A Satellite Sensor Based
Global Map of Irrigated Areas and Products

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Abstract: A Global map of irrigated area has been produced for a nominal year of 1999 using Multi sensor, Multi date, Multi scale satellite sensor based data and secondary data. The digital datasets consisted of : (a) AVHRR 4-band and NDVI 10-km monthly time series for 1981-1999, (b) SPOT vegetation NDVI 1-km monthly time series for 1999, and (c) East Anglia University Climate Research Unit Rainfall and Temperature 50-km monthly time series for 1961-2000. Additional major global data sets used were (a) GTOPO-30 1-km elevation, (b) JERS SAR data for the rainforests during two seasons in 1996, and (c) University of Maryland Global Tree Cover 1-km data for 1992-93.

The paper espouses a number of new methods and techniques. The study first segmented the world into climate and elevation zones and analyzed satellite images separately for these zones. Since times series are analogous to spectral plots, spectral matching techniques were used to identify, group, and label classes with similar time series characteristics. The class time series were also compared with the target ones obtained from ground truthed locations. The spectral correlation similarity was found to be the most useful spectral matching technique. Decision tree algorithms, NDVI time series plots, NDVI thresholds, principal component analysis, and unsupervised clustering algorithms were widely used to define and refine classes. A wide array of ground truth data also helped identify and label classes.

The final product consisted of a 34-class irrigated area map of the world that includes 20 irrigated area classes, 8 supplemental irrigation classes, and 6 other LULC classes with significant irrigation. A new sub-pixel decomposition technique was developed to estimate the total global irrigated area for three reference seasons: (a) 317,960,831 hectares during June-September, (b) 194,255,688 hectares during October-February, and (c) 125,220,366 hectares during March-May. A suite of products and data are freely made available on a dedicated web site at: http://www.iwmigmia.org.

Keywords: Remote Sensing, Global, Irrigated Areas, Time series.

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1. Introduction

To meet food demand of ever increasing population, some estimate that at least another 2000 cubic kilometers of water (equivalent to the mean annual flow of 24 additional Nile rivers) will be needed by year 2050 (Postel, 1999). Water use for irrigation varies considerably across the globe. It accounts for 2-4 % of diverted water. Globally, the irrigated landscape remains very dynamic. Although the annual rate of increase of irrigated areas has slowed to about 1 %, this still represents an increase of between 2 and 3 million hectares each year. 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, 2005). Reservation and re-allocation of flows for environmental purposes will in the end place even greater competing demands in terms of water volume. Climate change will impose additional challenges that will reshape the irrigated landscape through changes in snow-melt runoff and rainfall.

Historical estimates of global irrigated area began with an estimate of 8 million hectares in year 1800, rising to 95 Mha in 1940, to the current ones. Currently, there is one irrigated area map of the World produced by FAO/ Frankfurt University based on irrigated area statistics of various nations. Approximately at 10-km grids, this map presents areas that are "equipped for irrigation" but not necessarily irrigated (Döll and Siebert, 1999, 2000; Siebert et al., 2002). The FAO/Kassel study estimates area equipped for irrigation to be 257 Mha or about 16 percent of the total croplands (1.5 billion ha) around year 1995. It has two known limitations. First, extrapolation the statistical numbers to spatial domain can be a rough approximation of the actual location of the irrigated areas. Second, irrigated area statistics provided by different countries have various inconsistencies. This may still 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. 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 under and over-reporting of irrigation different contexts and countries.

Given the above background, the International Water Management Institute (IWMI) initiated a Global Irrigated Area Mapping (GIAM) project in year 2002 (Droogers, 2002, and Turral, 2002) supported by the Comprehensive Assessment on Water Management in Agriculture and by IWMI core funds. The main motivation to develop the IWMI map lies in the potential of 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; and elaborate the extent of multiple cropping over a year, particularly in Asia, where two or three crops may be planted in one year, but cropping intensities are not accurately known or recorded in secondary statistics.

