in standard image processing formats (e.g., ERDAS Imagine) in IWMIDSP (*http://www.iwmidsp.org*).

Methods

An overall summary of the methods and analytical techniques used is shown in figure 4a and b. The basic process involves segmenting the world into characteristic regions that are easier to analyze and then performing an unsupervised classification on each segment, containing all the 159-band information from the AVHRR time series and the single year of SPOT VGT data. Identification of the resulting classes is performed using a suite of new techniques to interpret vegetation dynamics in multi-temporal series, which are explained in more detail below. A number of classes could not be clearly identified, and so were subdivided and classified using simple decision trees and "groundtruth" data sourced from GeoCover 150-m and other secondary information (Tucker et al. 2005). This resulted in the generic class map of 951 "unique" classes. As far as possible, class naming was harmonized with earlier Global Land Cover classifications. Irrigation classes were then derived by aggregation of similar irrigated land use in the generic map, resulting in a 28 irrigation class map (GIAM10 km-28 classes). This map was used to estimate irrigated crop areas in each of the three reference seasons (see section 8). A further aggregation of this map into eight broad irrigated area classes of the world (GIAM10 km-8 Classes) gives a more visually friendly presentation, with class names that are more familiar to irrigation professionals.

Image Segmentation

Mega-File of Segments

The original 159 band mega-file was converted into a mega-file of segments, each with its own set of 159 bands (see figure 1). The seven global masks created are listed below and illustrated for one segment in figure 5. The global masks are:

- precipitation less than 360 mm per year (PLT360)
- precipitation greater than 2,400 mm per year (PGT2400)
- temperature less than 280 degree Kelvin per year (TLT280)
- forest cover greater than 75 percent canopy cover (FGT75)
- special forest SAR (FSAR)
- elevation greater than 1,500 meters (EGT1500)
- all other areas of the world (AOAW)

The segment with less than 360 mm per year identifies areas where any green vegetation has a very high likelihood of being irrigated, since the average evaporation rates of 30 mm per month, however distributed in reality, will be considerably less than evaporative demand. This segment will mainly identify arid and semiarid areas and deserts, as shown in figure 5. In contrast, the segment with rainfall of over 2,400 mm per year mainly identifies the rain-forest areas of the world, although there are considerable areas of irrigation within the SE Asian lands. Where the temperature is less than 280 K on average, it is too cold for agriculture, and irrigation is not likely to be found there. However, some northern hemisphere areas have a low average temperature but short summer seasons in which supplemental irrigation is actually practised.

Classification

Each segment is processed using unsupervised ISOCLASS K-means classification (Tou and Gonzalez 1975).

Class Identification and Naming Process

On completion of an unsupervised classification, it was necessary to identify what the classes were and label them accordingly. In more localized applications, it was common to undertake groundtruth after a preliminary

Figure 4a.

Summary of analysis to determine irrigation land use classes (part 1).

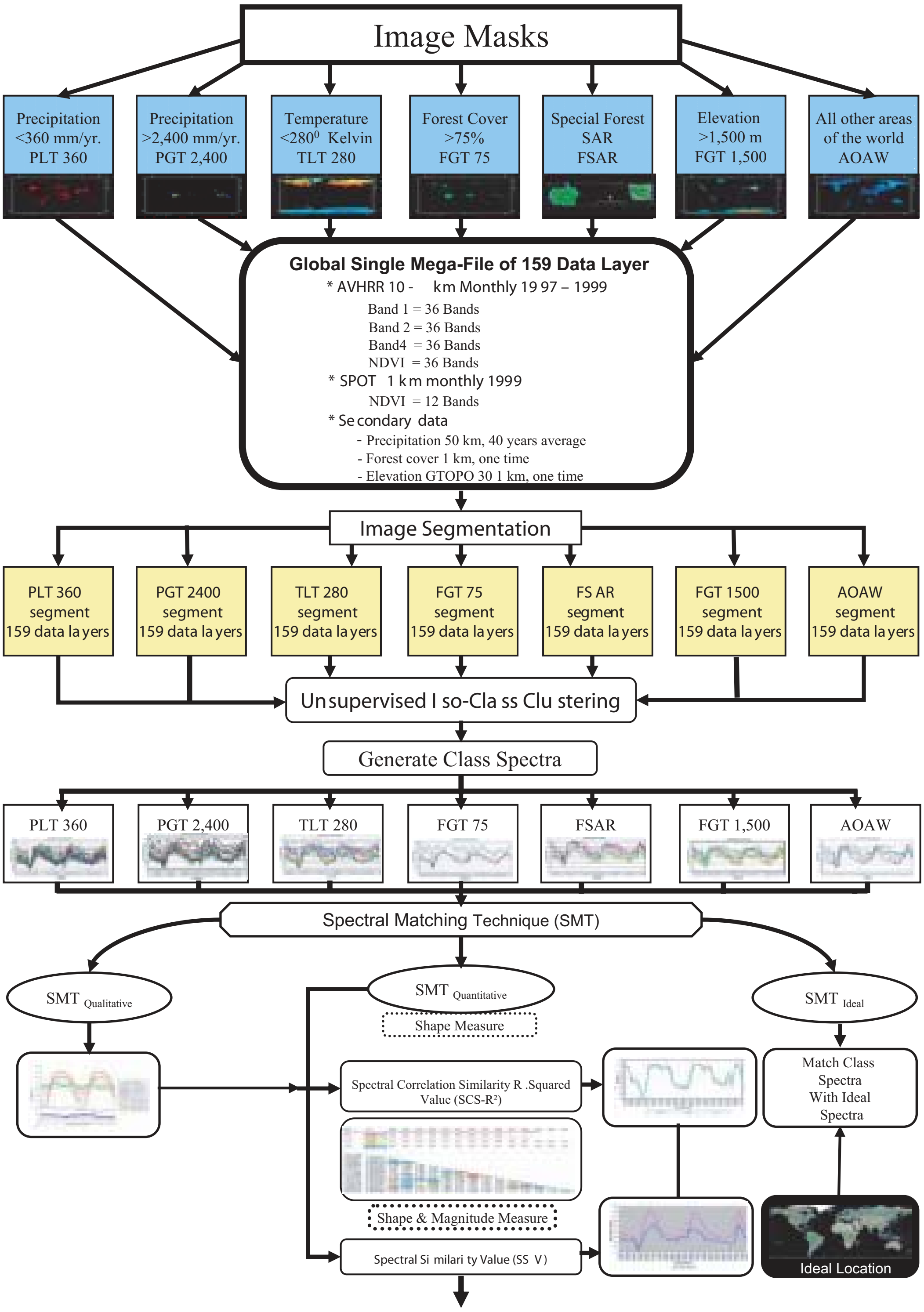


Figure 4b.

Summary of analysis to determine irrigation land use classes (part 2).

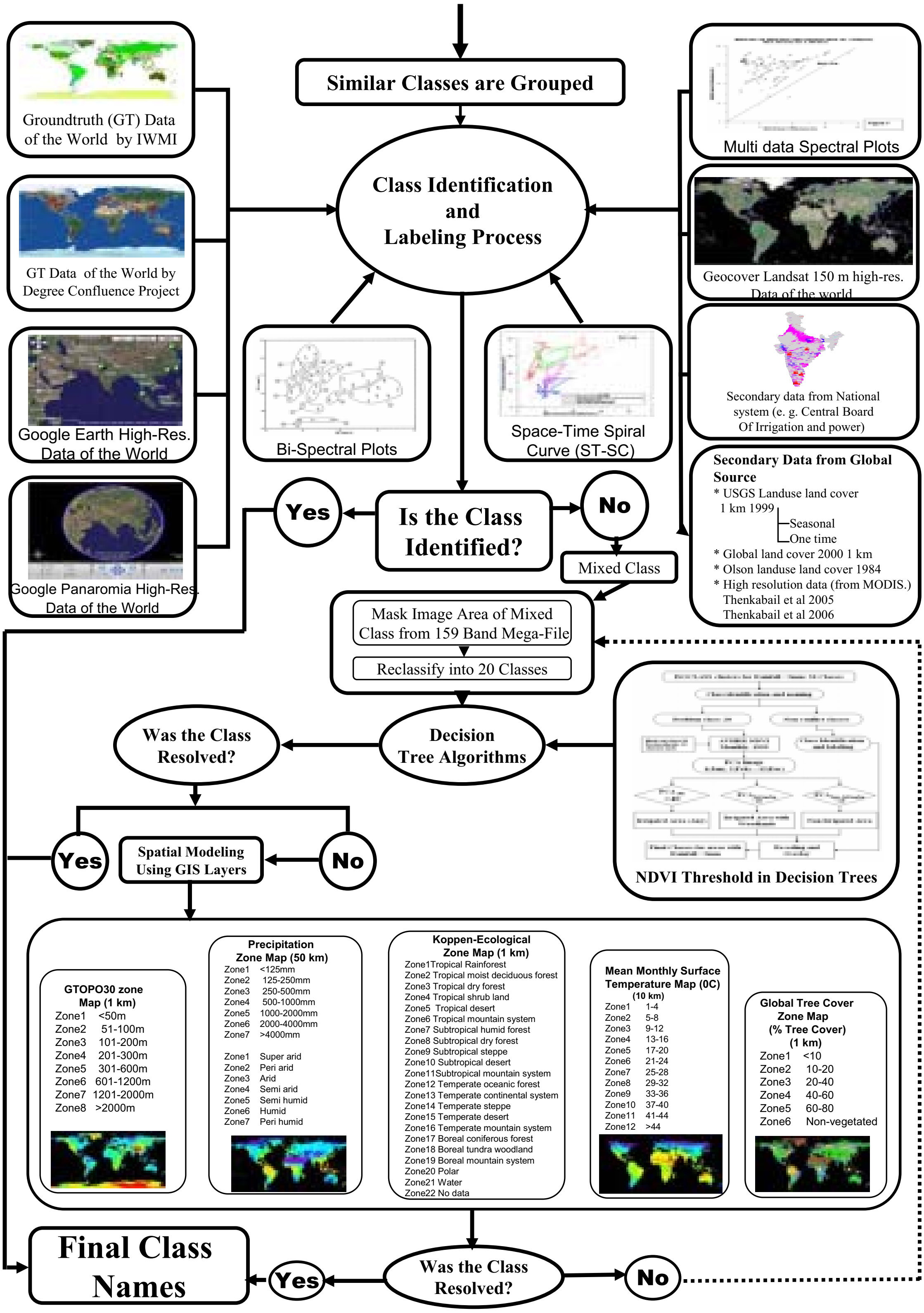
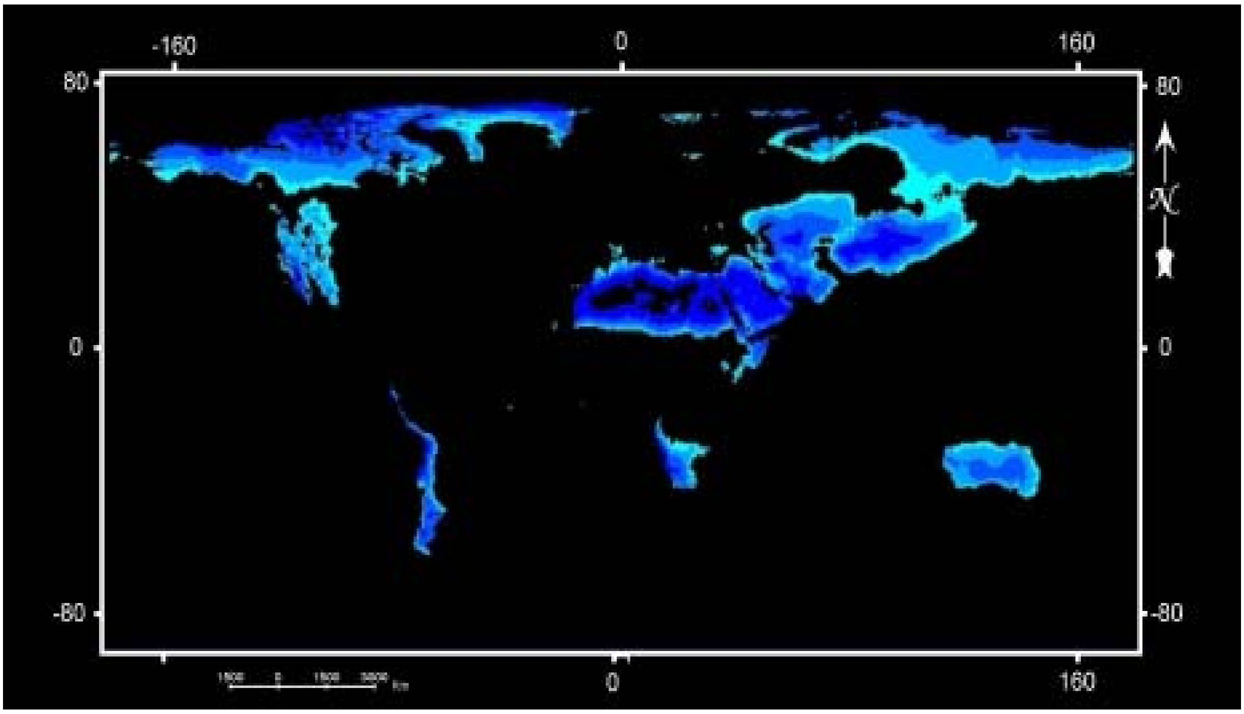


Figure 5.

Precipitation less than 360 mm segment (PLT360-segment). These arid or semiarid areas provide distinct contrasts between areas with and without vegetation.



unsupervised classification, which identified characteristic land units for investigation and this was done for the IWMI field campaigns in India. However, at global scale this was not possible, and a combination of techniques was employed to first group classes based on the similarity of their time-series behavior, then identified in more detail what they were through understanding the spatial-temporal variations in reflectance and cross referencing to higher-resolution images (GeoCover 150; Tucker et al. 2005), existing GIS, maps and groundtruth data.

Spectral Matching Techniques

Time series of NDVI or other metrics are analogous to spectra, where time is substituted for wavelength. Considerable research effort has been made into hyperspectral imagery analysis and this yields a number of promising avenues, developed here, for the analysis of time series. Spectral Matching Techniques (SMTs) have mostly been applied to hyperspectral data analysis of minerals (Homayouni and Roux 2003; Shippert 2001; Tou and Gonzalez 1975; Farrand and Harsanyi 1997; Granahan and Sweet 2001; Thenkabail et al. 2005a, b).

The principle in spectral matching is to match the shape or the magnitude or (preferably) both to an ideal or target spectrum (commonly known as a pure class or “end-member”). The time-series signatures of irrigated crops across the globe can match (tropics) or be out of phase (tropics and the southern hemisphere).

We also attempted to use Modified Spectral Angle Similarity (MSAS) (Shippert 2001; Homayouni and Roux 2003; Farrand and Harsanyi 1997; Schwarz and Staenz 2001; Thenkabail et al. 2006) which measures the hyperspectral angle between spectra of any two classes or between target and sample class spectra. However, the practical implementation of this was troublesome (see also Thenkabail et al. 2006), often providing uncertain results, and so it is not discussed further.

Qualitative Spectral Matching

Qualitative spectral matching is often performed before quantitative approaches (e.g., figure 6a). It provides a preliminary indication of which classes group together and which stand apart. Indeed the classes that match up through: a) shape only, and/or b) magnitude only, and/or c) both shape and magnitude, are identified visually. When two classes, such as continuous irrigation and forests, match and provide high quantitative correlations, it is essential to plot both classes with reference to their spatial location using groundtruth or ancillary data.

Quantitative Spectral Matching

Two quantitative spectral matching techniques were used in this study. These were:

- spectral correlation similarity (SCS) R^2
- spectral similarity value (SSV)

The SCS R^2 value has been applied to match the shape of any class to the selected target class. The SSV has been used to determine the match of both shape and magnitude (SAS Institute 2004). The SMTs are discussed in detail by Thenkabail et al. (2006).

The process of spectral matching is illustrated beginning with a plot of multiple time series and two selected target series in figure 6b, which are characteristic of two irrigated crops per year in the Indian subcontinent.

The extraction and geographical location of similar classes are shown in a more pictorial way in figure 7.

Figure 6a.

Time-series AVHRR 10-km profile of spectral classes is illustrated for AOAW-segment. Initially, the AOAW-segment had 350 classes. The plot of some of these classes highlights the spectral characteristics of each class. A quantitative approach to determine which of these classes match is performed through SCS R^2 (e.g., table 4).

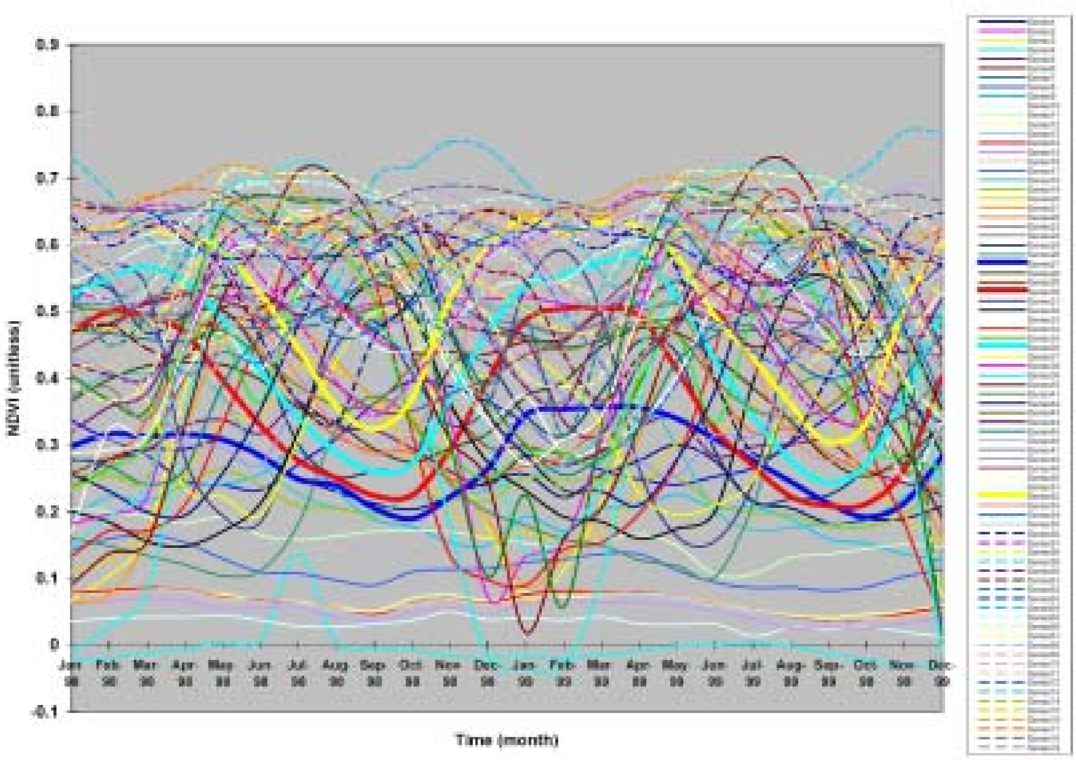


Figure 6b.

Identifying similar irrigated classes using spectral matching. Spectral matching in combination with ground truthing and ideal spectra helps group similar irrigated (shown in dark green, for classes 25, 26, and 27). The same logic was used to group: forests (sown in light green; class numbers 1, 2, 3, 4 and 5), Savanna/Croplands mix (Orange; class 50, 59, 60, 67, 74), and Barren/Deserts (shown in blue; classes 10 to 15).

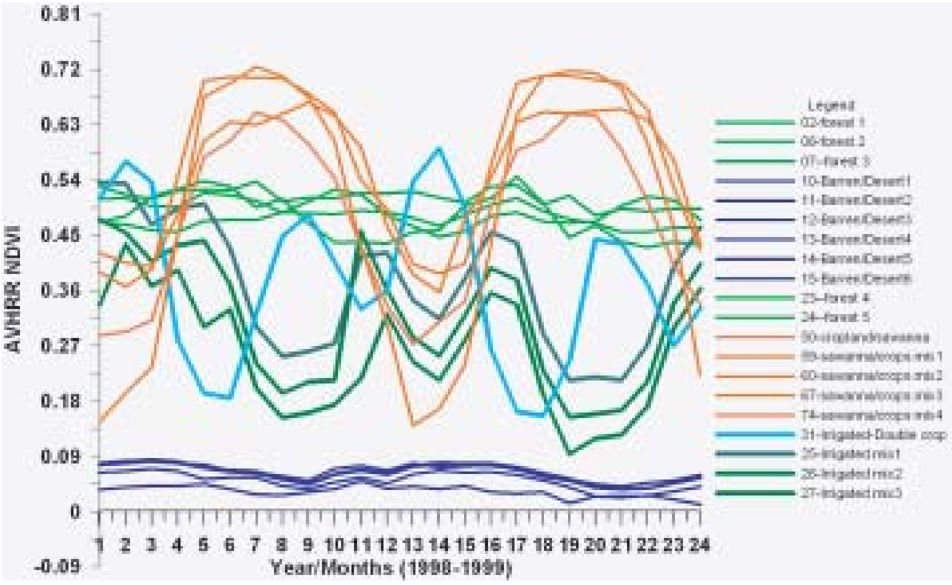
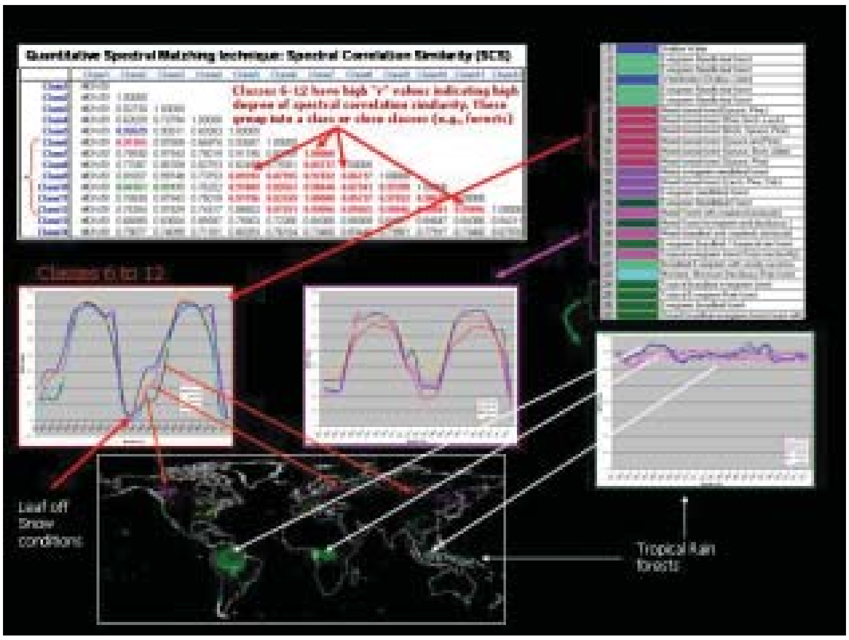


Figure 7.

The process of combining classes in spectral matching techniques (SMTs) is illustrated. First, the SCS R^2-values are determined for a matrix of classes. The time-series spectra of classes with high SCS R^2-values are then matched. Grouped classes are investigated further, using all other types of information including groundtruth. This leads to distinct groups such as boreal forests and tropical forests. Finally, the classes of similar types are color-coded.



Google Earth as a Resource for Class Naming

Once the classes are grouped by spectral similarity, each one is investigated by taking 20-50 sample points on Google Earth spread across the world (figure 8). If there is overwhelming evidence that the class falls into a particular category, an indicative name is assigned. The interpretation of a class is based on visual indicators such as shape (e.g., central pivot circles), size (e.g., reservoir size for large and small scale), pattern (e.g., contiguous farms) and texture (e.g., smooth texture of a farm compared to rough texture of a forest). The process is repeated for every class in a group. If the Google Earth sample points for a class indicate a mixed land use/land cover, then the class is further processed either through decision trees or is reclassified, or GIS spatial modeling is applied to derive homogeneous classes.

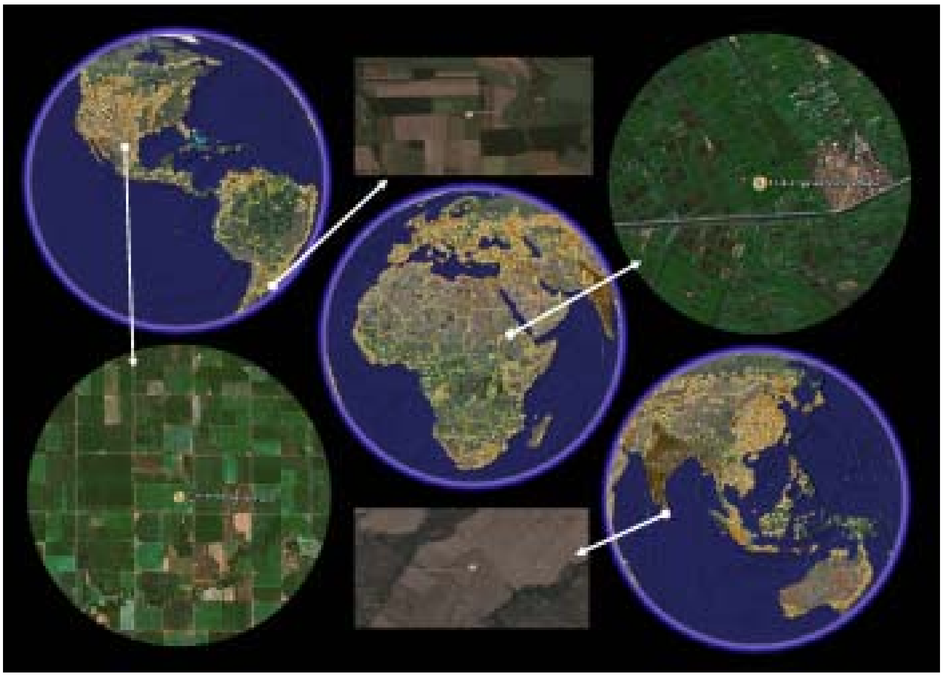
Advanced Techniques for Class Identification

In addition to section 5.1 through 5.4, a rigorous class identification and labeling process was followed as follows (see figure 4 and GIAM web portal: *http://www.iwmigiam.org*):

- brightness, greenness and wetness for a single date
- space-time dynamics of brightness, greenness and wetness
- NDVI time series and cropping intensity
- brightness temperature
- class refinement
- rule-based decision trees
- simple decision trees with principal components
- GIS spatial modeling

Figure 8.

Google Earth “zoom in” views to identify a class. One preliminary class is spread out across the world. The class was investigated using 50 Google sample points that were randomly chosen. The figure shows the spread of the class across the world and Google Earth hi-res image at two locations: Center pivot groundwater irrigation in the USA and surface irrigation in Sudan.



Overall, ~10,726 points (e.g., yellow points also called “place marks” in figure 8) were used in identifying and providing indicative class labels in the generic 951 class GIAM10 km map.

Class-Naming Convention

The GIAM work, based on interpretation of classes from various segments, leads to 951 dissaggregated classes; each of these classes in turn coming from several other classes. Standardized naming of classes becomes even more important when several interpreters are involved, to avoid interpreter bias. The standardardized class naming convention involved watering method, type of irrigation, crop type, scale, intensity, location and type of signature (see figure 9).

- disaggregated 28-class global irrigated area map (GIAM10 km-28 class)
- aggregated 8-class global irrigated area map (GIAM10 km-8 classes)
- disaggregated 323-class global irrigated area map (GIAM10 km-323 class)

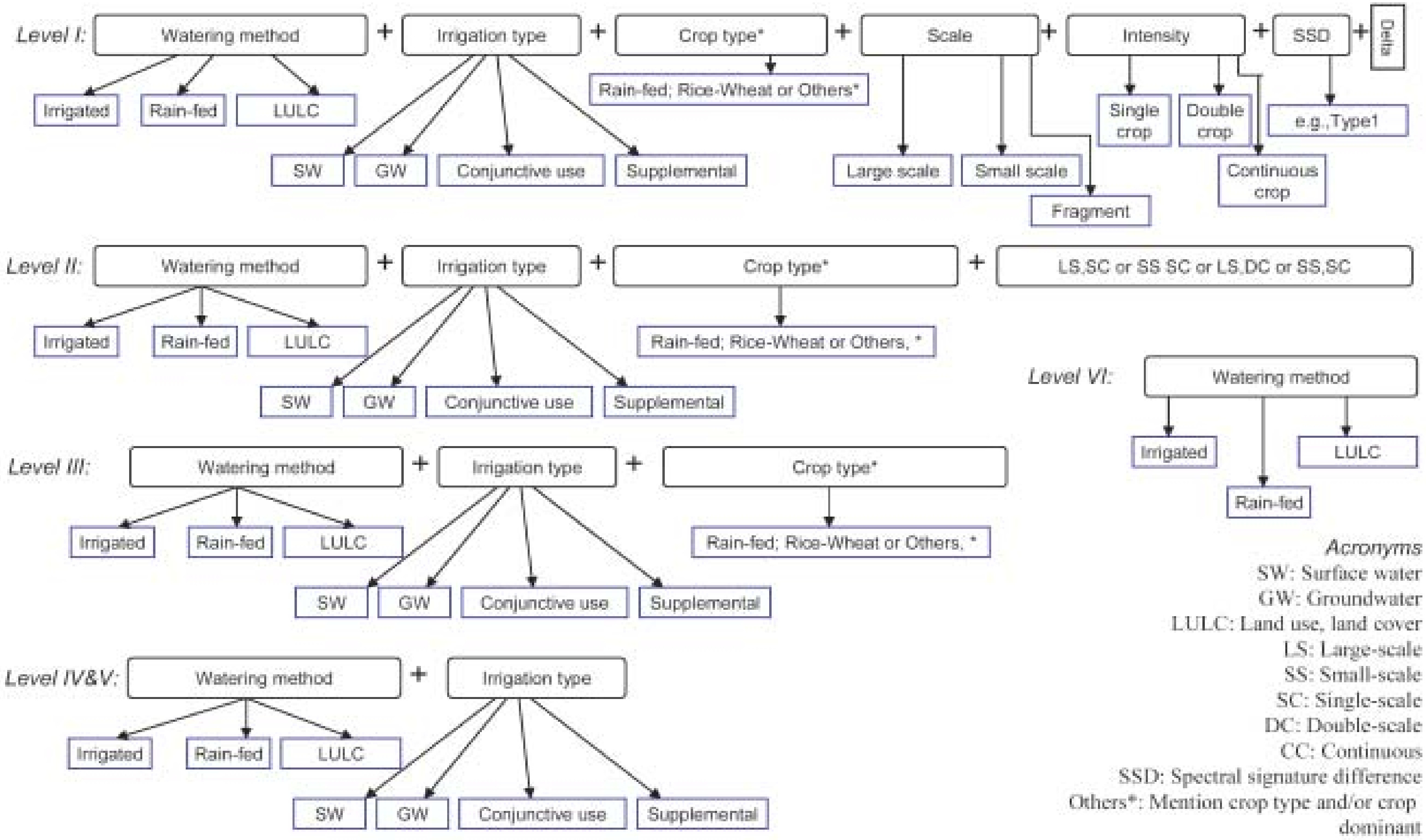
The GIAM10 km-28 class irrigated area map is the main irrigated area product, but two simplified GIAM10 km M-8 class, and GIAM10 km-3 class maps have been produced to ease visualization and understanding by irrigation practitioners. The GIAM10 km-3 class map consists of the following classes:

- irrigated surface water
- irrigated groundwater
- irrigated conjunctive use

The standardized class-naming convention is depicted in figure 9. At different levels, the class naming may or may not include a particular category, such as the scale of irrigation or the intensity.

Figure 9.

Class naming convention. The standardized class naming convention is depicted in this figure. At different levels, the class naming may or may not include a particular category such as scale of irrigation or the intensity.



Estimating Irrigated Areas Using Three Methods

An estimate of the irrigated areas of the world must take account of different crop seasons, cropping patterns and intensity. In this analysis, we estimate the area based on the cropping calendar and then determine whether the crop is single, double or continuous.

Since pixel sizes are large at 1 km, and dominated by AVHRR time series at 10 km, it is important to estimate the proportion of any one pixel that is irrigated in each season. The use of total pixel area would result in a massive overestimate. The full pixel areas (FPAs) were converted to sub-pixel areas (SPAs) using irrigated area fractions (IAFs). The overall procedure is shown in figure 10. In order to obtain reliable estimates of sub-pixel areas, we use three methods:

- Google Earth estimates (GEE) (figure 11; section 7.1)
- high resolution imagery (HRI) (figure 12; section 7.2)
- sub-pixel decomposition techniques (SPDT) (figure 13; section 7.3)

Figure 10.

Summary of area abstraction from the 28 irrigation class map.

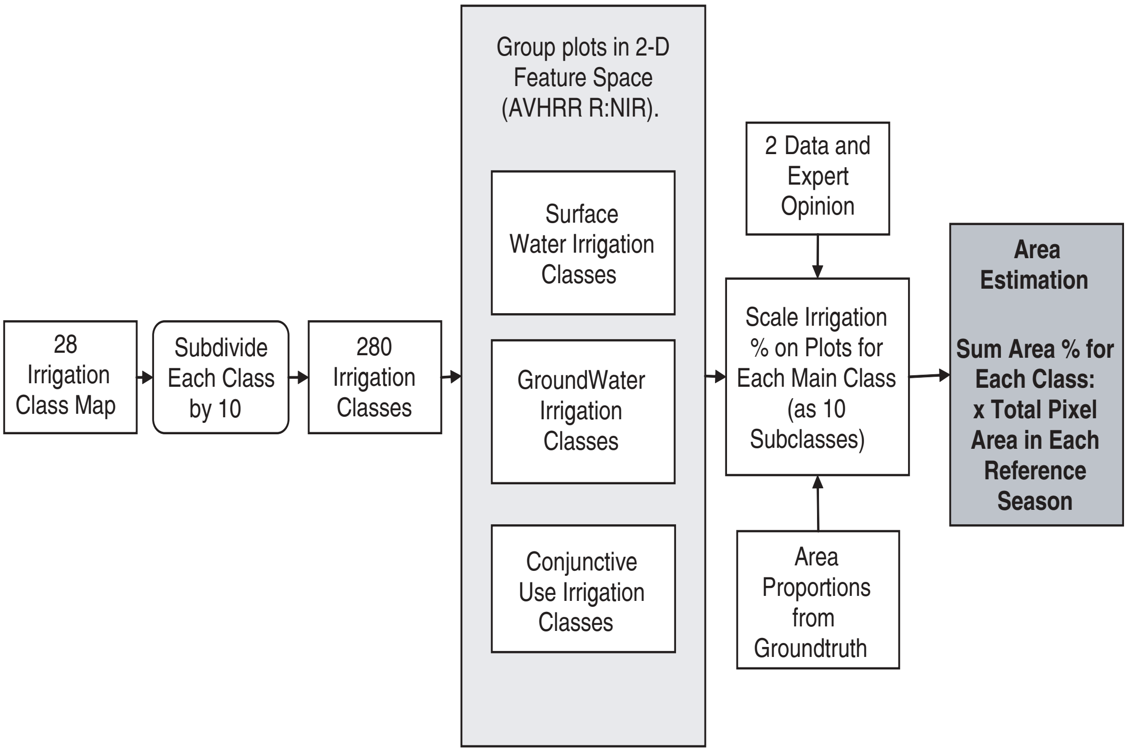
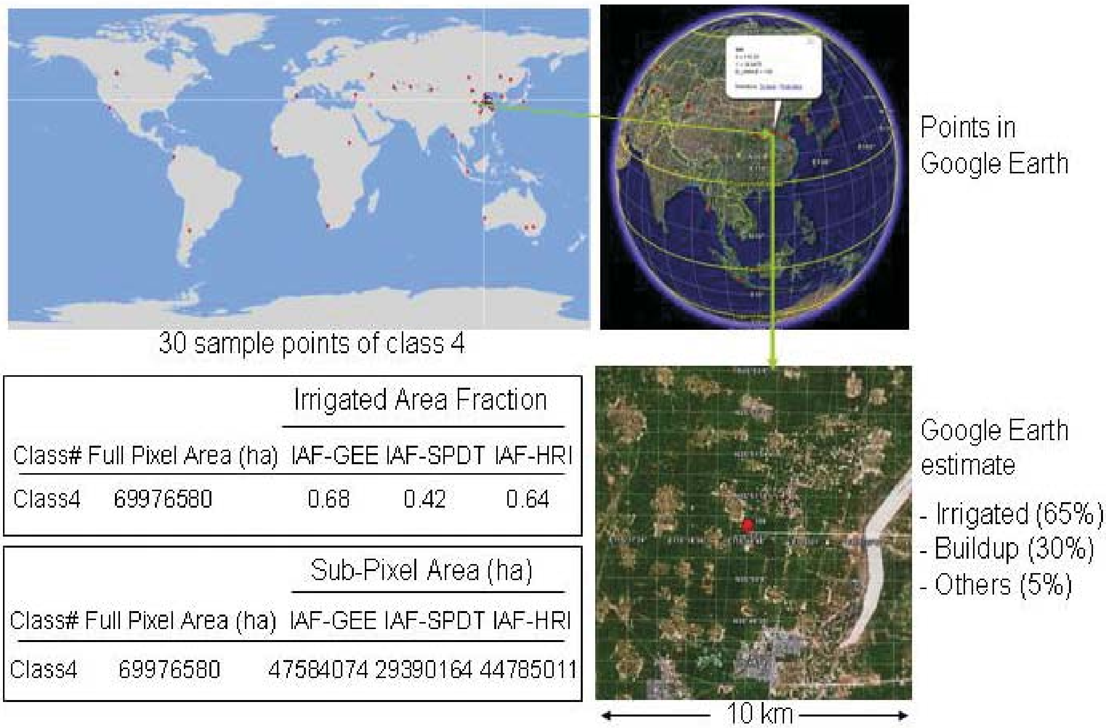


Figure 11.

Irrigated area by Google Earth estimates (GEE). For each GIAM10 km-28 classes GEE of irrigated area fraction (IAF) were estimated using Google Earth images. Thirty points were taken for each class and averaged. The fraction calculation for one class is illustrated.



The SPDT (figure 13) and HRI approaches provide irrigated area intensities for different crop-growing seasons (see table 3), whereas the GEE approach provides net irrigated areas without intensity

Irrigated Area Fraction (IAF) Based on Google Earth Estimates

The IAF from Google Earth estimates (GEE) involves determining percent area irrigated for every GIAM10 km-28 class by zooming into Google Earth images (e.g., figure 11). On average, at least 30 points were randomly surveyed for every class and the IAF determined as the average area irrigated from all these points. The process is repeated for all classes. The GEE approach acts as “groundtruth” for the class.

SPA of Pixels Based on High-Resolution Imagery

The second method of SPA estimation uses Landsat ETM+ images at 30 m resolution. At least three high-resolution images are downloaded per growing season for each of the 28 irrigation classes. The Landsat ETM+ grid is overlaid on the GIAM class and images for estimation of the actual irrigated area within 10 km pixels. If a class has two seasons, six images are downloaded and analyzed so that three images are studied and averaged to determine the IAF in a given season.

Figure 12.

Irrigated area fraction from high-resolution imagery (IAF-HRI). For each of the GIAM10 km-28 classes the IAF-HRI were estimated by masking Landsat images for the area occupied by the class and then determining irrigated vs. nonirrigated areas.

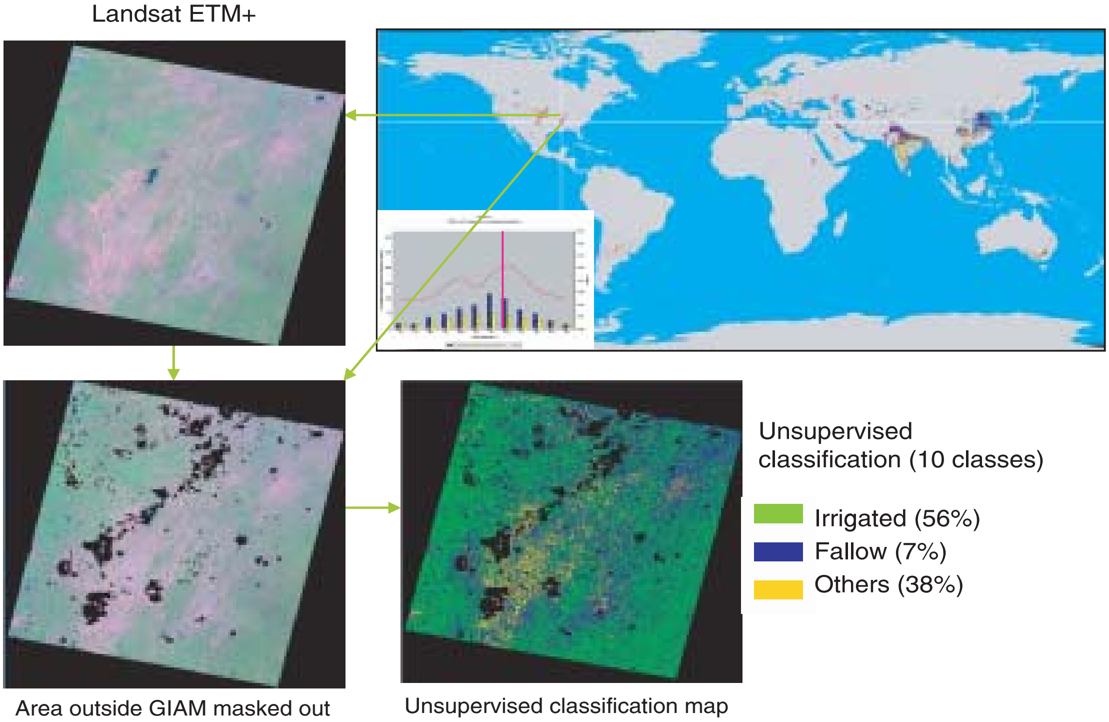


Figure 13.

Sub-pixel decomposition technique (SP-DCT).