2. Material and Methods

The availability of an increasing number of global datasets from satellite sensors of various eras offered 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. 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. Along with advanced datasets, sub-pixel disaggregation of the component irrigation areas defines land classes as a mix of characteristic land use and cover providing possibility for estimating actual irrigated area.

The process starts with a number of publicly available data sets, which are processed into one large time series file, known as a mega-file. The time series analysis is conducted on the mega-file and is described in section 5. The DEM, temperature, and rainfall data is combined into the mega-file to allow segmentation of a set of masks of different characteristic regions of the world to made and which are analyzed separately and then combined in the class naming and area calculation steps. A number of other data sets are used to provide contextual and detailed information to assist in identifying, separating and aggregating classes. All input data, all mega-files and outputs are stored in the IMWI Data Storehouse Pathway, an on-line archive which stores all remote sensing and GIS data collected by IWMI, hereafter known as IWMIDSP. The site can be accessed at: **http://www.iwmidsp.org.**

Considerable research effort has been made into hyper-spectral imagery analysis and this yields a number of promising avenues, developed here, for the analysis of time series. The principle involved quantitative and qualitative spectral matching technique wherein the shape and/or the magnitude of the class spectra is matched with target or reference spectra (Homayouni and Roux, 2003; Thenkabail et al. 2004c and 2004d). Time series of NDVI or other metrics are analogous to spectra, where time is substituted for wavelength. The time series signatures of irrigated crops across the globe can match (tropics) or be out of phase (tropics and southern hemisphere). We also attempted to use Modified Spectral Angle Similarity (MSAS) (Shippert, 2001, Farrand and Harsanyi, 1997, Thenkabail et al. 2005b) which measures hyper-spectral angle between spectra of any 2 classes or between target and sample class spectra.

A summary of the application of brightness, greenness and wetness characteristics applied to multi-temporal imagery is discussed recently by Thenkabail et al (2005) with respect to irrigation mapping in the Ganges Basin in India. A 2-dimensional near-infrared vs. red band spectral reflectivity plots of unsupervised classes are referred to as the brightness-greenness-wetness (BGW) plots. The BGW plots are very useful tool to determine whether a class is: (a) green, (b) bright, (c) wet, and (d) somewhere in-between these classes. Classes that occupy green area have high NIR reflectivity and low red reflectivity. Typically, these areas are forests, agricultural lands, and natural vegetation. Classes that occupy bright areas have high NIR and high red reflectivity. The land use/land cover (LULC) categories of these classes are likely to be open/barren areas, sparse vegetated areas, dry vegetation areas, clouds, and the build up. Classes that occupy wet areas have low NIR and low red reflectivity. These classes are likely to be wetlands, moist lands, water bodies, cloud shadows, and swamp forests. The classes that are in between these classes have different degrees of above LULC classes.

Identification of the resulting classes is performed using a suite of new techniques to interpret vegetation dynamics in multi-temporal series. 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 150m and other secondary information. This resulted in generic class map of 628 "unique" classes. Class naming was harmonized with earlier Global Land Cover classifications, as far as possible. Irrigation classes were then derived by aggregation of similar irrigated land use in the generic map, resulting in a 34 irrigation class map (see Fig. 1). This map is used to estimate irrigated crop areas in each of three reference seasons.