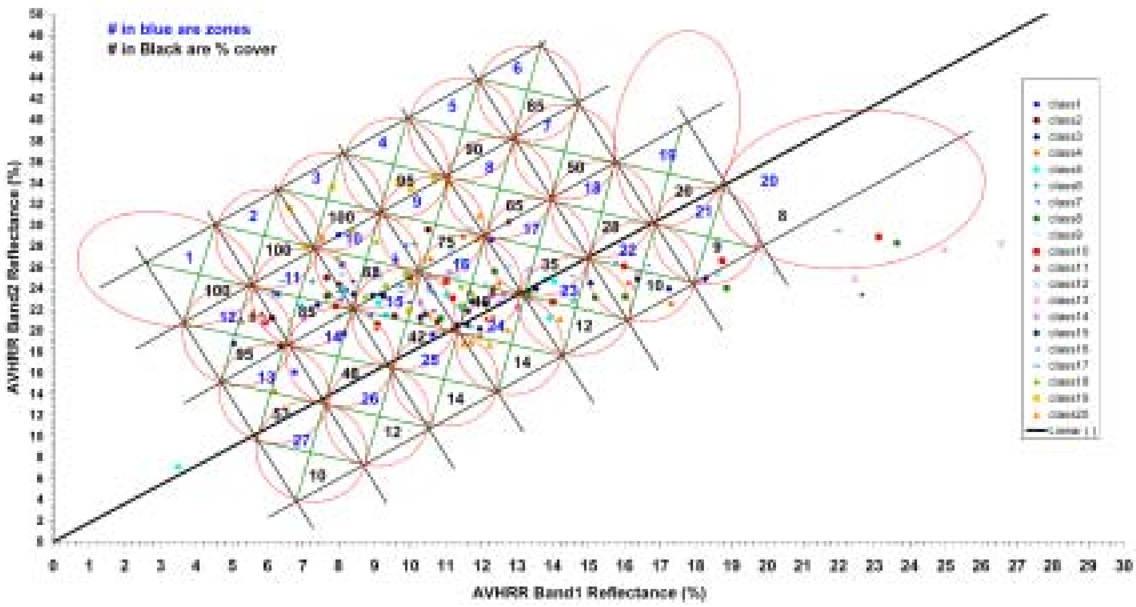


Table 3.

Characterization of class-wise cropping calender based on the AVHRR NDVI (1999).

Class no.	GMIA 28 Classes Class Name	Single Crop	Double Crop First	Double Crop Second	Continuous Crop
1	01 Irrigated, surface water, single crop, wheat-corn-cotton	Mar-Nov			
2	02 Irrigated, surface water, single crop, cotton-rice-wheat	Apr-Oct			
3	03 Irrigated, surface water, single crop, mixed-crops	Mar-Oct			
4	04 Irrigated, surface water, double crop, rice-wheat-cotton		Mar-Jun	Jul-Oct	
5	05 Irrigated, surface water, double crop, rice-wheat-cotton-corn		Jun-Oct	Dec-Mar	
6	06 Irrigated, surface water, double crop, rice-wheat-plantations		Jul-Nov	Dec-Mar	
7	07 Irrigated, surface water, double crop, sugarcane		Jun-Nov	Dec-Feb	
8	08 Irrigated, surface water, double crop, mixed-crops		Jul-Nov	Dec-Apr	
9	09 Irrigated, surface water, continuous crop, sugarcane				Jul-May
10	10 Irrigated, surface water, continuous crop, plantations				Jan-Dec
11	11 Irrigated, ground water, single crop, rice-sugarcane	Jul-Dec			
12	12 Irrigated, ground water, single crop, corn-soybean	Mar-Oct			
13	13 Irrigated, ground water, single crop, rice and other crops	Mar-Nov			
14	14 Irrigated, ground water, single crop, mixed-crops	Jul-Dec			
15	15 Irrigated, ground water, double crop, rice and other crops		Jul-Nov	Dec-Mar	
16	16 Irrigated, conjunctive use, single crop, wheat-corn-soybean-rice	Mar-Nov			
17	17 Irrigated, conjunctive use, single crop, wheat-corn-orchards-rice	Mar-Nov			
18	18 Irrigated, conjunctive use, single crop, corn-soybeans-other crops	Mar-Oct			
19	19 Irrigated, conjunctive use, single crop, pastures	Mar-Dec			
20	20 Irrigated, conjunctive use, single crop, pasture, wheat, sugarcane	Jul-Feb			
21	21 Irrigated, conjunctive use, single crop, mixed-crops	Mar-Nov			
22	22 Irrigated, conjunctive use, double crop, rice-wheat-sugar cane		Jun-Nov	Dec-Mar	
23	23 Irrigated, conjunctive use, double crop, sugarcane-other crops		Apr-Jul	Aug-Feb	
24	24 Irrigated, conjunctive use, double crop, mixed-crops		Jul-Nov	Dec-Feb	
25	25 Irrigated, conjunctive use, continuous crop, rice-wheat				Mar-Feb
26	26 Irrigated, conjunctive use, continuous crop, rice-wheat-corn				Jun-May
27	27 Irrigated, conjunctive use, continuous crop, sugarcane-orchards-rice				Jun-May
28	28 Irrigated, conjunctive use, continuous crop, mixed-crops				Jun-May

Classification Approach

The Landsat images are first “masked” to match areas defined in the global map (see figure 12). The image is then classified into 10 unsupervised classes. The irrigated versus nonirrigated areas are then identified using our class identification schemes (see figure 4). Then the IAF is the percent area irrigated compared to total area of the masked Landsat image. Two other methods were assessed (7.2.2 and 7.2.3), but were not as effective as this technique (7.2.1).

Regression Relationships

The HRI images were also resampled to 10-km to match with AVHRR pixels and co-registered (see DeFries and Townshend 1994). 325 AVHRR 10-km pixels are equivalent to one Landsat image (185 x 170 km). The AVHRR NDVI from the 325 pixels were then plotted against the Landsat ETM+NDVI (“vegetation area fraction”) from the resampled 10-km Landsat data. However, the resulting relationship was not clear as a result of pixel size differences as well the problems associated with precise co-registration. Hence, the classification approach in section 7.3.1 is considered superior

Irrigated Area Fraction (IAF) Coefficient

At times, a clear regression relationship between AVHRR NDVI and IAF with high R^2-value may be absent. In such a case, it will suffice to determine IAF for the entire class, based on the selected Landsat image by digitizing the irrigated versus nonirrigated areas on the Landsat image. However, this approach is tedious and has limitations of visual interpretation.

Sub-Pixel Decomposition Technique

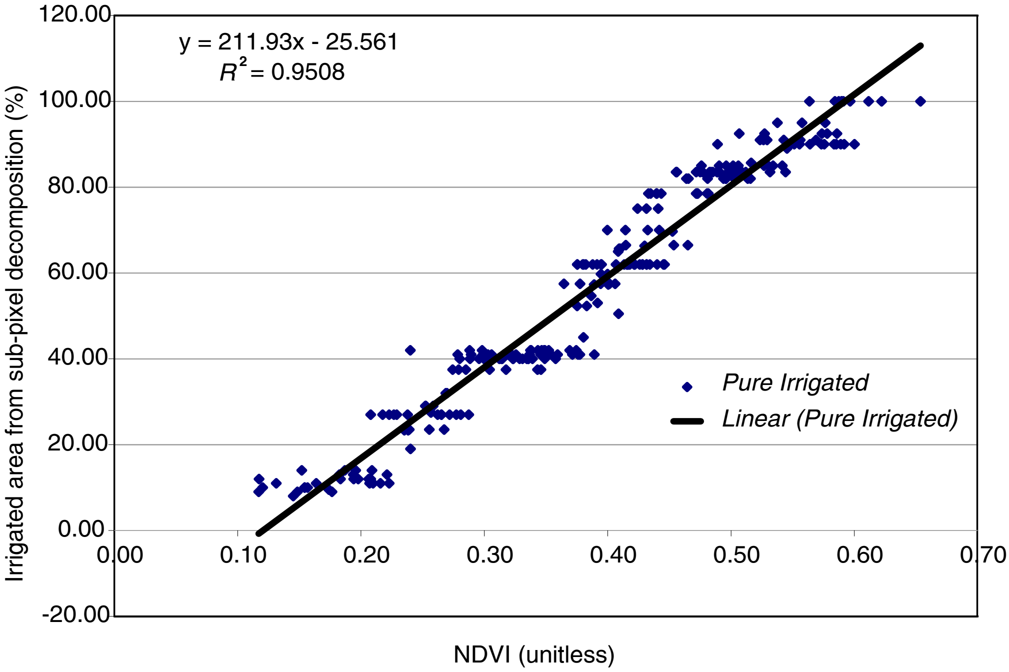
Determination of IAFs by sub-pixel decomposition (SPDT) involves plotting AVHRR band 1_{min} (absorption maxima) versus AVHRR band 2_{max} (reflection maxima) of all the pixels in 10 subclasses of a class and then scaling percentage across them. The scaling is based on the knowledge base from groundtruth data, digital photos, high-resolution images, literature and relative positioning of the pixels in the greenness-wetness-brightness areas in the RED versus NIR plots.

Each of the 28 irrigation classes is subdivided into 10 giving a total class number of 280 for area estimation. The AVHRR band 1_{max} and AVHRR band 2_{max} values for each subclass are plotted, as for a BGW plot (e.g., figure 13), and the percentage area irrigated is determined, based on the location of the point in 2-d feature space (figure 13). The percentage of irrigation is assigned according to a) percent irrigated area canopy cover versus AVHRR 10-km band reflectivity and NDVI relationships from the Krishna and Ganges groundtruth data; b) percent cover recorded in IWMI groundtruth data of the world versus AVHRR 10-km NDVI or band reflectivity, and c) extensive literature review (Settle and Drake 1993; Drake et al. 1997; Purevdorj et al. 1998; Xiaoyang et al. 1998; Purevdorj and Tateishi 2001; Li et al. 2003). The actual irrigated area for a given class is determined as the sum of the total pixel areas, multiplied by the sub-pixel percentages for each of the 10 subclasses.

The greater the understanding one has of percent irrigated area versus band reflectivity, the greater the reliability of the resulting area calculations. In this case, the understanding comes from a combination of field and remote sensing experience and is therefore limited by the available geographical and farming system coverage. Figure 13 shows an illustration for 20 classes, each with 10 subclasses, plotted on a 2-dimentional SPDC plot. Figure 14 shos the relationship between percent irrigated area of class 1-20 and the AVHRR NDVI computed using band 1_{max} and AVHRR band 2_{max} reflectivity.

Figure 14.

Relationship between percent irrigated area of class 1-20 and the AVHRR NDVI computed using band 1_{max} and AVHRR band 2_{max} reflectivity.



Accuracy Assessment

A number of different approaches were adopted to assess accuracies and errors (see Congalton and Green 1999; Thenkabail et al., 2005c). We concentrated on the irrigated area classes and point-based accuracy and error estimates were performed on two data sets based on:

$$\text{Accuracy of irrigated area class} = \frac{\text{Groundtruthed irrigated points classified as irrigated area}}{\text{Total number of groundtruthed points for irrigated area class}} * 100$$

$$\text{Errors of commission for irrigated area} = \frac{\text{Nonirrigated groundtruth points falling on irrigated area class}}{\text{Total number of nonirrigated groundtruth points}} * 100$$

$$\text{Errors of omission for irrigated area} = \frac{\text{Irrigated groundtruth points falling on nonirrigated area class}}{\text{Total number of irrigated area groundtruth points}} * 100$$

Accuracy assessment makes use of three distinct sources of reference data, so as to obtain a robust understanding of the accuracies of the GIAM10 km map V2.0 so that it can be compared to the Food and Agricultural Organization and University of Frankfurt (FAO/UF) map of global irrigated area. We also make a three-way comparison for India, with reference to the Central Board for Irrigation and Power (CBIP). The distinct sources of reference data are listed in section 4. The GEE data are completely independent, and are randomly generated. The degree confluence project (DCP) groundtruth (GT) data are relatively independent in that the DCP points are independent, but not the other GT points. The other GT data were also used in class identification and labeling.

Groundtruth Data Sets from the GIAM Project

A total of 895 GT points were gathered by the GIAM project during 2004 and 2005 through a series of groundtruth campaigns that included missions to all of India, and separate missions to Krishna and Ganges basins, Sri Lanka, Uzbekistan, South Africa, and Mozambique. These data are far more refined for accuracy assessment than the second data set because of their exclusive focus on irrigated areas. However, we do not have broad coverage across the world.

Other Groundtruth

A larger set of groundtruth data with 1,863 points is also used for accuracy assessment. This data set has far better spatial distribution across the world. However, the data themselves come from various sources that include a) Degree Confluence Project (DCP), b) various IWMI projects (e.g., wetlands, water productivity) and c) the GIAM project.

Google Earth Estimates

Accuracy assessments were also made using 670 locations inspected in Google Earth at 30-m pixel scale or better. All GIAM irrigated area classes were combined into a single irrigated class. The 670 sample locations were randomly chosen and their land use determined in terms of irrigated or not irrigated. These points were overlaid on the irrigated area map and overall accuracy and errors of omission and commission were determined.

Results

Global Irrigated Area Map Version 2.0 (GIAM10 km V2.0)

The spatial distribution of the irrigated area classes in the global irrigated area map (GIAM) are produced as a disaggregated map (GIAM10 km-28 classes; figure 15) and aggregated maps (GIAM10 km-8 classes, figure 16). GIAM10 km-28 classes provide information on irrigation type (surface water, groundwater and conjunctive use), irrigation intensity (single, double or continuous crop) and crop type. The 8 class map provides watering method, irrigation type and intensity. The 3 classes in the third map are surface water irrigation, groundwater irrigation and conjunctive use (surface water and groundwater) irrigation. The GIAM10 km-28 class map has a complex set of classes and provides an understanding of their distribution and class characteristics over time and space (table 3). The proportion of single, double and continuous cropping allows calculation of areas based on cropping intensities (i.e., single, double, continuous) leading to annualized areas (summation of areas from different seasons). The cropping intensities and calendars in table 3 become more accurate if we look at individual countries or sub-national administrative units.

Areas of Irrigation Derived from GIAM10 km Map V2.0

The irrigated areas of the world were estimated by the three methods (section 7) and the results are presented here.

First, the areas are determined using irrigated area fraction from GEE total 401 Mha, without any specific information on cropping intensity.

The seasonal and annualized irrigated areas are determined using irrigated area fraction from the high-resolution imagery and sub-pixel decomposition technique (table 4a). For each of the 28 classes (figure 15), we used the average IAF coefficients to calculate seasonal and annualized areas (summed over all seasons). The estimated total global irrigated areas for the 3 seasons are (table 9a): a) 263 Mha for season 1, b) 176 Mha for season 2, and c) 41 Mha for season 3. The annualized global irrigated area at the end of the last millennium was 480 Mha.

The areas have also been summarized for the 8 class map (table 4b).

The major finding of the IWMI analysis is that the net (401 Mha) and the annualized (480 Mha) cropped area under irrigation very significantly exceeds the estimates of equipped area (274 Mha) by FAO, due to the extent of multiple cropping and private and community-developed irrigation. The area estimates in the map are derived for each characteristic agricultural system around the world (e.g., long-season winter-sown cereals in the northern hemisphere; triple rice cropping in SE Asia; wet monsoon season (kharif) and dry winter (rabi) systems in the Indian subcontinent). The figure of 412 Mha of the total area available for irrigation equates the equipped area in FAO and other estimates (257 Mha to 274 Mha; see van Schilfgaarde 1994; Siebert et al. 2002, Siebert et al. 2005). The development of global irrigated area over the last two centuries is summarized in figure 17, with and without estimates of cropping intensity. The presence of a large number of classes in GIAM10 km-28 classes (figure 15) ensures varying seasonality of classes by taking more precise cropping calendars between northern and southern hemispheres, the tropics, and the higher latitudes. The aggregated map (figure 16 and table 9b) loses this distinction. The spatial characteristics of the GIAM class information can be visualized using the higher- resolution Landsat ETM+ resampled 150-m images, digital photographs, and Google Earth images from the specific locations (figure 18). The GIAM class information, presented in this manner is of considerable value for the user who would like to have a “visual picture” (figure 18a to f).

Figure 15.

GIAM10 km V2.0 28 class map.

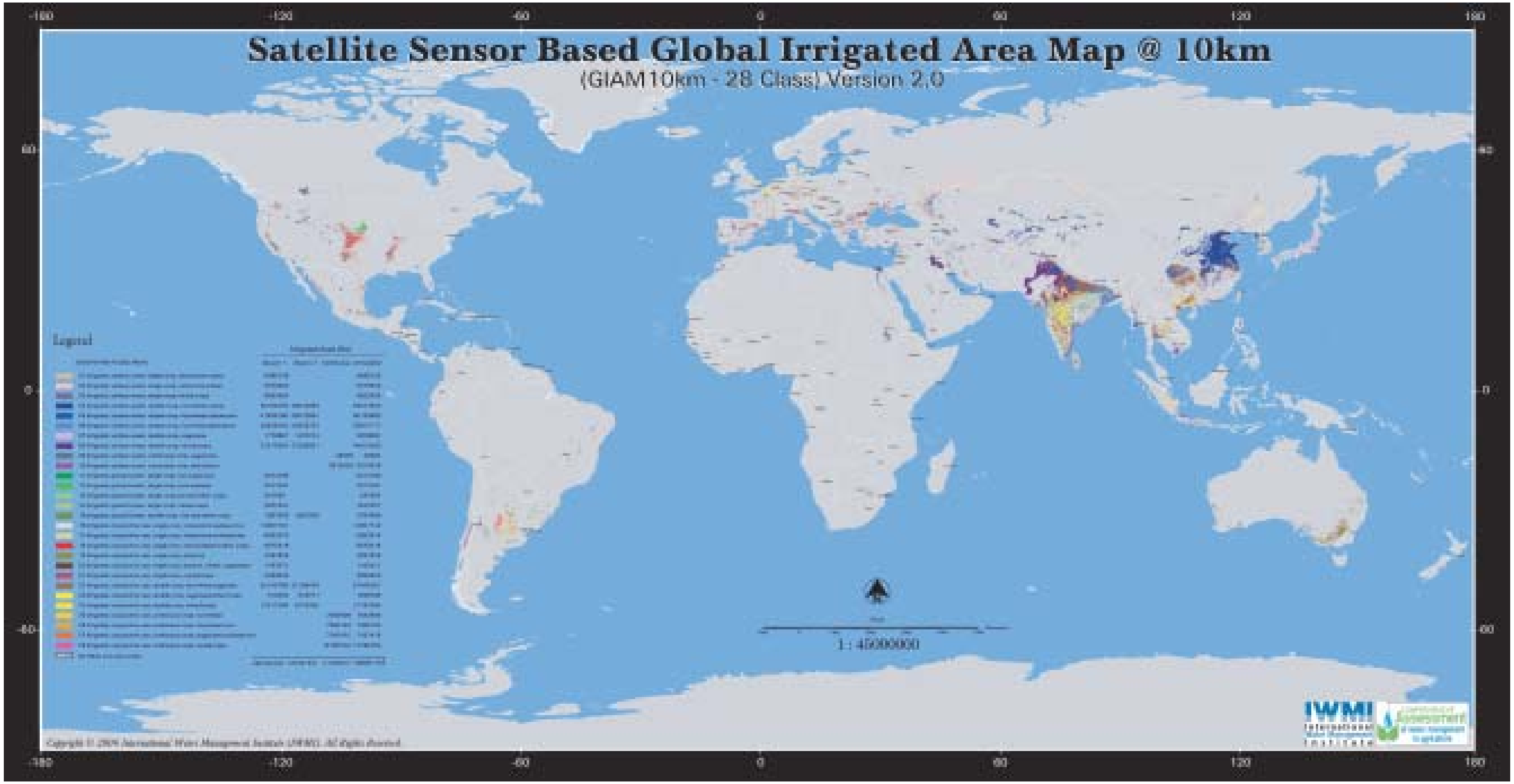


Figure 16.

GIAM10 km V2.0 8 class map.

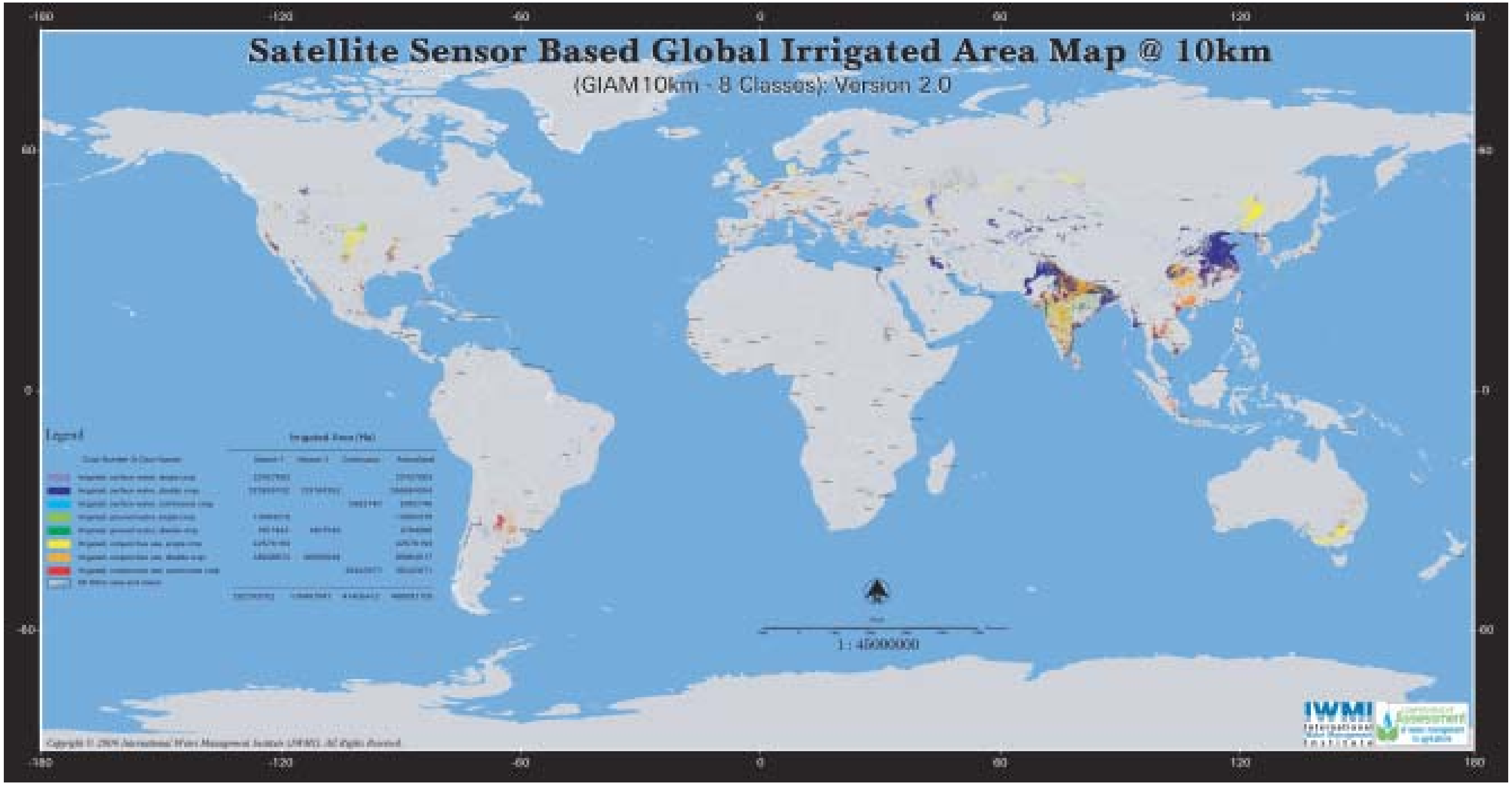
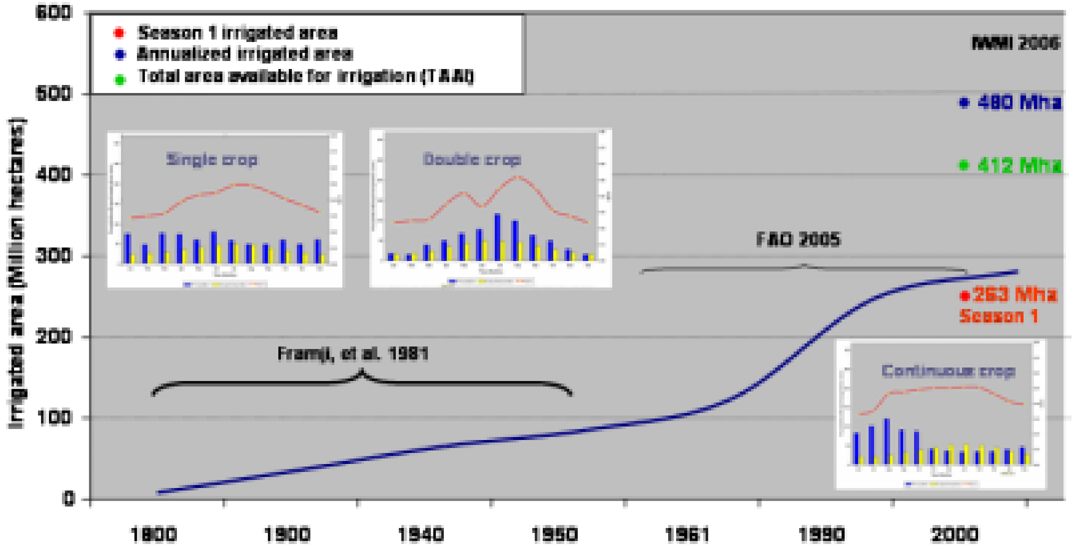


Figure 17.

Trends in irrigated area since 1800. The IWMI estimate (*http://www.iwmigmia.org*) at the end of the last millennium considered not only area irrigated but also the intensity (i.e., area irrigated during different seasons in a 12-month period and informal irrigation (e.g., groundwater, tanks). This gives an estimate of 263 million hectares (Mha) during the “main” cropping season (season 1) and a total of 480 Mha for three seasons: first crop (263 Mha), second crop (176 Mha), and continuous crop (41 Mha).



Irrigated Areas of Continents, Countries and River Basins

Irrigated areas were also calculated, based on combined IAF-HRI and IAF-SPDT, for the continents (table 5a), the countries (table 5b), and the IWMI and Challenge Program benchmark river basins (table 5c).

Of the 480 Mha annualized irrigated areas in the world, 78 percent (375 Mha) is in Asia, 8 percent in Europe, 7 percent in North America, 4 percent in South America, 2 percent in Africa and 2 percent in Australia. The area distributions for the seasons follow similar trends (table 5a). In Europe and North America, the overwhelming proportion of irrigation is during the one main cropping season. In Asia, 154 Mha are irrigated in

season 2 compared with 195 Mha during season 1. Surface water irrigation accounts for 61 percent of global irrigation, with the remaining 39 percent accounting for conjunctive use (surface water and groundwater) and groundwater. The surface water is well separated. The groundwater is often contained within (and often dominates) the conjunctive use class.

Of the total global irrigated area of 480 Mha, China (31.5%) and India (27.5%) constitute a total of 59 percent (table 5b). The next countries have comparatively low percentage irrigated areas: USA (5%), Russia (3.5%) and Pakistan (3.3%). There are 9 countries (Argentina, Australia, Bangladesh, Kazakhstan, Myanmar, Thailand, Turkey, Uzbekistan and Vietnam) with 1 to 2 percent. Brazil is ranked 15th with 0.85 percent (table 5a). All other countries of the world have less than 1 percent or less irrigated area. Forty countries have nearly 96 percent of all annualized irrigated areas of the world (table 5b). Normally, (see Droogers 2002; Postel 1999) India is considered the leading irrigated area country, closely followed by China. However, ourestimates show, China has 151 Mha of annualized irrigated area with India having 132 Mha. In the first season, China has 76 Mha and India 73 Mha, which is close. However, in the

Table 4a.

Irrigated area fractions and irrigated areas from 3 methods. The sub-pixel areas (SPAs) are calculated for GIAM10 km-28 classes using irrigated area fractions (IAFs).

Class No.	Class name	Full pixel area (FPA)	Irrigated area fraction based on Google Earth estimate & HRI+fallow (IAF-GEE & HRI+fallow) coefficient	Total area available for irrigation (TAAI) (FPA* mean of IAF-GEE & HRI + fallow	Season 1 irrigated area fraction based on mean IAF-HRI & IAF-SPDT coefficient	Season 1 sub-pixel Irrigated area from mean IAF-HRI & IAF-SPDT	Season 2 irrigated area fraction based on mean IAF-HRI & IAF-SPDT coefficient	Season 2 sub-pixel irrigated area from mean IAF-HRI & IAF-SPDT	Continuous irrigated area fraction based on mean IAF-HRI & IAF-SPDT coefficient	Continuous sub-pixel irrigated area from mean IAF-HRI & IAF-SPDT	Annualized sum sub- -pixel irrigated area from mean IAF-HRI & IAF-SPDT
		hectares	unitless	hectares	unitless	hectares	unitless	hectares	unitless	hectares	hectares
1	Irrigated, surface water, single crop, wheat-corn-cotton	10679303	0.73	7795588	0.61	6496129					6496129
2	Irrigated, surface water, single crop, cotton-rice-wheat	16958834	0.85	14461753	0.55	9378930					9378930
3	Irrigated, surface water, single crop, mixed-crops	14225471	0.68	9689678	0.46	6552505					6552505
4	Irrigated, surface water, double crop, rice-wheat-cotton	69927583	0.71	49779404	0.53	36762836	0.67	46810689			83573525
5	Irrigated, surface water, double crop, rice-wheat-cotton-corn	74107732	0.63	46375254	0.56	41846166	0.52	38313697			80159863
6	Irrigated, surface water, double crop, rice-wheat-plantations	51997087	0.72	37554189	0.58	29938425	0.48	24878752			54817177
7	Irrigated, surface water, double crop, sugarcane	2661700	0.74	1978644	0.67	1778681	0.53	1422213			3200894
8	Irrigated, surface water, double crop, mixed-crops	60653494	0.64	38998678	0.37	22573594	0.37	22339001			44912595
9	Irrigated, surface water, continuous crop, sugarcane	116418	0.49	56932					0.42	49302	49302
10	Irrigated, surface water, continuous crop, plantations	13537958	0.61	8251981					0.44	5913439	5913439
11	Irrigated, ground water, single crop, rice-sugarcane	12896743	0.52	6714206	0.49	6312789					6312789
12	Irrigated, ground water, single crop, corn-soybean	5999530	0.70	4182848	0.49	2917041					2917041
13	Irrigated, ground water, single crop,rice and other crops	1573138	0.68	1065690	0.15	241994					241994
14	Irrigated, ground water, single crop, mixed-crops	11811268	0.47	5596037	0.38	4522457					4522457
15	Irrigated, ground water, double crop, rice and other crops	3569220	0.73	2594007	0.55	1957442	0.51	1807545			3764986
16	Irrigated, conjunctive use, single crop, wheat-corn-soybean-rice	29947111	0.84	25105955	0.47	14007142					14007142
17	Irrigated, conjunctive use, single crop, wheat-corn-orchards-rice	10602237	0.68	7218666	0.57	6052474					6052474
18	Irrigated, conjunctive use, single crop, corn-soybeans-other crops	17728042	0.73	12860800	0.51	9075419					9075419
19	Irrigated, conjunctive use, single crop, pastures	9151304	0.62	5672903	0.25	2287826					2287826
20	Irrigated, conjunctive use, single crop, pasture, wheat, sugarcane	2521554	0.77	1942687	0.46	1162911					1162911
21	Irrigated, conjunctive use, single crop, mixed-crops	17399815	0.77	13326514	0.57	9990422					9990422
22	Irrigated, conjunctive use, double crop, rice-wheat-sugacane	72276584	0.67	48519345	0.49	35740789	0.43	31299478			67040267
23	Irrigated, conjunctive use, double crop, sugarcane-other crops	1838672	0.69	1265539	0.39	720494	0.50	916271			1636766
24	Irrigated, conjunctive use, double crop, mixed-crops	25785480	0.51	13072208	0.48	12477289	0.34	8710295			21187584
25	Irrigated, conjunctive use, continuous crop, rice-wheat	15795426	0.51	8125903					0.47	7482989	7482989
26	Irrigated, conjunctive use, continuous crop, rice-wheat-corn	16059416	0.69	11006705					0.50	7986163	7986163
27	Irrigated, conjunctive use, continuous crop, sugarcane-orchards-rice	13052610	0.76	9938650					0.55	7187415	7187415
28	Irrigated, conjunctive use, continuous crop, mixed-crops	23011703	0.81	18582955					0.56	12786104	12786104
		605,885,433		411,733,720		262,793,752		176,497,941		41,405,412	480,697,105

Table 4b.

Irrigated area fractions and irrigated areas from 3 methods. The sub-pixel areas (SPAs) are calculated for GIAM10 km 8 classes using irrigated area fractions (IAFs).

Class No.	Class name	Full pixel area (FPA)	Irrigated area fraction based on Google Earth estimate & HRI+fallow (IAF-GEE & HRI+fallow) coefficient	Total area avaialable for irrigation (TAAI) (FPA* mean of IAF-GEE & HRI + fallow	Season 1 Irrigated area fraction based on mean IAF-HRI & IAF-SPDT coefficient	Season 1 sub-pixel irrigated area from mean IAF-HRI & IAF-SPDT	Season 2 Irrigated area fraction based on mean IAF-HRI & IAF-SPDT coefficient	Season 2 sub pixel irrigated area from mean IAF-HRI & IAF-SPDT	Continuous Irrigated area fraction based on mean IAF-HRI & IAF-SPDT	Continuous sub-pixel irrigated area from mean IAF-HRI & IAF-SPDT	Annualized sum sub--pixel irrigated area from mean IAF-HRI & IAF-SPDT
		hectares	unitless	hectares	unmitless	hectares	unitless	hectares	unitless	hectares	hectares
1	Irrigated, surface water, single crop	41863608	0.75	31591365	0.54	22427563					22427563
2	Irrigated, surface water, double crop	259347595	0.69	178754813	0.54	132899702	0.51	133764352			266664054
3	Irrigated, surface water, continuous crop	13654376	0.55	7500204					0.43	5962740	5962740
4	Irrigated, ground water, single crop	32280679	0.59	19118438	0.38	13994279					13994279
5	Irrigated, ground water, double crop	3569220	0.73	2594007	0.55	1957442	0.51	1807545			3764986
6	Irrigated, conjunctive use, single crop	87350064	0.73	64069644	0.47	42576193					42576193
7	Irrigated, conjunctive use, double crop	99900735	0.62	62156597	0.46	48938572	0.42	40926044			89864617
8	Irrigated, conjunctive use, continuous crop	67919155	0.69	47013542					0.52	35442671	35442671
		605,885,433		412,798,611		262,793,752		176,497,941		41,405,412	480,697,105

Table 5a.

Irrigated areas of continets from GIAM10 km V 2.0 and other sources.

Serial no.	Country (name)	SPA-HRI/SPDT: IWMI GIAM 10 km V 2.0 (actual irrigated area)[1] Season 1 (ha)	Season 2 (ha)	Continuous (ha)	Annualized sum (ha)	Percent of world total[3] (%)	FAO/UF V3.0[2] (area equipped for irrigation) (ha)
1	Africa	5,621,232	3,694,108	1,022,129	10,337,469	2.15	12,236,901
2	Asia	194,567,156	153,788,757	26,312,408	374,668,320	77.94	192,478,089
3	Australia[4]	2,991,344	0	1,997,198	4,988,543	1.04	2,056,580
4	Europe	25,757,317	7,717,676	4,644,948	38,119,940	7.93	19,710,263
5	North America	22,334,236	6,456,566	3,093,179	31,883,980	6.63	36,558,227
6	South America	8,066,107	3,367,433	5,612,052	17,045,592	3.55	10,102,130
7	Oceania	68,146	58,034	15,505	141,686	0.03	581,254

Note:

1. Sub-pixel area from combined coefficients of high resolution images and sub-pixel decomposition technique.
2. Area irrigated obtianed from FAO-Aquastat.(http://www.fao.org/ag/agl/aglw/aquastat/water_use/croppat.htm).
3. World total was computed as per table 4a (480 m ha)
4. Australian irrigated area was computed using the procedure described in annex 2.

Table 5b.

Irrigated areas of countries from GIAM10 km V 2.0 and other sources.

Ranking / Serial no.	Country (name)	SPA-GEE[1] (total area available for irrigation) (ha)	SPA-HRI/SPDT: IWMI GIAM 10 km V 2.0 (actual irrigated area)[2] Season 1 (ha)	Season 2 (ha)	Continuous (ha)	Annualized sum (ha)	Percent of world total[4] (%)	FAO/UF V3.0[3] (area equipped for irrigation) (ha)
1	China	108,464,668	75,716,724	68,078,042	7,582,798	151,377,564	31.49	53,823,000
2	India	99,758,291	72,661,809	53,728,631	5,961,653	132,352,093	27.53	57,291,407
3	USA	27,593,858	18,187,246	4,009,305	2,122,793	24,319,345	5.06	27,913,872
4	Russia	21,724,537	14,433,390	2,116,702	224,828	16,774,920	3.49	4,878,000
5	Pakistan	13,169,652	7,904,691	7,310,581	761,592	15,976,865	3.32	14,417,464
6	Argentina	8,867,096	3,603,392	1,606,411	3,559,386	8,769,190	1.82	1,437,275
7	Thailand	6,457,890	3,231,776	2,211,410	1,960,171	7,403,357	1.54	4,985,708
8	Bangladesh	5,125,146	3,905,840	3,095,460	207,678	7,208,978	1.50	3,751,045
9	Turkey	5,974,186	2,761,592	1,760,856	2,035,164	6,557,613	1.36	4,185,910
10	Kazakhstan	6,992,104	4,642,545	1,771,090	83,740	6,497,375	1.35	1,855,200
11	Myanmar	4,332,698	3,374,777	2,811,490	148,298	6,334,565	1.32	1,841,320
12	Uzbekistan	3,478,349	2,756,935	2,450,146	136,167	5,343,248	1.11	4,223,000
13	Australia[5]	12,491,207	2,991,344	0	1,997,198	4,988,543	1.04	2,056,580
14	Vietnam	4,263,540	1,874,807	1,426,573	1,672,071	4,973,451	1.03	3,000,000
15	Brazil	4,045,823	2,169,411	871,121	1,054,221	4,094,752	0.85	2,656,284
16	Mexico	3,672,395	1,824,156	918,909	875,439	3,618,504	0.75	6,104,956
17	Indonesia	3,042,001	1,226,109	720,339	1,387,312	3,333,760	0.69	4,459,000
18	Egypt	2,086,783	1,635,864	1,492,034	165,802	3,293,700	0.69	3,245,650
19	Spain	3,297,105	1,518,353	684,889	825,576	3,028,818	0.63	3,268,306
20	Germany	2,243,204	1,645,822	1,320,932	40,618	3,007,371	0.63	531,120
21	Canada	2,552,921	1,730,705	1,125,880	21,616	2,878,200	0.60	785,046
22	France	2,392,733	1,253,032	832,465	609,042	2,694,538	0.56	2,000,000
23	Italy	2,738,565	1,343,532	540,518	762,720	2,646,771	0.55	2,698,000
24	Iraq	2,069,099	1,242,776	1,255,061	130,080	2,627,917	0.55	3,525,000
25	Iran	2,449,769	1,314,261	680,080	500,407	2,494,749	0.52	6,913,800
26	Japan	2,421,219	1,163,261	661,990	656,204	2,481,455	0.52	3,129,000
27	Ukraine	2,897,304	1,641,055	262,150	493,691	2,396,895	0.50	2,454,000
28	Korea, Dem.Rep	1,416,926	941,017	928,854	194,454	2,064,325	0.43	1,460,000
29	Romania	2,284,667	1,135,323	317,566	609,086	2,061,974	0.43	2,880,000
30	Turkmenistan	1,445,506	1,002,854	914,026	101,577	2,018,457	0.42	1,744,100
31	Sudan	1,655,761	1,185,367	643,653	101,686	1,930,706	0.40	1,946,200
32	Philipines	1,497,696	1,028,455	591,493	176,059	1,796,007	0.37	1,550,000
33	Nepal	1,246,620	695,610	542,955	269,266	1,507,830	0.31	1,168,349
34	Chile	1,406,997	703,642	346,252	396,457	1,446,351	0.30	1,900,000
35	Korea, Rep.	1,158,106	554,327	441,120	337,394	1,332,841	0.28	880,365
36	Morocco	980,306	579,448	460,976	114,810	1,155,234	0.24	1,258,200
37	UK	928,027	812,560	233,964	15,958	1,062,483	0.22	142,687
38	Netherlands	851,187	694,225	303,472	29,609	1,027,306	0.21	565,000
39	Bulgaria	1,278,137	583,272	63,415	372,702	1,019,389	0.21	800,000
40	Denmark	1,067,861	983,934	3,421	0	987,355	0.21	476,000
	Total	381,819,941	248,655,241	169,534,233	38,695,321	456,884,795		244,200,844

Table 5c.

Irrigated areas of river basins from GIAM10 km V 2.0 and other sources.

Serial no.	River basin (name)	SPA-GEE[1] (area available for irrigation) (ha)	SPA-HRI/SPDT: IWMI GIAM 10km V 2.0 (actual irrigated area)[2] Season 1 (ha)	Season 2 (ha)	Continuous (ha)	Annualized sum (ha)	Annualized percent (%)	FAO/UF V3.03 area equipped for irrigation (ha)	FAO Aquastat/ other statistics[4] irrigated area (ha)
1	Ganges	36,520,277	25,955,033	21,539,002	1,817,605	49,311,641	39.59	24,668,871	26,873,9344a
2	Indus	20,246,388	13,185,514	11,910,069	844,532	25,940,116	20.82	22,617,281	16,640,0004b
3	Yellow	12,559,119	9,816,991	10,218,022	312,617	20,347,631	16.34	8,003,487	7,126,0004c
4	Krishna	8,703,061	5,978,375	3,400,778	956,747	10,335,900	8.30	4,388,049	4,453,3004a
5	Mekong	4,542,048	2,191,840	1,297,229	1,642,728	5,131,797	4.12	3,098,364	3,280,000
6	Nile	3,581,753	2,755,680	1,988,472	219,334	4,963,486	3.98	4,557,015	5,500,000
7	Syr Darya	3,270,329	2,573,307	2,221,862	137,653	4,932,822	3.96	3,105,308	3,461,4604d
8	Rechna-doab	1,465,661	964,884	897,401	24,766	1,887,051	1.51	2,110,794	2,300,0004e
9	São-Francisco	832,723	442,761	397,312	102,661	942,733	0.76	329,166	333,000
10	Karhkeh	198,074	114,515	54,002	23,297	191,814	0.15	421,672	110,000
11	Andean	164,080	87,965	47,396	28,116	163,477	0.13	229,285	3,087,000
12	Ruhuna	76,821	38,843	24,417	22,316	85,577	0.07	52,256	N.A.
13	Volta	34,516	8,636	7,165	18,217	34,018	0.03	11,382	N.A.
14	Limpopo	171,078	151,887	9,916	1,293	163,096	0.13	204,224	244,000
15	Olifants	145,644	133,173	0	0	133,173	0.11	57,004	107,0004
	Total	92,511,572	64,399,404	54,013,045	6,151,884	124,564,333	100	73,854,159	73,515,694

Note:

1. Sub-pixel area from coefficients of Google Earth estimate.
2. Sub-pixel area from combined coefficients of high resolution images and sub-pixel decomposition technique.
3. Area equipped for irrigation from Food and Agriculture Organization and University of Frankfurt Global Map of Irrigated Area Version 3.0 (Based on national statistics).
4. Area irrigated obtained from FAO-Aquastat and other national statistics.