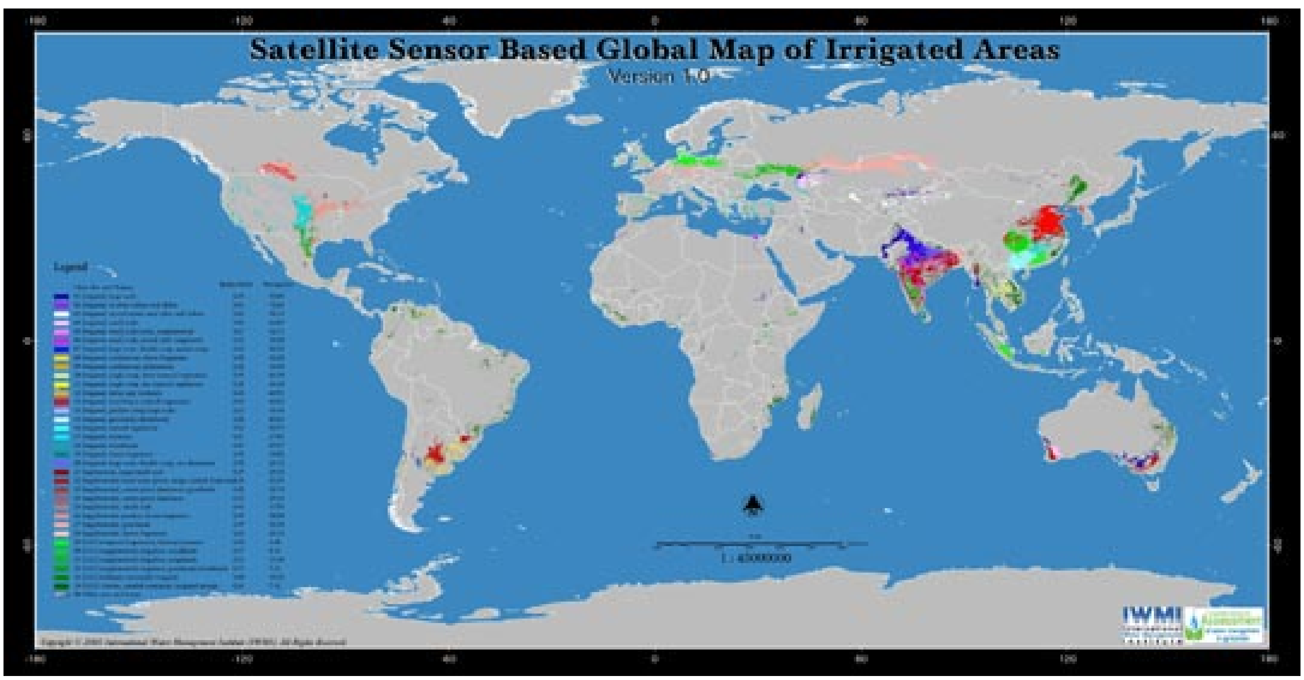

Figure 1. A global map of irrigated area at the end of the last millennium. [source: http://www.iwmigmia.org].

Theoretical evaluations of the brightness-greenness-wetness (BGW) 2d-FS (Thenkabail et al. 2005) helped assign irrigated area percentages with a greater degree of certainty. It must be noted that the greater the understanding of percent irrigated area vs. band reflectivity, greater the reliability of area calculations. This basically comes from a combination of field and remote sensing experience and is therefore limited by the geographical and farming system range of that experience. The exact data and assigned percentages in these plots can be progressively improved and expanded to different sub-groups of classes as the need arises. The decomposition plots are made so that they can be easily modified at local, regional, National, and Global levels using any additional data that that becomes available.

3. Discussion and Conclusion

The gross irrigated area in the nominal year of 1999 amounted to 637.5 million hectares with the component areas across 3 seasons being: (a) 317,960,831 hectares for June-September, (b) 194,255,688 hectares for October-February, and (c) 125,220,366 hectares for March-May. Thereby, this study has shown how, for the first time, the irrigated area of the world being determined taking explicit account of cropping intensity in different regions (Fig. 2).