4a. Includes surface + groundwater irrigation. Includes irrigated and supplemental. Areas are sub-pixel areas (SPA), leading to correct estimates of irrigated areas. The Global map is produced using a combination of fused datasets such as AVHRR, SPOT, GTOPO30, and rainfall data (Biggs et al. 2005, Thenkabail et al. 2005).

4b IWMI Working Paper 24.

4c Yellow River Conservancy Commission(YRCC 1990).

4d *http://www.cawater-info.net/syrdarya/watermanage_e.htm*

4e This is the total cultivated area in Rechna doab basin (http://www.iwmi.cgiar.org/benchmark/Rechnadoab.htm).

second season China has 68 Mha and India 54 Mha (table 5b). In “summer” there are only about 7 Mha in China and even less in India (about 6 Mha). The irrigated area fraction (IAF) for the classes in China was higher leading to greater sub-pixel area. For example, class 4 (see figure 15), which is mainly in China, has IAFs of 0.53 and 0.67. Classes 8 and 24, two of the classes with significant map area have low IAFs. Class 8, for example, has IAFs of 0.37 for season 1 and season 2 bringing the sub-pixel area (SPA) down. Almost all previous irrigated area maps either calculated areas based on FPA or from national statistics (which also often ignore fallow areas).

The irrigated areas of continents and countries have been calculated based on the cropping calendars and irrigated area fractions (IAFs) obtained from the global map (annexes 1 and 2). Our expectation is that the calculation of irrigated areas for the countries will be much more precise if cropping calendars are developed for individual countries and irrigated area fractions developed separately for every country. For this the GIAM team plans to work with national partners in 2007. However, we do not expect the trends in irrigated areas to change and only small (probably $\pm$ 10 percent) adjustments to irrigated areas (maintaining the present trend) are likely, especially for smaller countries.

The irrigated areas of the IWMI and CP benchmark river basins have been reported in table 5c. Maintaining the irrigated area trends of the continents and countries, the river basins of Asia and in particular India and China, dominate in irrigated area percentages (see table 5c). The annualized areas in the Ganges are nearly 50 Mha and in the Indus about 26 Mha and in the Yellow river about 20 Mha. These are staggering figures, given a basin like Nile with nearly 6,000 years of irrigation history and only about 5 Mha of irrigated area.

Accuracy Assessment of the GIAM10 km Map V2.0 and Its Comparison with Other Maps

The accuracies were determined through two methods:

- Groundtruth data
- Google Earth data

First, we discuss accuracies assessed using groundtruth data and follow that with accuracies determined using Google Earth data. Accuracies are assessed to determine whether the class mapped is irrigated or not.

Accuracies and Errors of GIAM10 km Map V2.0 Using Groundtruth Data

There were two independent groundtruth data sets used in accuracy assessment: First, an 895 point groundtruth data collected by the GIAM team. Second, the 1,861 point groundtruth data from the degree confluence project (DCP).

Based on the GIAM team’s 895 points, the accuracy of irrigated areas mapped as irrigated areas was 84 percent with a 16 percent error of omission and a 21 percent error of commission (table 6a). In comparison, the FAO map showed an accuracy of 79 percent with 21 percent for errors of omission and commission (table 6a). With a DCP of 1,861 the accuracy reduces to 77 percent but errors of omission and commission stay low at 23 percent. In comparison, the FAO/UF V3.0 map shows an accuracy of 70 percent and errors of omission and commission of 30 percent (table 6a).

Accuracies and Errors Using Google Earth Groundtruth (GEGT) Data for the World

The GEGT points are randomly distributed around the world, with a higher density of distribution of points where irrigated area is dense. Accuracies using GEGT can be considered even better than the groundtruth data as a result of: a) better distribution of points around the world and b) precise spatial view of the landscape in determining irrigation at 10-km scale which can often be unrealistic from the ground.

The GEGT determined the accuracy of GIAM irrigated area classes to be 92 percent with a very low error of omission of 8 percent and a low error of commission of 17 percent (table 6b). The FAO/UF V3.0 map had an accuracy of 79 percent

Table 6a.

Accuracy assessment of IWMI GIAM V2.0 versus FAO/FU V3.0 versus CBIP using groundtruth data. The IWMI global irrigated area map (GIAM) is compared with the a) global irrigated area map of the FAO/Frankfurt University and b) the map of India's Central Board of Irrigation and Power (CBIP).

Level of accuracy assessment	Total groundtruth sample size of irrigated and nonirrigated areas (number)	Total groundtruth sample size of irrigated areas (number)	Accuracy of irrigated area classes (irrigated GT points falling on irrigated areas) (percent)	Errors of omission (irrigated GT points falling on nonirrigated areas) (percent)	Errors of commission (nonirrigated GT points falling on irrigated areas) (percent)
I. Global map accuracy and errors					
1. GIAM	895[a]	466	84	16	21
	1861[aa]	726	77	23	23
2. FAO/FU	895[a]	436	79	21	29
(>10% irrigated)	1861[aa]	665	70	30	31
II. India portion accuracy and errors					
3. GIAM for India	1041[b]	568	86	14	20
4. CBIP for India	1041[b]	400	61	39	23
5. FAO/FU for India	1041[b]	500	76	24	26
(>10% irrigated)					

Note:

a. Groundtruth (GT) data points of the world for irrigated and nonirrigated areas collected by IWMI. The same data were used for identification of the classes. These are not independent data sets. The Google Earth data used in accuracy (table 6b) were completely independent. The GT data used in this table will provide supporting evidence to the completely independent Google Earth data.

aa. GT data points of the world for irrigated and nonirrigated areas collected by IWMI and from the degree confluence project (DCP).

Most of the points used in accuracy assessment were not used in class identification and labeling process. So this is mostly an independent data set.

b. GT data points of the world for the irrigated areas collected by IWMI.

bb. GT data points of the world for the irrigated areas collected by IWMI and DCP.

Table 6b.

Accuracy assessment of IWMI GIAM V2.0 Vs. FAO/FU V3.0 vs. CBIP using Google Earth groundtruth (GEGT). The IWMI global irrigated area map (GIAM) is compared with the a) global irrigated area map of the FAO/Frankfurt University and b) the irrigated area map of India's CBIP.

Level of accuracy assessment	Total groundtruth sample size of irrigated and nonirrigated areas (number)	Total groundtruth sample size of irrigated areas (number)	Accuracy of irrigated area classes (irrigated GT points falling on irrigated areas) (percent)	Errors of omission (irrigated GT points falling on nonirrigated areas) (percent)	Errors of commission (nonirrigated GT points falling on irrigated areas) (percent)
I. Global map accuracy and errors					
1. GIAM	670[a]	321	91	9	17
2. FAO/FU	670[a]	321	79	21	11
(>10% irrigated)					
II. India portion accuracy and errors					
3. GIAM for India	83[a]	55	87	13	11
4. CBIP for India	83[a]	55	53	47	24
5. FAO/FU for India	83[a]	55	76	24	11
(>10% irrigated)					

Note:

a. groundtruth (GT) data points of the world for irrigated and nonirrigated areas collected by IWMI. The same data were used for identification of the classes. These are not independent data sets. The Google Earth data used in accuracy (table 6b) were completely independent. The GT data used in this table will provide supporting evidence to the completely independent Google Earth data.

aa. GT data points of the world for irrigated and nonirrigated areas collected by IWMI and from the degree confluence project (DCP).

Most of the points used in accuracy assessment were not used in class identification and labeling process. So this is mostly an independent data set.

with higher errors of omission with 21 percent but lower errors of commission with 11 percent (table 6b).

Accuracies and Errors for India in GIAM10 km V2.0 for India

The accuracies and errors of the irrigated area classes were also determined for India for two main reasons: a) the groundtruth data for India are dense and well distributed as a result of several GT missions, at various times, by the GIAM team; and b) India is one of the two largest irrigating nations in the world. Accuracies and errors were determined for the IWMI GIAM10 km V2.0 India portion and compared with: a) FAO/UF V3.0 map and b) India's CBIP map.

The accuracy of GIAM V2.0 map in India was 86 percent with errors of omission of 14 percent and errors of commission of 20 percent. In comparison the FAO/UF V3.0 map and India's CBIP map have substantially low accuracies and higher errors of omission and commission (table 6a). In comparison, the FAO/UF V3.0 map had an accuracy of 76 percent with 24 percent errors of omission and 26 percent errors of commission. The CBIP map had a much lower accuracy at 61 percent and much higher errors of omission (39%) and errors of commission (23%). This is because the CBIP irrigated area map for India almost completely ignores groundwater irrigation, conjunctive (surface water plus groundwater) use within irrigated areas and the supplemental irrigated area as its focus is almost completely on large-scale surface water irrigated areas with some medium to small-scale surface water irrigated areas.

The trends in accuracies and errors between GIAM V2.0, FAO/UF V3.0 and CBIP using the Google Earth groundtruth (GEGT) remain the same, with higher accuracies and lower errors in GIAM V2.0 (see table 6b).

Accuracy Assessment Discussions

Overall, the results show that the accuracies of the IWMI GIAM V2.0 were about 7 to 12 percent higher than in FAO/UF V3.0. The errors of omission and commission were only slightly better in GIAM. The area calculations in the two maps differ significantly since IWMI GIAM uses: a) intensity of irrigation to obtain irrigated areas based on seasons, and b) sub-pixel decomposition techniques to obtain the irrigated fraction within a pixel. The areas are reported directly from country statistics and the spatial distribution of irrigation is "adjusted" to fit the country statistics, using known extents of surface irrigation and other secondary information. India's CBIP underestimates irrigation since, largely, it ignores informal (e.g., groundwater) irrigation. For the India portion GIAM10 km V2.0 map accuracies and errors were significantly better statistically than those of FAO/UF V3.0 and CBIP (table 6a and 6b), which is to be expected given the extent of groundtruth data collected. Especially, the errors of omission and commission were much better, among other things indicating that IWMI GIAM is picking the informal (e.g., small reservoirs, tanks, groundwater) irrigation better.

There are fundamental issues related to accuracy assessments at such large scales as 1-km or 10-km resolution pixel size. There are considerable difficulties in groundtruthing and establishing the exact percent of area irrigated in a 1-km x 1-km (100 ha) and, especially, at 10 km x 10 km (or 10,000 ha) resolutions. For example, when GT data are collected in a portion of a pixel that has land cover other than irrigation and has irrigation in patches (say 25% of pixel area), we may not even see irrigated portions during GT data collection. This will lead to the pixel being labeled "other LULC" in GT data whereas in reality it has 25 percent irrigation. Satellite sensors capture the average reflectivity from the pixel and hence are influenced by both the irrigated as well as nonirrigated components within the pixel leading to an average spectrum for the pixel. Whereas satellite data distinctly show the difference in a pixel with zero irrigation and one with 25 percent irrigation, GT data often fail to do so. This will lead to situations such as, for example: a) rain-fed GT points falling on a pixel mapped as other LULC (errors of omission). This can lead to somewhat higher omission and commission errors. The phenomenon is acute when dealing with pixels of low percent (<20) of irrigation which have greater likelihood of being labeled as classes other than irrigation, resulting in highly exaggerated errors of commission. This also implies an area-based accuracy assessment, which may be more powerful and robust than point-based accuracy assessment. However, the quality of area-based reference data is nearly nonexistent. Offset against this spatial advantage of remote sensing is the fact that there are multiple reasons for an average pixel-scale signal, and it is therefore possible to confound interpretation with another reality. The very high resolution (sub-meter to 4 meter) images available in Google Earth facilitate determining the land cover and irrigation structural patterns which will be invaluable in determining irrigation versus nonirrigation. Hence, the GEGT is considered a better data system for accuracy assessment.

The accuracy assessment comparison between the GIAM10 km, FAO/UF and CBIP maps (tables 6a and 6b) are indicative and not definitive. In a strict sense, none of these maps can be directly compared with one another as a result of considerable differences in scale/ resolution, primary data sets used to derive the map information and differences in methods used.

Accuracies and Areas

Even if the accuracies and errors between the IWMI GIAM10 km and FAO/UF maps are similar, the calculated areas differ as a result of fundamental differences in how the maps are produced. In IWMI-GIAM, the global annualized (i.e., taking cropping intensity or seasons) irrigated area is 494.4 Mha and the net areas per season are: 278 Mha, 176.5 Mha and 39.9 Mha (figure 15 and table 4a). In contrast, the other global irrigated area estimates vary between 257 and 274 Mha (Siebert et al. 2005; Siebert et al. 2002; Siebert and Döll 2000) in which the FAO/FU provides area “equipped for irrigation” to be 274 Mha (Siebert et al. 2005). Accuracies can be similar, but areas can differ because of:

A. *Intensity (seasonality) consideration.* The IWMI GIAM10 km V2.0 provides gross areas based on cropping intensity (single crop, double crop, triple crop, continuos crop). Other area estimates count the area once (net) based on area equipped and assuming irrigation once during a major cropping season.

B. *Sub-pixel fraction differences.* The irrigation fraction used with remote sensed data depends on the three methods (GEE, HRI and SPDT). The FAO/UF is dependent on country statistics at subnational level, and estimates of the reliability of data in each case.

C. *Area estimation approaches.* The FAO/UF area calculations are dependent on the national statistics and their extrapolation onto spatial maps. The IWMI GIAM is interpreted directly from the satellite imagecharacteristics.

A Discussion on Mapping Irrigated Areas and Comparison of Maps

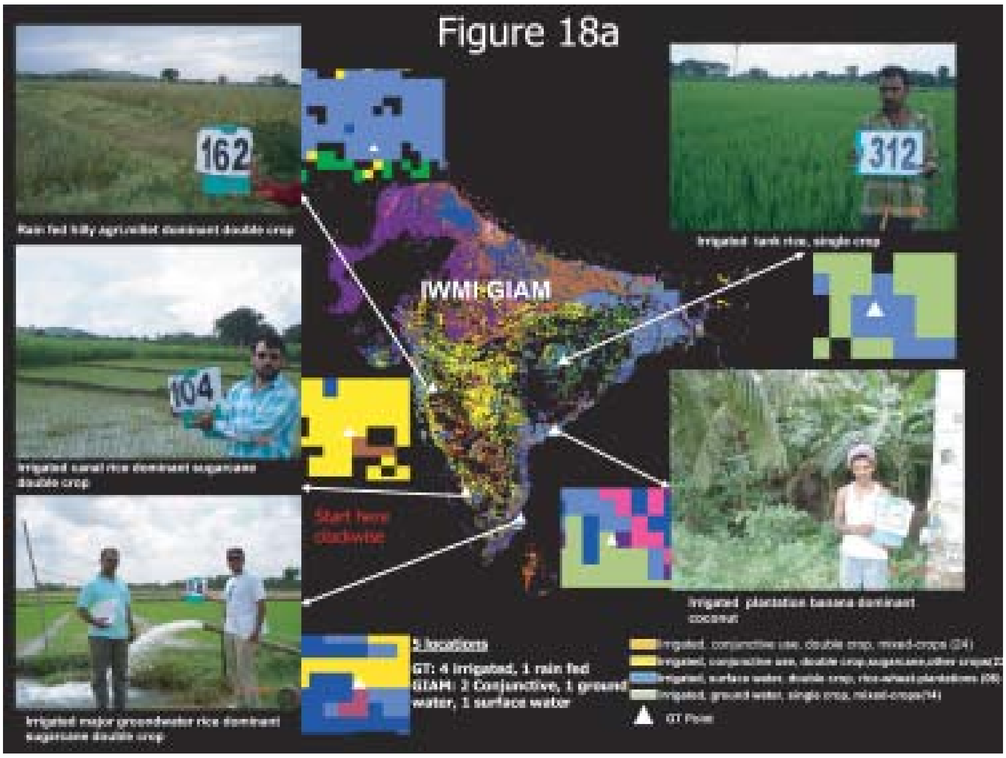
Irrigated area maps of IWMI GIAM10 km V2.0, Food and Agricultural Organization\University of Frankfurt (FAO/UF) V3.0, and India's CBIP maps are compared and discussed. We shall begin with detailed illustrations of comparisons in India where we have detailed groundtruth data collected by the GIAM team and very reliable and detailed maps from the CBIP. The extensive groundtruth data collected during the field campaigns were invaluable in these comparisons.

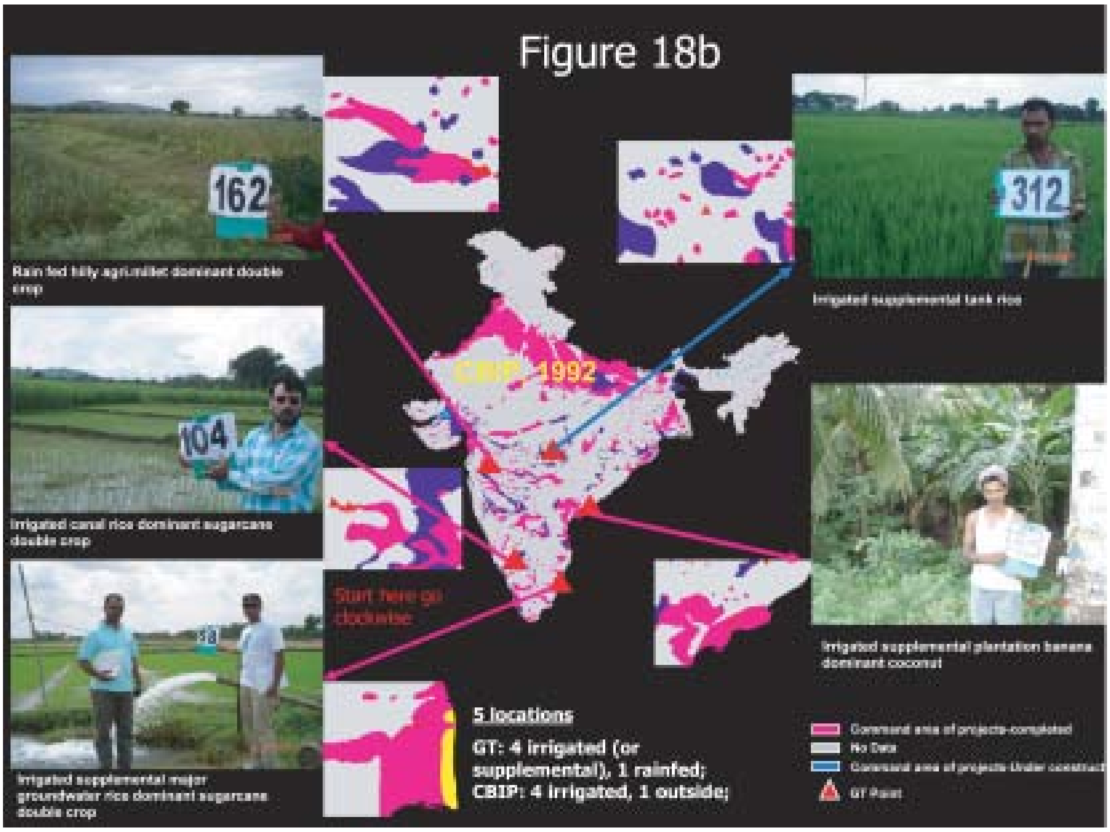
Major Irrigation

First, we shall illustrate a comparison of maps for major irrigation. The CBIP map, basically, represents major irrigated areas (leaving out informal irrigation) and is considered accurate for major command area irrigation. For the purpose of comparison we took five random groundtruth (GT) points falling within the CBIP map (figure 18b) and overlaid them on the IWMI GIAM10 km V2.0 for India (figure 18a) and CBIP irrigated area map for India (figure 18b). According to GT data, two were informal (tank, groundwater) irrigation, one was major irrigation, one naturally irrigated and one rain-fed. The GIAM10 km classes (figure 18a) showed three informal (two conjunctive and one groundwater) and two surface water. The CBIP (figure 18b) showed all points as major irrigation. These results clearly implied that the GIAM10 km has a closer match with ground reality in terms of type of irrigation.

Figure 18.

Evaluation of the GIAM for large-scale, small-scale, informal and supplemental irrigation. The IWMI GIAM and India's Central Board of Irrigation and Power (CBIP) irrigated area maps are evaluated for: a) large-scale irrigation- (figures 18a,b); b) informal irrigation such as groundwater and tanks (figures 18 c,d); and c) small-scale (e.g., minor reservoirs) irrigation (figures 18e,f).





Informal Irrigation

Next, we illustrate how well the informal irrigation (e.g., small reservoirs, tanks, groundwater) is captured between maps. For this purpose, we randomly selected five GT points with informal irrigation. The CBIP map missed all the randomly selected groundwater check points (figure 18c). The GIAM10 km V2.0 identified all of them—three as conjunctive and one as groundwater irrigation (figures 18c and 18d). This is very close to groundtruth data which also had three supplemental irrigated area classes. Finally, identification of small-scale irrigation from minor reservoirs and groundwater is illustrated in figure 18e for CBIP and figure 18f for IWMI GIAM10 km V2.0. Of the five randomly chosen GT points (two irrigated small scale, one irrigated large scale and two rain-fed) CBIP missed all (figure 18e) whereas GIAM mapped three as conjunctive and two outside. It actually mapped two correctly as informal irrigation, and one rain-fed correctly as “outside” irrigated areas. Of the other two points, it mapped a rain-fed class as informal irrigation, and informal irrigation as “outside irrigated area,” leading to some errors of omission and commission. However, as we see in figure 18a through 18f, informal irrigation is well captured in GIAM10 km.

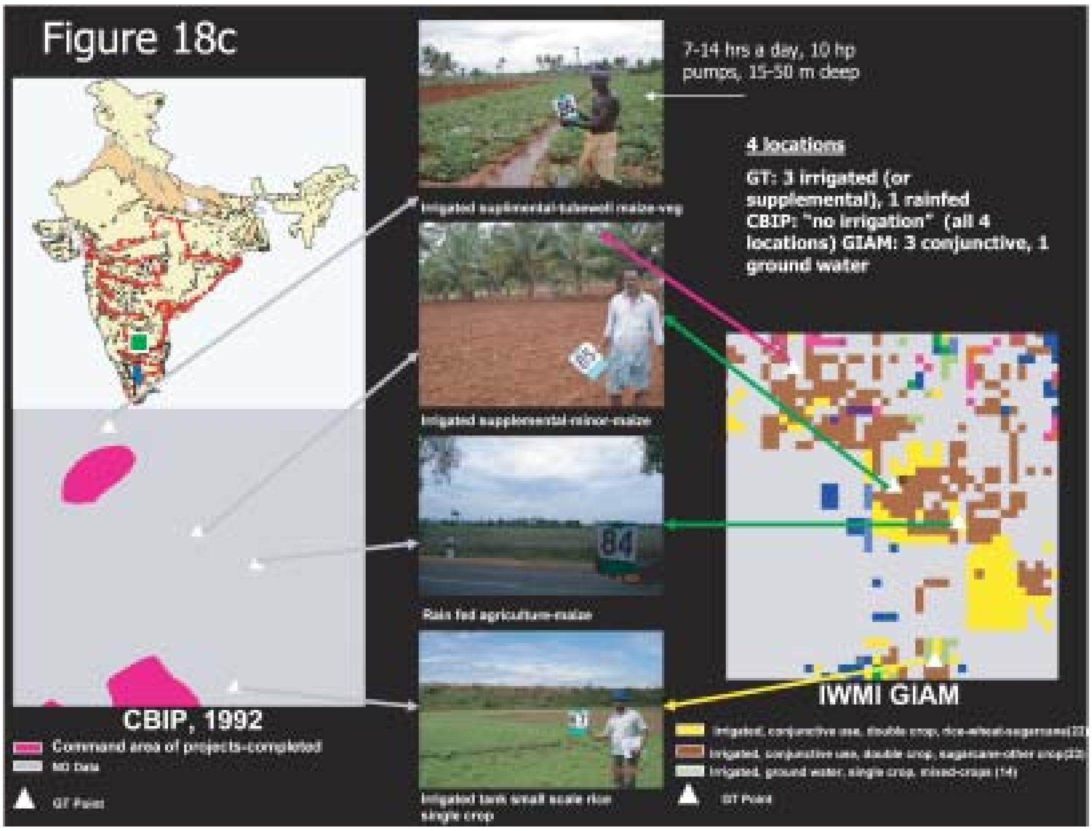


Figure 18c
7-14 hrs a day, 10 hp pumps, 15-50 m deep
4 locations
GT: 3 irrigated (or supplemental), 1 rainfed
CBIP: "no irrigation" (all 4 locations) GIAM: 3 conjunctive, 1 ground water
Irrigated supplemental-tubewell maize-veg
Irrigated supplemental-minor-maize
Rain fed agriculture-maize
Irrigated tank small scale rice single crop
CBIP, 1992
Command area of projects-completed
NO Data
GT Point
IWMI GIAM
Irrigated, ground water, single crop, mixed-crops (14)
GT Point

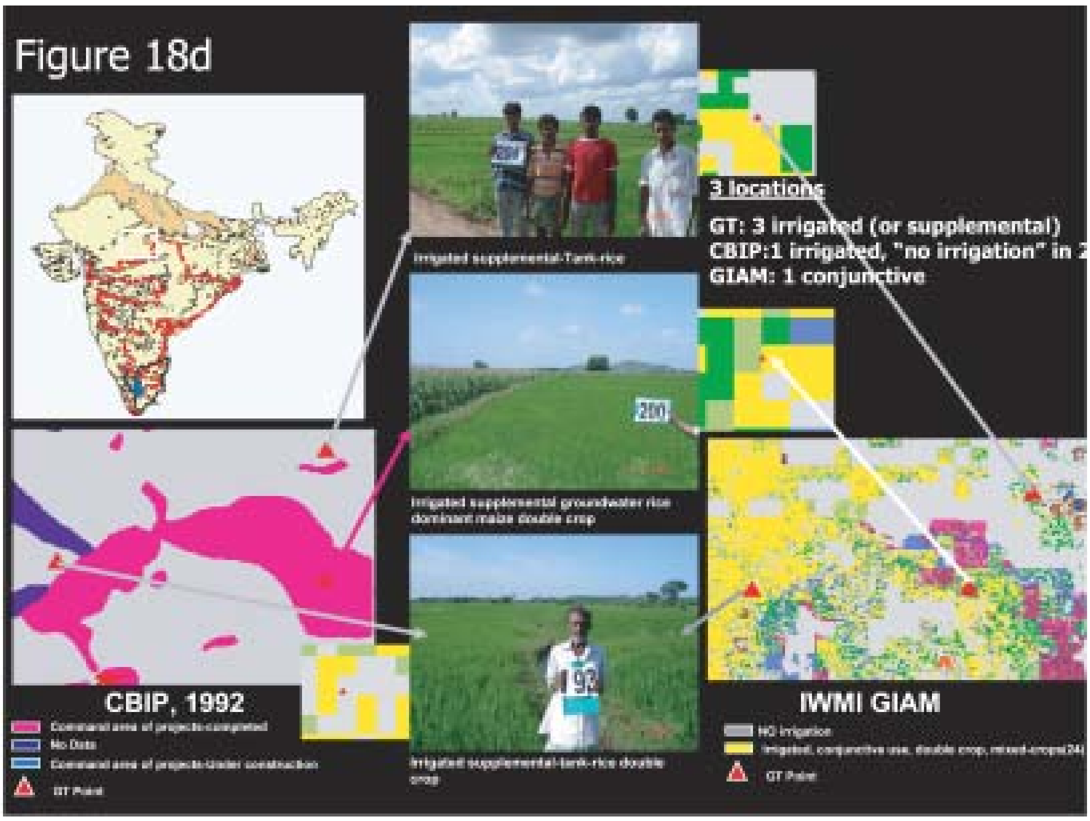


Figure 18d
3 locations
GT: 3 irrigated (or supplemental)
CBIP:1 irrigated, "no irrigation" in 2
GIAM: 1 conjunctive
Irrigated supplemental-Tank-rice
Irrigated supplemental groundwater rice dominant maize double crop
Irrigated supplemental-tank-rice double crop
CBIP, 1992
Command area of projects-completed
No Data
Command area of projects-under construction
GT Point
IWMI GIAM
NO irrigation
Irrigated, conjunctive use, double crop, mixed-crops(24)
GT Point

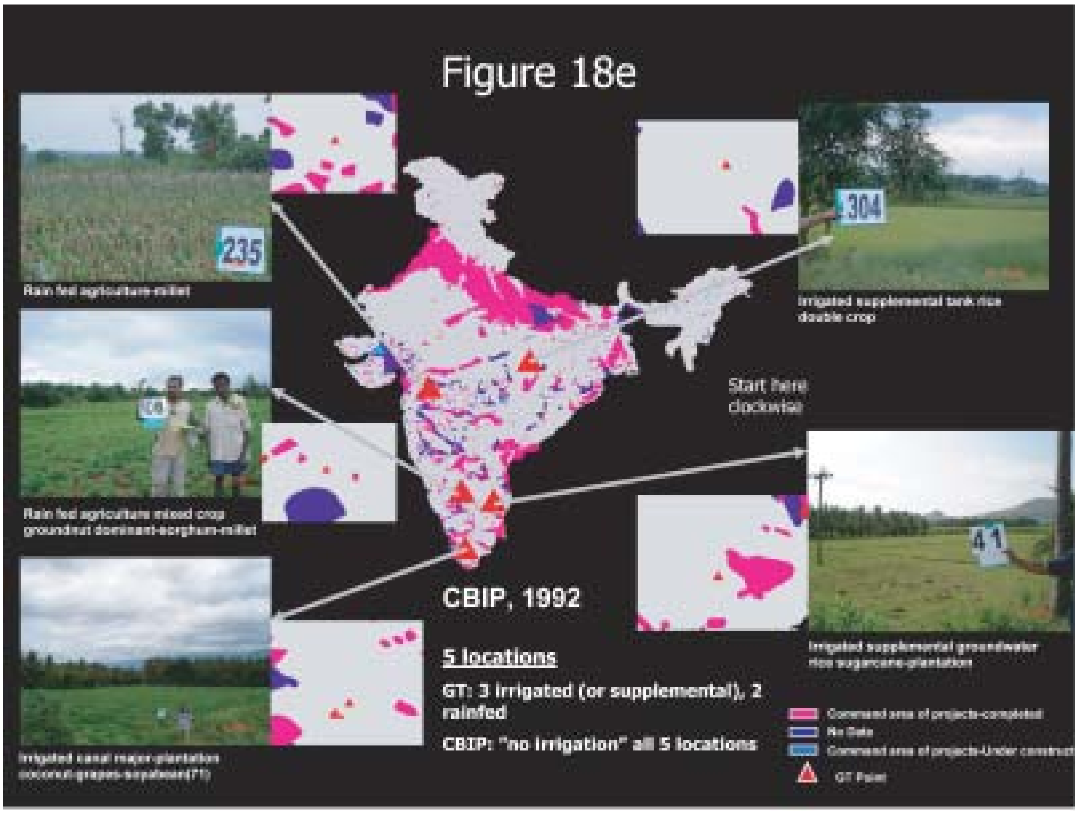


Figure 18e
235
Rain fed agriculture-millet
Rain fed agriculture mixed crop
groundnut dominant-sorghum-millet
Irrigated canal major-plantation
coconut-grapes-soyabean(71)
304
Irrigated supplemental tank rice
double crop
Start here
clockwise
41
Irrigated supplemental groundwater
rice sugarcane-plantation
CBIP, 1992
5 locations
GT: 3 irrigated (or supplemental), 2 rainfed
CBIP: "no irrigation" all 5 locations
Command area of projects-completed
No Data
GT Point

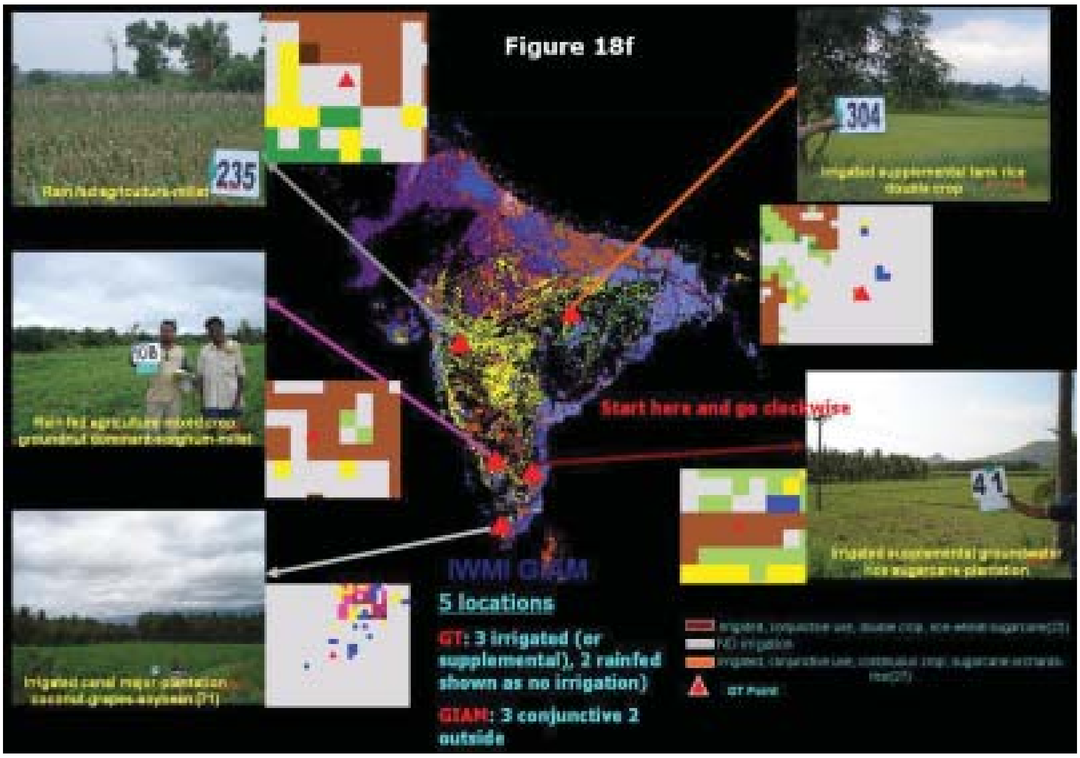


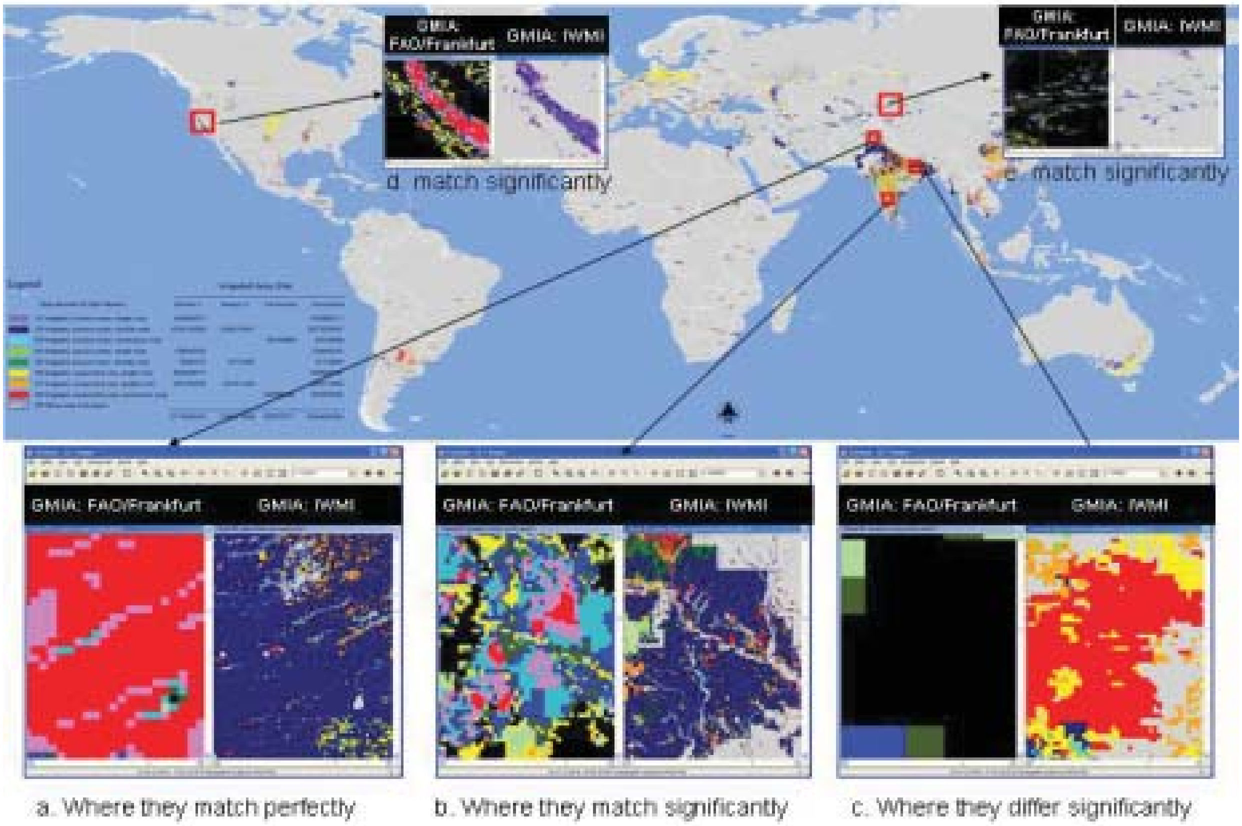
Figure 18f
235
304
Irrigated supplemental tank rice
double crop
Start here and go clockwise
41
Irrigated supplemental groundwater
rice sugarcane plantation
IWMI GIAM
5 locations
GT: 3 irrigated (or supplemental), 2 rainfed shown as no irrigation)
GIAM: 3 conjunctive 2 outside

Comparing Global Products in India

The comparison between FAO/UF global irrigated area map and GIAM10 km V2.0 highlights the distinct features of areas where the two maps: a) perfectly match (e.g., figure 19a in the Upper Ganges basin), b) broadly match (e.g., figure 19b in the Cauvery delta), and c) do not match at all (e.g., figure 19c in the Ganges delta). This illustration is a "representative" comparison of the two global irrigated area maps as we see similar trends in other places of the world.

Figure 19 (a, b and c).

Comparison of the two global irrigated area maps: GIAM10 km V2.0 and FAO/FU V3.0.



Irrigated Area Class Names

At this stage it is useful to discuss the issues involved in final class labeling and the approach used in IWMI GIAM10 km V2.0. Classes were named based on a set protocol and rigorous methods (see figure 4) that had a clear class-naming convention (figure 9). In addition, the final class labeling (see figures 15 and 16) was also based on consultation with irrigation experts so that the class names represent the commonly understood meaning of a particular irrigation type. More generic and detailed names are provided in GIAM10 km-28 classes (figure 15), and simpler and broadly understood names are provided in GIAM10 km-8 classes (figure 16).

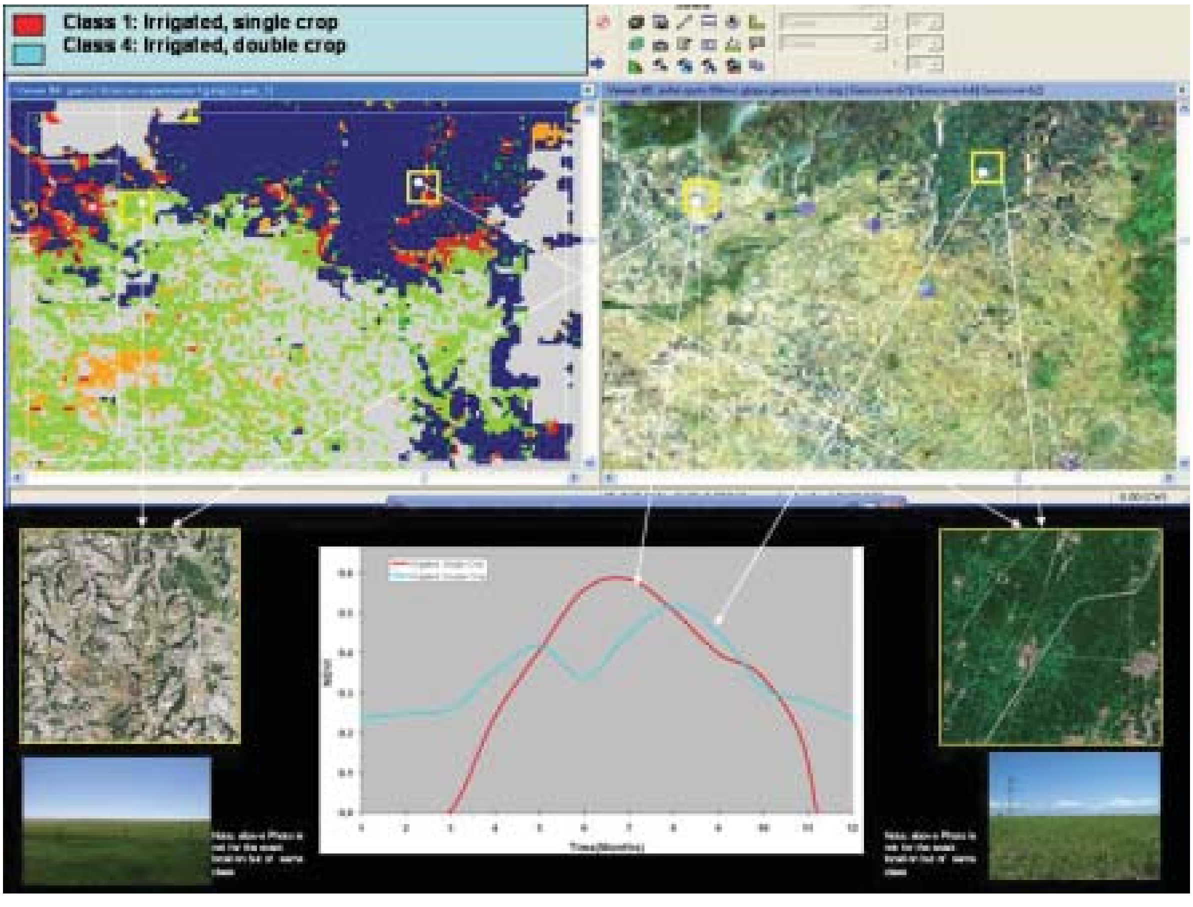
The final class labeling was categorized under the following groups:

- irrigated, surface water, single crop, crop type or dominance
- irrigated, surface water, double crop, crop type or dominance
- irrigated, surface water, continuous crop, crop type or dominance

The watering method (irrigated or rain-fed) and irrigation type (surface water, groundwater or conjunctive use) are determined based on the protocols and methods (see figure 4 and sections 4, 5 and 6). The single, double or continuous crop is determined based on the spectral signature for every class based on time-series satellite imagery (see example for class 1 and 4 in figure 20). The same classes 1 and 4 also occur in Iran showing somewhat different signature characteristics (in magnitude and timing of peaks and lows). Indeed, it is possible to get a cropping calendar for every pixel of irrigated area classes by simply clicking on any point on irrigated area class and looking through the time-series imagery of a mega-file as we have done in figures 20 and

Figure 20.