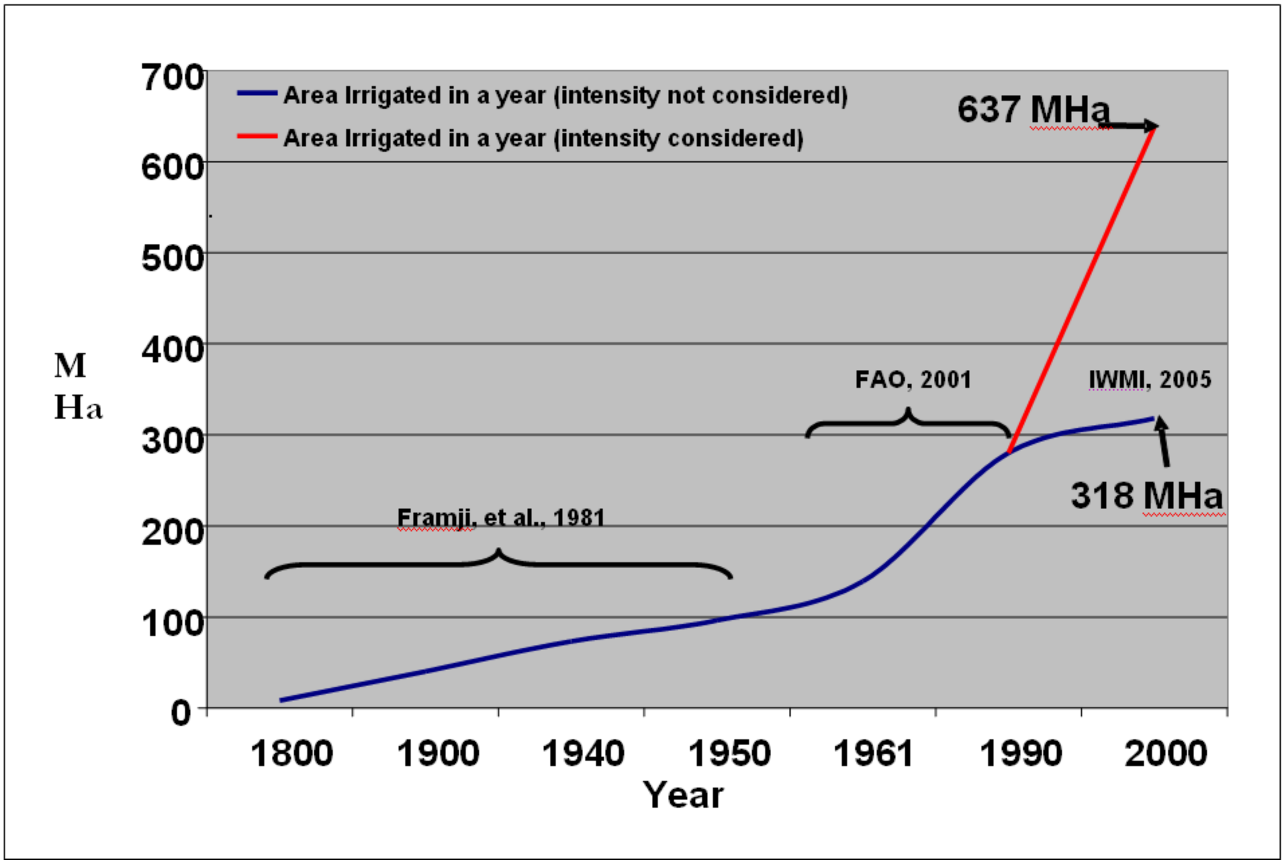

Figure 2. Historical development of global irrigated area, with and without cropping intensity expressed in Million Hectares. [Source: IWMI research highlights; and http://www.iwmigmia.org].

The approach is based on the development of land-use classes containing full, partial and supplemental irrigation in different landscape settings (forest, mixed rainfed areas and so on.) The seasonal areas have been extracted by proportioning the relationships between NIR and R reflectances between the maxima and minima of a class, based on groundtruth information (e.g., from degree confluence project) and extensive use of hi-resolution imagery such as GeoCover. Accuracies have been tested using high-resolution imagery, degree confluence project, and ground truth data. The error matrix showed the accuracies were between 68.90 and 94.03.

The project demonstrates and makes (http://www.iwmigmia.org) available a series of data, products, and methodologies for mapping irrigated areas at a wide array of scales using satellite sensor data of different characteristics: The website includes, irrigated area class maps, class spectral characteristics over time, sub-pixel estimations of irrigated areas, links to suite of primary datasets used in the project, animations of irrigation over last two decades month-by-month, and and accuracy assessments. The detailed methodological documentation of the work is also made available through the web link. The emphasis is placed on wide use of these data and products through the dedicated web site made available as a global public good for free. It is hoped that these efforts play a role in future updates of irrigated area maps using consistent data and methods.

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