Single crop (red) and double crop (cyan) irrigation in the lower Ganges.



21. The final variable (crop type or dominance) in naming is based on groundtruth data and literature.

This convention is repeated for groundwater and conjunctive use irrigation.

In figure 15, classes 1-10 are surface water irrigation, classes 11-15 are groundwater irrigation, and classes 16-28 are conjunctive use irrigation. These classes were combined appropriately to produce the simplified eight-class irrigated area map (see figure 16).

The class labeling process of one class has been discussed in detail. First, we go through a normal protocol (figure 8), methods (sections 5 and 6), and class naming convention (figure 9). In addition, the detailed approach to name a class is illustrated below for one class. Class 28 (figure 22) was labeled "irrigated, conjunctive use, continuous crop, mixed crop" in GIAM10 km-28 class map (figure 15). It occurs mainly in the Pampas of Argentina, which is predominantly rain-fed. However, different degrees of

Figure 21.

Double crop (left) and single crop (right) irrigation in Zayandeh and Rud.

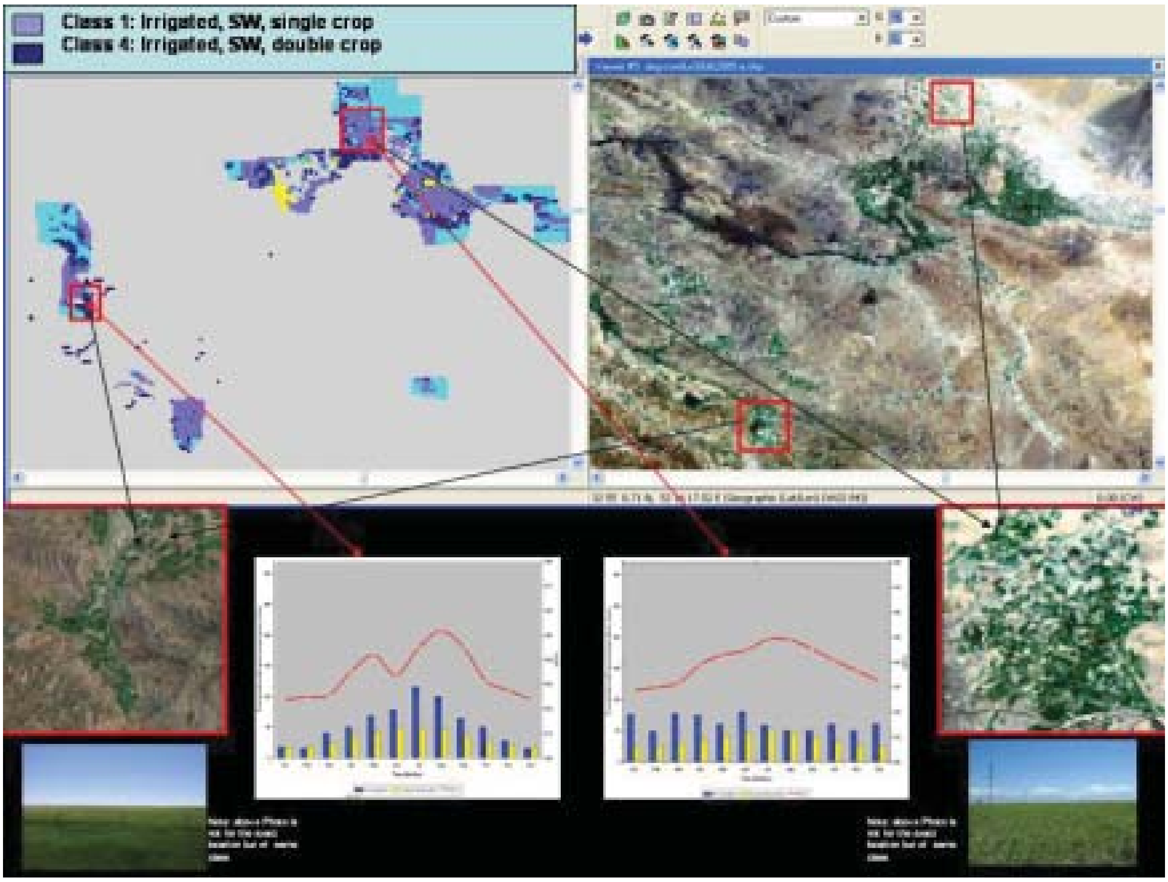
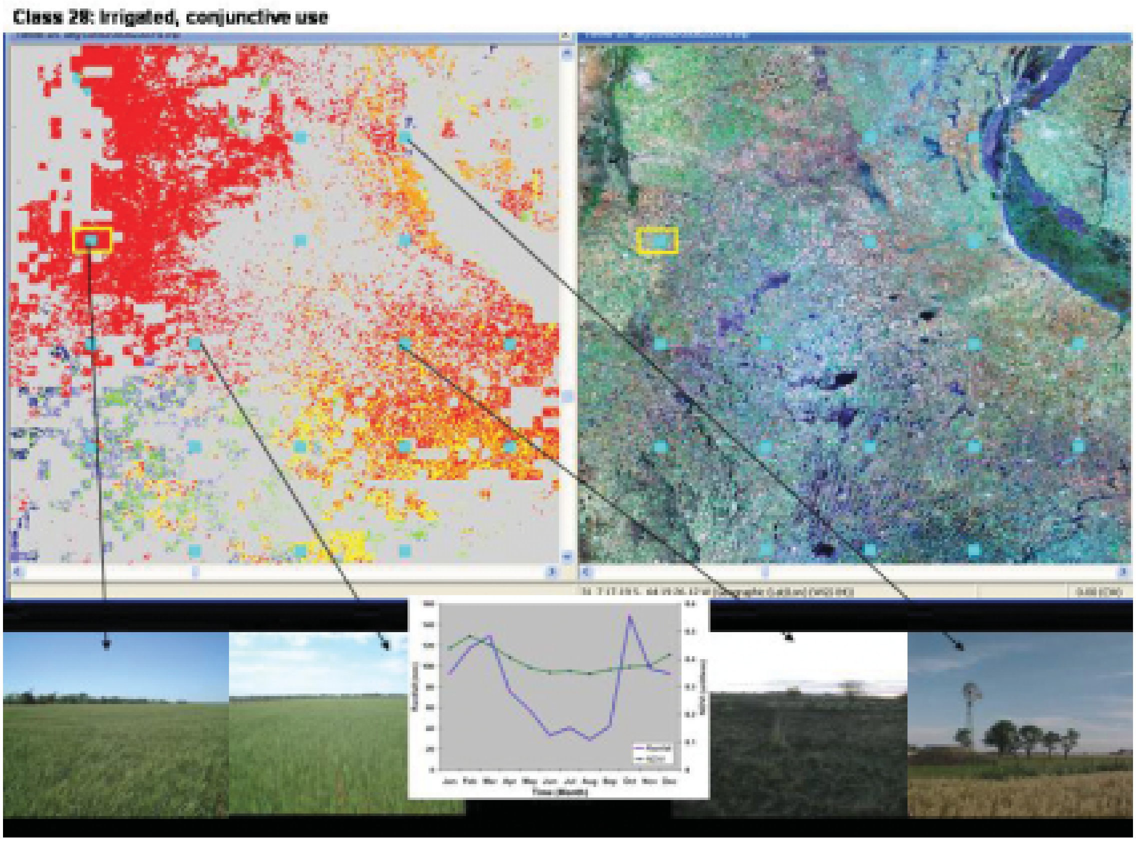


Figure 22.

Evaluation of GIAM for conjunctive irrigation. The rain-fed class with significant central pivot supplemental irrigation in the Pampas in Argentina.



supplemental groundwater irrigation (e.g., pivots, drip) and some pumping from rivers also exist. Center-pivot irrigation is used in humid plains of Pampas to supplement rainfall (Maletta 1998, 1999).

The spectral characteristics of the class show near continuous cropping, with AVHRR NDVI greater than 0.35 or more throughout the year (figure 22). Rainfall during May-September is low, averaging less than 40 mm per month (see figure 22) and is insufficient to sustain such high vegetation in an agricultural belt. The Pampas is a humid plain, which is very flat and is poorly drained. This and man-made obstacles such as roads and railroad embankments lead to flooding and waterlogging for months, favoring growth of weeds and natural pasture in the vicinity even during relatively dry spells (Maletta personnel communication). The long period of deficit rainfall and continuously high NDVI strongly imply some degree of irrigation.

Evidence (Maletta personal communication) from the field suggests that center-pivot irrigation in the Pampas is mostly used for complementary irrigation while drip irrigation is used for horticulture. Maletta summarizes the situation: “There is indeed a need to irrigate more, as witnessed by the fact that average yields (especially for maize) are quite below potential. But a) massive use of irrigation is not yet happening, b) aquifers may not support such an extensive use of underground water, and c) gravity irrigation is in general difficult due to very flat land, thus requiring pumping (which is not generally done) from the many streams flowing through the plains.” The data from the Government administration (*http://www.indec.mecon.ar/*) show nearly 1.4 Mha are irrigated. These do not account for an occasional irrigation (e.g., one or two irrigations during the cropping period, during deficit rainfall periods) or informal (individual farmers irrigating without governmental knowledge mainly through groundwater pumping). Overall, the Pampas region depends on rainfall, but has a significant proportion of irrigated land (pivots, drip, river pumps), humid flat waterlogged regions and scattered informal irrigation. These characteristics lead the class to be named "conjunctive use." In the past, irrigated area maps only included areas with formal canal networks and major works such as reservoirs or barrages. But many parts of the world have various levels of irrigation that need to be accounted for, to obtain a realistic estimate of actual irrigated areas.

GIAM10 km V2.0 Products and Dissemination

The IWMI GIAM10 km V2.0 data and products are distributed via a dedicated web page at *http://www.iwmigiam.org.* The web page consists of GIAM10 km V2.0 products at global level mapped at 1-10 km and include maps, images, class characteristics, area calculations, snapshots (high-resolution images) and photos, animations, and accuracies. The products are made available at nominal resolution of approximately 1 km since all data were resampled and analyzed at 1-km scale. However, we urge the users to treat it as a nominal 10 km^2 since the overwhelming proportion of the data used in analysis were at this scale. But it must be noted that a significant proportion of the mega data used in the analysis included SPOT time series for 1999 and GTOPO30 at 1-km. The GIAM10 km map was also available for Google Earth. Please download *GIAMv2.kmz* file from the home page of GIAM main site (*http://www.iwmigiam.org*)

The primary GIAM10 km V2.0 products are:

- GIAM10 km V2.0 28 class map (GIAM10 km-28 classes)
- GIAM10 km V2.0 8 class map (GIAM10 km-8 classes)
- GIAM10 km V2.0 3 class map (GIAM10 km-3 classes)

The website contains three other global agricultural products and their associated documentation:

- Global map of rain-fed cropped areas (GMRCA)
- Disaggregated 273 class map
- Aggregated 22 and 8 class map
- Global map of all land use/land cover (LULC) areas (GMLULCA)
- Disaggregated 73 class map
- Aggregated 12 class map
- Global IWMI generic 951 class map (Generic-IWMI-951)

Conclusions

IWMI has produced a global irrigated area map at 10-km scale (GIAM10 km V2.0) for the end of the last millennium, using remote sensing data. The total annualized irrigated areas of the world are 480 Mha. Globally, the total area available for irrigation is 412 Mha (nearest equivalent of FAO's equipped area for irrigation). Annualized area takes into consideration irrigated areas during different seasons over the same areas within a given year. Of the total annualized area of 480 Mha, a total of 75 percent (375 Mha) of all irrigated areas of the world is in Asia, followed by Europe with 8 percent, North America with 7 percent, South America 4 percent, Africa 2 percent and Australia 2 percent. The irrigated areas that spread across the season are: a) 263 Mha for season 1, b) 176 Mha for season 2, and c) 41 Mha for continuous.

Two countries, China and India, together have a staggering 59 percent (284 Mha) of all the global annualized irrigated areas. Of the 59 percent, China has 31.5 percent and India 27.5 percent. China has an annualized area of 151 Mha and India 132 Mha. The first or the major cropping seasonal areas follow a pattern similar to annualized areas. China and India have extensive double cropping. In the first season, China has 76 Mha irrigated, followed by 68 Mha in the second season. In India, the area irrigated is 73 Mha in the first season and 54 Mha in the second season. The next leading irrigated area countries (as a percentage of the global annualized sum of 480 Mha) are USA (5%), Russia (3.5%) and Pakistan (3.3%). There are nine countries (Argentina, Australia, Bangladesh, Kazakhstan, Myanmar, Thailand, Turkey, Uzbekistan and Vietnam) having between 1 and 2 percent. Every other country in the world, individually, has less than 1 percent area irrigated. The 40 leading irrigated area countries have nearly 96 percent of all irrigation in the world. Surface-water irrigation is 61 percent and the rest (39%) is conjunctive (surface water and groundwater) or pure groundwater.

There are two global irrigated area mapsproduced by the GIAM team: GIAM10 km 28 class map and GIAM10 km 8 class map. The classes represent a) irrigation by surface water, groundwater and conjunctive use; b) cropping intensity (e.g., single crop, double crop and continuous crop) is provided for every class; and c) crop type or dominance. The accuracy of mapping irrigated areas was determined using three independent data sets—two groundtruth data sets and one Google Earth estimate data set. The accuracies varied between 84 and 91 percent, the errors of omission less than 16 percent, and errors of commission less than 21 percent. The results of our study were compared with the irrigated area map statistics of the Food and Agricultural Organization of the United Nations (FAO) and the University of Frankfurt (UF) version 3.0 (FAO/UF V3.0). The FAO/UF used national statistics and GIS techniques to derive irrigated areas. FAO/UF V3.0 determined "area equipped for irrigation" (but not necessarily irrigated) for the world as 274 Mha which is quite different from GIAM10 km V2.0 TAAI of 412 Mha.

The key achievements of the GIAM10 km V2.0 work have been:

1. *Methodology development.* A comprehensive set of methods and techniques for mapping irrigated areas of the world using remote sensing data at various scales or where pixel resolution has been developed; see also work by Thenkabail, et al. (2005a, 2006) and Biggs et al. (2006):

   1.1 *Advances in approaches and data sets.* Mega-file compositions through fusion of multi-resolution time-series imagery.

   1.2 *Advances in methods.* Hyper-spectral techniques for multispectral time-series mega-file imagery. The methods include spectral matching techniques (SMTs) and space-time spiral curves.

   1.3 *Class identification and labeling*. Rigorous strategies for class identification and labeling have been developed. Strategies for resolving mixed classes through GIS modeling, in which a wide array of secondary data sets have been used, have been established.

1.4 *Sub-pixel areas (SPAs) and irrigated area fractions (IAFs).* Innovative sub-pixel area (SPA) calculation methods using irrigated area fractions (IAF) have been developed. Three IAF methods were developed: a) IAF, based on GEE, b) IAF, based on high-resolution imagery (HRI), and c) IAF, based on the sub-pixel decomposition technique. Generally, the areas calculated from remote sensing are, almost always, reported as full pixel areas (FPAs). But the correct areas can be obtained only through SPA. This is especially true in coarser resolution imagery. Development of practical methods to obtain SPAs through IAFs is, thereby, a highly significant achievement.

2. *Annualized areas (or intensity of irrigation) and irrigated area fractions (IAFs)*. The study determined and provided IAFs through three methods. The irrigated area fractions from the Google Earth estimate (IAF-GEE) when used to multiply the full pixel areas (FPAs) provide total area available for irrigation (TAAI). The IAF from high resolution imagery (IAF-HRI) and sub-pixel decomposition technique (IAF-SPDT) can be obtained for different seasons (e.g., season 1 crops, season 2 crops and so on). The seasonal IAF coefficients helped determine irrigated areas of every class for season 1, season 2, and continuous. Annualized (or intensity) is summation of season 1, season 2, and continuous. The coefficients of IAF-HRI and IAF-SPDC were combined to provide more robust SPAs. The annualized areas are unique. The ability to determine annualized areas has huge implications for the intensity of irrigation in a given land and the implications in determining the quantum of food production and water consumption.

3. *Informal irrigation.* The GIAM10 km demonstrated the ability to map informal irrigation (i.e., irrigation from minor reservoirs, tanks and groundwater) well. This is especially crucial given the quantum of informal irrigation in the world, especially from millions of tube wells.

4. *Crop characteristics.* Every class (or for that matter every pixel within a class) will have its own characteristics in terms of its vegetation dynamics and seasonality. GIAM10 km product is not just a map. It is a dynamic tool from which one can study variables such as cropping calendars, crop growth stages, biomass levels and fraction of areas irrigated.

5. *Precise location of irrigated areas.* Most irrigated area maps provide areas without showing precise location of irrigated areas. For example, an entire state or country is often shown to have a certain percentage area irrigated without showing where exactly it is. The GIAM10 km map provides precise location with errors of omission (less than 16%) and commission (less than 21%).

6. *Product line*. GIAM data and products are made accessible online free of charge as a global public good (GPG) from anywhere in the world (*http://www.iwmigiam.org*). The products consist of, for example, irrigated area maps, statistics, 20-year every month animations, snapshots of higher-resolution imagery to help visualization of classes, class characteristics, irrigated area fractions for area calculations, methods and data sets.

Particular strengths of this work are in: a) establishing seasonal and annualized irrigated areas (or intensity of irrigation), b) mapping informal irrigation (e.g., small reservoirs, tanks, groundwater) in addition to conventional surface water irrigation, c) determining irrigated crop calendar, d) studying historical (e.g., last 20 years, every month) biomass dynamics for every irrigated area class and for every pixel within that class. By-products of GIAM include global maps of rain-fed agriculture and land use/land cover.

Within the scope of the GIAM project, irrigated areas are also mapped at 500-m resolution for India, as a start, and 30-m resolution for the Ruhuna basin in Sri Lanka and Krishna basin in India.

Currently, IWMI is in the process of developing a joint vision and strategy with FAO/UF on GIAM. We are also developing partnerships and collaborations with the national governments and institutes. To that end, work continues on the development of techniques to map and test the accuracy of classification across the full extent of the Indian subcontinent (Pakistan, India, Bangladesh) and Sri Lanka, covering a range of agro-ecologies and degrees of difficulty for remote sensing (in terms of cloud cover, heterogeneity and scale of landscapes and land use). The work is expected to be expanded to China and other countries. A Consortium for Irrigated Area Mapping and Assessment (CIAMA) is expected to be set up, with an array of international partners, during the GIAM2006 International Workshop to be held in Colombo, Sri Lanka.

The team seeks feedback from all users, readers and interested parties, and continues to harvest groundtruth data to verify and upgrade the map. The team welcomes any feedback on the methods and results, and actively seeks to expand the available groundtruth in order to build a global groundtruth database within the IWMIDSP (*http://www.iwmidsp.org*). All the imagery and documentation associated with GIAM are made available through the dedicated portal: *http://www.iwmigiam.org*. The products consist of maps, images, class characteristics, area calculations, snapshots, animations, and accuracies. It is our hope that these products will, in time, be a useful resource for the remote sensing and water management community, both for researchers and practitioners.

Annexure

Annex 1 Table 1.

Irrigated areas of countries from GIAM10km V 2.0 and other sources

Ranking / Serial no.	Country (name)	SPA-GEE[1] (total area available for irrigation) (ha)	SPA-HRI/SPDT: IWMI GIAM 10 km V 2.0 (actual irrigated area)[2] Season 1 (ha)	Season 2 (ha)	Continuous (ha)	Annualized sum (ha)	FAO/UF V3.0[3] (area equipped for irrigation) (ha)
1	China	108,464,668	75,716,724	68,078,042	7,582,798	151,377,564	53,823,000
2	India	99,758,291	72,661,809	53,728,631	5,961,653	132,352,093	57,291,407
3	United States	27,593,858	18,187,246	4,009,305	2,122,793	24,319,345	27,913,872
4	Russia	21,724,537	14,433,390	2,116,702	224,828	16,774,920	4,878,000
5	Pakistan	13,169,652	7,904,691	7,310,581	761,592	15,976,865	14,417,464
6	Argentina	8,867,096	3,603,392	1,606,411	3,559,386	8,769,190	1,437,275
7	Thailand	6,457,890	3,231,776	2,211,410	1,960,171	7,403,357	4,985,708
8	Bangladesh	5,125,146	3,905,840	3,095,460	207,678	7,208,978	3,751,045
9	Turkey	5,974,186	2,761,592	1,760,856	2,035,164	6,557,613	4,185,910
10	Kazakhstan	6,992,104	4,642,545	1,771,090	83,740	6,497,375	1,855,200
11	Myanmar(Burma)	4,332,698	3,374,777	2,811,490	148,298	6,334,565	1,841,320
12	Uzbekistan	3,478,349	2,756,935	2,450,146	136,167	5,343,248	4,223,000
13	Australia[5]	12,491,207	2,991,344	0	1,997,198	4,988,543	2,056,580
14	Vietnam	4,263,540	1,874,807	1,426,573	1,672,071	4,973,451	3,000,000
15	Brazil	4,045,823	2,169,411	871,121	1,054,221	4,094,752	2,656,284
16	Mexico	3,672,395	1,824,156	918,909	875,439	3,618,504	6,104,956
17	Indonesia	3,042,001	1,226,109	720,339	1,387,312	3,333,760	4,459,000
18	Egypt	2,086,783	1,635,864	1,492,034	165,802	3,293,700	3,245,650
19	Spain	3,297,105	1,518,353	684,889	825,576	3,028,818	3,268,306
20	Germany	2,243,204	1,645,822	1,320,932	40,618	3,007,371	531,120
21	Canada	2,552,921	1,730,705	1,125,880	21,616	2,878,200	785,046
22	France	2,392,733	1,253,032	832,465	609,042	2,694,538	2,000,000
23	Italy	2,738,565	1,343,532	540,518	762,720	2,646,771	2,698,000
24	Iraq	2,069,099	1,242,776	1,255,061	130,080	2,627,917	3,525,000
25	Iran	2,449,769	1,314,261	680,080	500,407	2,494,749	6,913,800
26	Japan	2,421,219	1,163,261	661,990	656,204	2,481,455	3,129,000
27	Ukraine	2,897,304	1,641,055	262,150	493,691	2,396,895	2,454,000
28	Korea, Dem. Rep.	1,416,926	941,017	928,854	194,454	2,064,325	1,460,000
29	Romania	2,284,667	1,135,323	317,566	609,086	2,061,974	2,880,000
30	Turkmenistan	1,445,506	1,002,854	914,026	101,577	2,018,457	1,744,100
31	Sudan	1,655,761	1,185,367	643,653	101,686	1,930,706	1,946,200
32	Philippines	1,497,696	1,028,455	591,493	176,059	1,796,007	1,550,000

Annex 1 Table 1—*Continued*

33	Nepal	1,246,620	695,610	542,955	269,266	1,507,830	1,168,349
34	Chile	1,406,997	703,642	346,252	396,457	1,446,351	1,900,000
35	Korea, Rep.	1,158,106	554,327	441,120	337,394	1,332,841	880,365
36	Morocco	980,306	579,448	460,976	114,810	1,155,234	1,258,200
37	United Kingdom	928,027	812,560	233,964	15,958	1,062,483	142,687
38	Netherlands	851,187	694,225	303,472	29,609	1,027,306	565,000
39	Bulgaria	1,278,137	583,272	63,415	372,702	1,019,389	800,000
40	Denmark	1,067,861	983,934	3,421	0	987,355	476,000
41	Cambodia	720,137	484,187	333,182	130,837	948,207	284,172
42	Afghanistan	947,542	407,380	220,990	302,120	930,489	3,199,070
43	South Africa	784,336	576,713	207,303	47,075	831,090	1,270,000
44	Azerbaijan	799,114	443,714	219,278	162,853	825,845	1,453,318
45	Sri Lanka	952,459	170,126	111,959	529,747	811,831	570,000
46	Venezuela	858,551	500,989	94,309	214,156	809,455	570,219
47	Kyrgyzstan	677,822	454,213	252,222	75,962	782,396	1,075,040
48	Greece	903,007	274,386	107,522	393,260	775,167	1,422,000
49	Czech Republic	530,117	381,198	322,088	245	703,531	24,000
50	Taiwan, Province of China	478,783	283,242	314,976	81,017	679,235	525,528
51	Cuba	472,586	343,565	269,846	25,386	638,797	870,319
52	Syria	530,763	303,170	235,858	60,399	599,428	1,266,900
53	Colombia	520,214	337,011	176,585	79,445	593,042	900,000
54	Saudi Arabia	633,218	143,566	89,075	319,015	551,655	1,730,767
55	Belgium	339,050	298,109	207,725	8,293	514,127	40,000
56	Tajikistan	379,993	285,599	162,341	15,504	463,444	719,200
57	Poland	358,917	269,367	186,154	779	456,300	100,000
58	Somalia	362,273	162,650	118,095	123,533	404,279	200,000
59	Mongolia	409,334	266,498	110,864	0	377,362	57,300
60	Peru	340,094	189,812	113,944	71,243	374,999	1,195,228
61	Uruguay	385,666	312,476	25,694	22,431	360,602	181,200
62	Guinea	303,231	154,644	96,324	71,445	322,412	92,880
63	Portugal	347,119	133,746	54,648	126,582	314,976	632,000
64	Senegal	205,909	151,324	131,809	13,213	296,345	71,400
65	Ecuador	272,538	128,255	85,158	68,145	281,558	863,370
66	Malaysia	250,224	124,916	67,419	85,408	277,743	362,600
67	Serbia	170,062	141,236	92,620	1,910	235,766	57,000
68	Moldova	285,993	164,373	20,450	48,490	233,313	307,000
69	Albania	222,984	118,384	55,931	53,745	228,060	340,000
70	Nigeria	194,048	103,263	61,984	51,069	216,317	300,350
71	Libya	216,115	67,172	60,075	82,771	210,018	360,500
72	Hungary	226,338	167,588	15,320	5,162	188,070	210,000
73	Bolivia	210,739	28,854	9,777	124,402	163,033	128,240

Annex 1 Table 1—*Continued*

74	Ethiopia	179,682	62,157	25,604	75,047	162,809	160,785
75	Guinea-Bissau	109,103	86,441	68,305	4,076	158,821	17,115
76	Georgia	127,484	97,552	46,535	2,907	146,994	300,000
77	New Zealand	120,277	68,146	58,034	15,505	141,686	577,882
78	Algeria	138,198	91,202	35,104	11,759	138,065	555,500
79	Macedonia	178,927	113,304	9,663	8,814	131,781	55,000
80	Armenia	104,091	75,467	38,389	8,089	121,945	286,027
81	Laos	106,678	80,672	22,460	8,562	111,694	295,535
82	Israel	100,739	40,098	37,233	32,025	109,356	183,408
83	Kenya	83,045	53,136	37,446	14,303	104,886	66,610
84	Guyana	91,488	61,989	31,006	10,253	103,249	150,134
85	Cote d'Ivoire	94,620	79,734	20,856	1,742	102,332	72,750
86	Tunisia	104,157	30,355	23,664	46,628	100,647	384,943
87	Austria	116,114	70,292	19,415	10,670	100,377	46,000
88	Swaziland	143,177	97,323	0	0	97,323	67,400
89	Guatemala	66,888	47,948	40,864	2,726	91,538	129,803
90	Dominican Republic	68,524	45,574	25,957	8,335	79,866	269,710
91	Yemen	84,925	43,244	16,073	20,203	79,521	388,000
92	Honduras	66,580	51,243	21,117	5,623	77,984	73,210
93	Slovakia	101,600	72,363	1,094	2,671	76,128	174,000
94	Madagascar	70,356	41,957	19,277	14,634	75,869	1,087,000
95	Ghana	60,614	28,560	24,306	19,395	72,261	6,374
96	Finland	122,773	72,205	0	0	72,205	64,000
97	Sweden	77,749	70,806	1,173	0	71,979	115,000
98	United Arab Emirates	87,658	10,249	4,867	55,486	70,602	280,341
99	Thegambia	39,778	36,530	29,693	0	66,222	0
100	Mali	58,389	38,220	26,101	1,559	65,879	191,470
101	Rwanda	67,983	64,918	0	0	64,918	4,000
102	Belarus	79,442	61,047	195	0	61,243	115,000
103	Mozambique	53,332	39,384	16,703	4,539	60,627	116,715
104	Haiti	52,310	30,563	15,657	8,491	54,710	91,502
105	Jordan	68,752	718	710	51,622	53,050	76,912
106	Cameroon	53,793	35,752	5,990	10,944	52,686	20,970
107	Tanzania	47,976	34,289	7,852	5,467	47,609	150,000
108	Croatia	35,690	29,150	15,898	1,225	46,273	3,000
109	Panama	47,954	22,418	6,552	16,803	45,772	34,626
110	Lithuania	54,132	41,892	0	0	41,892	9,000
111	Switzerland	30,375	21,175	15,939	0	37,114	25,000
112	Angola	22,810	16,672	14,371	3,116	34,159	75,000

Annex 1 Table 1—*Continued*

113	Sierra Leone	22,071	17,160	13,408	213	30,781	29,360
114	Uganda	31,372	27,004	3,447	183	30,634	9,120
115	Oman	17,486	15,335	14,962	0	30,297	72,630
116	Qatar	36,633	0	0	27,975	27,975	12,520
117	Chad	24,686	15,986	8,070	3,747	27,803	14,020
118	Kuwait	35,695	0	0	27,259	27,259	6,968
119	Mauritania	18,780	12,287	12,462	877	25,625	49,200
120	Paraguay	28,575	13,331	1,754	10,499	25,584	67,000
121	Lebanon	23,421	11,313	8,234	5,943	25,490	117,113
122	Togo	21,917	9,886	7,583	6,892	24,361	7,008
123	Nicaragua	16,054	12,314	10,070	614	22,998	61,365
124	Suriname	19,581	14,680	5,070	1,159	20,909	51,180
125	Congo, Dem. Rep.	22,666	19,326	191	773	20,291	10,500
126	Costa Rica	12,273	9,730	5,448	613	15,791	103,084
127	Benin	15,192	4,492	3,897	7,283	15,671	10,236
128	Burkina Faso	14,684	4,539	4,420	5,702	14,661	24,331
129	Estonia	24,053	14,521	0	0	14,521	4,000
130	Bosnia and Herzegovina	10,670	6,697	5,445	2,062	14,204	2,000
131	Montenegro	10,611	7,048	5,704	1,417	14,169	0
132	Eritrea	16,190	11,749	2,309	0	14,058	28,124
133	Puerto Rico	11,350	7,181	1,689	2,588	11,457	37,079
134	El Salvador	11,262	7,887	2,508	54	10,448	44,993
135	Namibia	10,041	7,508	1,795	0	9,303	6,142
136	Burundi	11,548	880	36	8,005	8,921	14,400
137	Gaza Strip	6,990	4,144	4,161	375	8,680	0
138	Latvia	12,647	7,395	65	0	7,460	20,000
139	Niger	4,622	3,822	1,836	0	5,659	66,480
140	Cyprus	6,851	2,787	165	1,983	4,934	55,813
141	Jamaica	4,767	3,113	492	1,006	4,611	25,214
142	Botswana	5,363	3,794	590	0	4,384	1,381
143	East Timor	3,885	3,312	850	0	4,162	14,000
144	Mauritius	5,024	2,381	0	1,528	3,910	17,500
145	Lesotho	5,431	3,681	0	0	3,681	2,722
146	Belize	3,507	2,977	306	286	3,568	3,000
147	Zimbabwe	4,505	3,234	299	0	3,533	116,577
148	Antigua and Barbuda	2,453	1,635	965	384	2,984	130
149	French Guyana	2,956	2,264	351	254	2,869	2,000

Annex 1 Table 1—*Continued*

150	West Bank	3,036	682	675	1,444	2,801	0
151	Malawi	3,275	2,794	0	0	2,794	28,000
152	Equatorial guinea	3,005	2,691	0	0	2,691	0
153	Guadeloupe	1,910	1,498	342	183	2,022	2,000
154	Trinidad and Tobago	2,096	1,822	46	48	1,916	3,600
155	Bhutan	1,305	1,073	831	0	1,904	38,734
156	Norway	2,257	1,458	130	0	1,589	127,000
157	St. Kitts and Nevis	1,508	1,314	84	48	1,445	18
158	Virgin Islands	859	611	403	91	1,105	0
159	Central African Republic	1,213	1,086	0	0	1,086	135
160	Brunei	780	481	369	152	1,002	1,000
161	San Marino	1,268	0	0	903	903	0
162	Reunion	661	517	329	0	846	12,000
163	Comoros	415	381	349	0	730	130
164	Djibouti	866	587	0	0	587	407
165	Zambia	748	0	0	536	536	46,400
166	Slovenia	468	293	217	0	510	2,000
167	Liberia	442	302	142	53	497	2,100
168	Anguilla	414	404	0	0	404	0
169	Montserrat	130	101	129	0	231	0
170	Turks and Caicos Islands	192	117	0	53	170	0
171	Papua New Guinea	68	56	46	0	102	0
172	Luxembourg	66	48	42	0	89	0
173	St. Pierre and Miquelon	59	59	0	0	59	0
174	Cayman Islands	60	55	0	0	55	0
175	Monaco	75	0	0	53	53	0

Note:

1. Sub-pixel area from coefficients of Google Earth estimate
2. Sub-pixel area from combined coeficients of high resolution images and sub-pixel decomposition technique
3. Area equipped for irrigation from Food and Agricultural Organization and University of Frankfurt Global Map of Irrigated Area Version 3.0 (based on national statistics)
4. Area irrigated obtianed from FAO-Aquastat and Earth trends (http://faostat.fao.org/faostat / http://earthtrends.wri.org/country_profiles/)
5. Wold total was computed as per table 9a (480 m ha)
6. Australian irrigated area was computed using the procedure described in annex 2

Annex 2

The crop calendars of the classes for Australia differ significantly from those of the rest of the world. Hence, the Australian area was calculated based on the country crop calendar. However, we have retained the same irrigated area fractions as global, except for class 19 for which the fraction was 0.10. Based on this approach, the country area for Australia is shown in table A2 below.

Annex 2 Table 1.

Irrigated areas of Australia, based on GIAM 10-km.

Class No.	Full pixel name	estimate area (FPA)	**Irrigated** area fraction based on Google earth Estimates (IAF-GEE) coefficient	**Sub pixel** Irrigated area from Google Eye Mean (SPA-GEE)	**Season 1** Irrigated area fraction based on Mean IAF-HRI & IAF-SPDT coefficient	**Season 1** sub pixel Irrigated area from Mean IAF-HRI & IAF-SPDT	**Season 2** Irrigated area fraction based on Mean IAF-HRI & IAF-SPDT coefficient	**Season 2** sub pixel Irrigated area from Mean & IAF-SPDT	**Continuous** Irrigated area fraction based on IAF-HRI & IAF-SPDT coefficient	**Continuous** sub pixel Irrigated area from IAF-HRI & IAF-SPDT	**Annualized sum** sub pixel Irrigated area from Class & IAF-SPDT
		hectares	unitless	hectares	unitless	hectares	unitless	hectares	unitless	hectares	hectares
1	Irrigated, surface water, single crop, wheat-corn-cotton	2,323,345	0.61	1409496	0.61	1,413,271					1,413,271
2	Irrigated, surface water, single crop, cotton-rice-wheat	0	0.82	0							0
3	Irrigated, surface water, continuous crop, mixed-crops	154,806	0.62	95438					0.46	28,575	28,575
4	Irrigated, surface water, double crop, rice-wheat-cotton	1,101,872	0.68	744131	0.53	579,284					579,284
5	Irrigated, surface water, double crop, rice-wheat-cotton-corn	374,332	0.62	230339	0.56	211,373					211,373
6	Irrigated, surface water, double crop, rice-wheat-plantations	0	0.71	0							0
7	Irrigated, surface water, double crop, sugarcane	0	0.70	0							0
8	Irrigated, surface water, double crop, mixed-crops	927,486	0.60	551854	0.37	343,170					343,170
9	Irrigated, surface water, continuous crop, sugarcane	14,757	0.49	7168					0.42	6,250	6,250
10	Irrigated, surface water, continuous crop, plantations	158,568	0.57	90701	0.44	69,263					69,263
11	Irrigated, ground water, continuous crop, rice-sugarcane	1,095,506	0.55	598877					0.49	536,236	536,236
12	Irrigated, ground water, single crop, corn-soybean	675	0.69	463	0.49	328.27					328
13	Irrigated, ground water, single crop,rice and other crops	0	0.78	0							0
14	Irrigated, ground water, continuous crop, mixed-crops	22,859	0.42	9572					0.38	3,015	3,015
15	Irrigated, ground water, single crop, rice and other crops	4,147	0.71	2945	0.55	2,275					2,275
16	Irrigated, conjunctive use, single crop, wheat-corn-soy bean-rice	396,998	0.82	326472	0.47	185,688					185,688
17	Irrigated, conjunctive use, continuouscrop, wheat-corn-orc hards-rice	33,855	0.62	20964					0.57	10,596	10,596
18	Irrigated, conjunctive use, continuous crop, corn-soybeans -other crops	175,158	0.77	135017					0.51	33,672	33,672

Annex 2 Table 1—*Continued*

19	Irrigated, conjunctive use, continuous crop, pastures	8,545,969	0.74	6341109			0.05	427,298	427,298
20	Irrigated, conjunctive use, single crop, pasture, wheat, sugarcane	404,811	0.74	299560	0.46	186,694			186,694
21	Irrigated, conjunctive use, continuous crop, mixed-crops	743,262	0.73	540930			0.57	240,337	240,337
22	Irrigated, conjunctive use,continuous crop, rice-wheat-sugacane	273,153	0.69	187793			0.49	67,470	67,470
23	Irrigated, conjunctive use, double crop, sugarcane-other crops	0	0.64	0					0
24	Irrigated, conjunctive use, continuous crop, mixed-crops	65,684	0.53	34484			0.48	14,073	14,073
25	Irrigated, conjunctive use, continuous crop, rice-wheat	37,231	0.48	17899			0.47	17,638	17,638
26	Irrigated, conjunctive use, continuous crop, rice-wheat-corn	342,888	0.67	228153			0.50	170,514	170,514
27	Irrigated, conjunctive use, continuous crop, sugarcane-orchards-rice	358,996	0.77	277531			0.55	197,681	197,681
28	Irrigated, conjunctive use, continuous crop, mixed-crops	438,858	0.78	340244			0.56	243,845	243,845
		17,995,215		12,491,139		2,991,344		1,997,198	4,988,543

During the next phase, the irrigated areas will be computed based on a) country-wise crop calendar, and b) country-wise crop coefficient.

Acronyms and Abbreviations

2d-FS	2-Dimensional Feature Space
AOAW	All Other Areas of the World Segment
AVHRR	Advanced Very High Resolution Radiometer
BGW	Brightness-Greenness-Wetness
CRU	Climatic Research Unit
CBIP	Central Board of Irrigation and Power
DAAC	Distributed Active Archive Centers
DCP	Degree Confluence Project
DTED	Digital Terrain Elevation Data
DEM	Digital Elevation Model
EDC	EROS Data Center
EGT1500	Elevation Greater than 1,500 m Segment
ERDAS	Earth Resources Digital Analysis System
EROS	Earth Resources Observation Systems
ETM+	Enhanced Thematic mapper plus
FAO	Food and Agriculture Organization of the UN
FGT75	Forest Cover Greater than 75 Percent
Generic-IWMI-628	Generic IWMI 628 Class Map
GIS	Geographic Information System
GLC2000	Global Land Cover Classification for the Year 2000
GIAM	Global Irrigated Area Map
GMRCA	Global Map of Rain-fed Cropland Areas
GMLULCA	Global Map of Land Use/Land Cover Areas
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GTOPO30	Global Digital Elevation Model (DEM) with a Horizontal Grid Spacing of 30 Arc-Seconds (Approximately 1 km)
IGBP	International Geosphere Biosphere Program
IMW	International Map of the World
IWMI	International Water Management Institute
IWMI-DSP	International Water Management Institute Data Storehouse Pathway
ISOCLASS	Statistical Clustering Algorithm in ERDAS
JERS-SAR	Japanese Earth Resources Satellite-Synthetic Aperture Radar
JPEG2000	Joint Photographic Experts Group New Imaging Compression Standard
LULC	Land Use/Land Cover
MODIS	Moderate Resolution Imaging Spectroradiometer
NPOESS	National Polar Operational Environmental Satellite System
MIR	Mid-Infrared
MODIS	Moderate-Resolution Imaging Spectro-Radiometer
MVC	Maximum Value Composite
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NESDIS	National Environmental Satellite Data and Information System
NIR	Near-Infrared
NGDC	National Geophysical Data Center

NOAA	National Oceanic and Atmospheric Agency
NPOESS	National Polar Operational Environmental Satellite System
PCA	Principal Component Analysis
PGT2400	Precipitation Greater than 2400
RFSAR	Rain Forest Synthetic Aperture Radar
SCS	Spectral Correlation Similarity
SMT	Spectral Matching Technique
SP-DCT	Sub-Pixel Decomposition Technique
SSV	Spectral Similarity Value
SPOT	Satellites Pour l'Observation de la Terre or Earth-Ubserving Satellites
SPOT VGT	SPOT Végétation Sensor
ST-SC's	Space Time Spiral Curves
TAAI	Total Area Available for Irrigation
Terra	Earth Observing System (EOS) Satellite-NASA Flagship Satellite under Earth System Enterprise
TLT280	Temperature Less than 280 Degree Kelvin
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VNIR	Visible and Near-Infrared
VIIRS	Visible and Infrared Imaging Radiometer Suite
WGS84	World Geodetic System 1984

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