Irrigated Land Use and Irrigation Distribution Systems of Four Schemes in the Polonnaruwa District of Sri Lanka

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IRRIGATED LAND USE AND IRRIGATION DISTRIBUTION SYSTEMS OF FOUR SCHEMES IN THE POLONNARUWA DISTRICT OF SRI LANKA

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EXECUTIVE SUMMARY

A complete understanding of the four irrigation systems in Sri Lanka was required to effectively design, implement, and evaluate a rehabilitation and improvement effort. Because population and economic pressures have resulted in encroachment of irrigated acreage relative to the original command area design, current irrigated acreage figures and accurate, detailed maps of the distribution systems were needed. The purpose of this study was to provide this basic information for use in other irrigation schemes in similar areas. The mapping of distribution systems and land use included interpretation of aerial photos and extensive field verification. Gross irrigated acreage for the area actively managed by the Irrigation Department was 20 percent to 32 percent above the specified design for the four systems.

An alternative method used to map irrigated land use was digital processing of Landsat images. Because of diverse spectral properties of the major irrigated crop, rice, the unsupervised method was used as the basic classifier. Rectified digital maps were stratified according to cloud cover and used in sample extraction and to assess accuracy. Irrigated acreage determined by Landsat classification was within 1 percent to 3 percent of ground mapping results for cloud-free areas and within 8 percent of ground mapping results for cloud-affected areas. Overall, accuracy for classification of cloud-free areas was a satisfactory 87 percent. Digital smoothing improved overall classification accuracy to 90 percent. Multitemporal class combination did not improve accuracy.

The ground and aerial photo mapping met all data needs, but required intensive field work. This method may be less applicable in Sri Lanka in the future because of suspension of aerial photo sales. Digital classification of Landsat images required considerably less field work than ground and aerial photo mapping and was satisfactory for land use mapping of cloud-free areas. Application of this method depends upon the availability of cloud-free images.

I. INTRODUCTION

Several large irrigation systems have been constructed by the government in Sri Lanka in conjunction with resettlement schemes in the Dry Zone. The irrigation projects are meant to increase the agricultural productivity of the Dry Zone and provide a livelihood for Sri Lankans resettled from the densely populated Wet Zone. In response to less than optimal performance in many of the irrigation systems, new institutional policies and programs have been implemented to improve the physical irrigation systems and operations (Fowler and Kilkelly, 1987). One of these programs, the Irrigation Systems Management (ISM) Project, was funded by the United States Agency for International Development (USAID) to rehabilitate and improve four irrigation systems in the Dry Zone (Polonnaruwa District): Parakrama Samudra, Giritale, Minneriya, and Kaudulla.

As part of the ISM Project, the Diagnostic Analysis Project was designed to provide an understanding of the physical systems and operations of the four irrigation systems prior to system rehabilitation and improvement. The ISM Project will use this information to assist in establishing methods for system improvement and as baseline data for use in monitoring and evaluating the improvement efforts.

A. BASIC DATA NEEDS

This activity, the mapping of irrigation systems and land use in Polonnaruwa District, was designed to meet some basic data needs of the Diagnostic Analysis Project. Upon initiation of the Diagnostic Analysis Project, it became apparent that there was a lack of reliable, basic data regarding the location and areal extent of irrigated command areas under the four irrigation systems. Also, no maps existed that adequately depicted the layout of the irrigation distribution systems.

Prior to this mapping activity, irrigated acreage figures were considered approximate and maps for the irrigation distribution systems were not sufficiently detailed. More accurate information was desired by the Irrigation Department and other government agencies to properly plan, make policy decisions, and implement policy (Elkaduwa, 1984).

Accurate map and irrigated acreage data was also considered essential for effective water management and operation of the irrigation systems, and for effective rehabilitation and improvement of the systems. Without specific knowledge of irrigated acreage, irrigation water delivery requirements are uncertain at every level of operation -- from reservoir to field channel. Thus, irrigated acreage figures were necessary to properly design or reconstruct conveyance systems and water control structures. Accurate maps of the delivery system would also facilitate project planning, design, and logistics in the field.

B. OBJECTIVES

The primary objective of this special studies activity was to provide basic data for each of the four irrigation systems to the Government of Sri Lanka, the Diagnostic Analysis Project, and the ISM Project. The basic data required included the location and aereal extent of current and historic (designed) irrigation subcommand areas, and accurate, detailed maps of irrigation distribution systems.

An early assumption was that this basic information would be supplied, to the extent possible, by digital processing of satellite images and analysis by a computer-based geographic information system. However, upon initiation of field investigations, relatively recent high quality aerial photographs were discovered which covered most of the study area. This resource was considered superior to the relatively low resolution satellite images as a source for some of the required information. There was a remaining interest in the alternative computer-based techniques for similar areas in Sri Lanka and Asia, where aerial photography was not accessible or was not cost-effective to obtain. It was decided that the basic data acquired under the first objective would be used for assessing the use of these alternative methods.

Therefore, the second objective was to investigate the utility of computer-based geographic information systems and processing of satellite images for rapid assessment and monitoring of the irrigation systems. If satellite image processing methods were successful in this study, the methods could be extended to other irrigation systems in similar areas.

II. BACKGROUND

A. DESCRIPTION OF THE STUDY AREA

The two major regions of Sri Lanka are characterized by their climatic properties: the dry and wet zones. The study area was located in the Dry Zone's North Central Province, in the Polonnaruwa District (Figure 1). Although the mean annual rainfall is about 58 inches, most is received during the wet season (maha). The dry season (yala) is characterized by low effective precipitation, low humidity, and high rates of evaporation (Tennakoon, 1986).

Most cultivated land is served by the irrigation systems and is on gently sloping to nearly level terrain with slopes of 0 to 4 percent. Slope length within minor watersheds ranges from about 1000 to 5000 ft, with the nearly level or level terrain occupying the lower slopes and valley floors. Elevation within the study area ranges from about 300 ft above sea level at Minneriya to 90 ft above sea level along the Periya Aru.

Three major soils have been identified in the study area: reddish-brown earths, low humic gley, and alluvial soils (Moorman and Panabokke, 1961). These three soils correspond with the following subgroups according to the U.S. soil classification system (Soil Survey Staff, 1975), respectively: Rhodustalfs and Haplustalfs, Tropaqualfs, and Tropaquents and Ustifluvents. Reddish-brown earths have sandy loam and sandy clay loam texture, are well-drained to imperfectly drained, and are located in the highlands and on the upper slopes of the irrigation systems. Low humic gleys have sandy clay loam and sandy clay texture. These soils are in valley floors and are poorly drained with high chroma mottles grading to gley and an associated water table at varying depths. The alluvial soils are in narrow floodplains adjacent to active streams. These soils have little profile development, variable texture, and typically, due to their proximity to streams, a high water table.

The two main cropping seasons in the Dry Zone coincide with the two major climatic seasons. The yala cultivation depends almost entirely on irrigation and occurs from April to September. Crops grown during maha (from October to March) require supplemental irrigation. During yala, over 95 percent of the cultivated area is planted to rice paddy. The remaining area is in subsidiary crops such as chili, tobacco, soybeans, and vegetables. In the highlands, gardens are kept and permanent groves of trees have been established including coconut, mango, and banana.

Major land use in nonirrigated areas consists of forest, rangeland, and urban areas. Forests have native evergreen and deciduous trees with varying composition and canopy, depending on the associated landscape, soils and degree of human influence. There are forest reserves, but most forest is continually used as a source for fuelwood, particularly near villages and settled areas. Secondary scrub and poor grasses have replaced native forests to various degrees, depending on

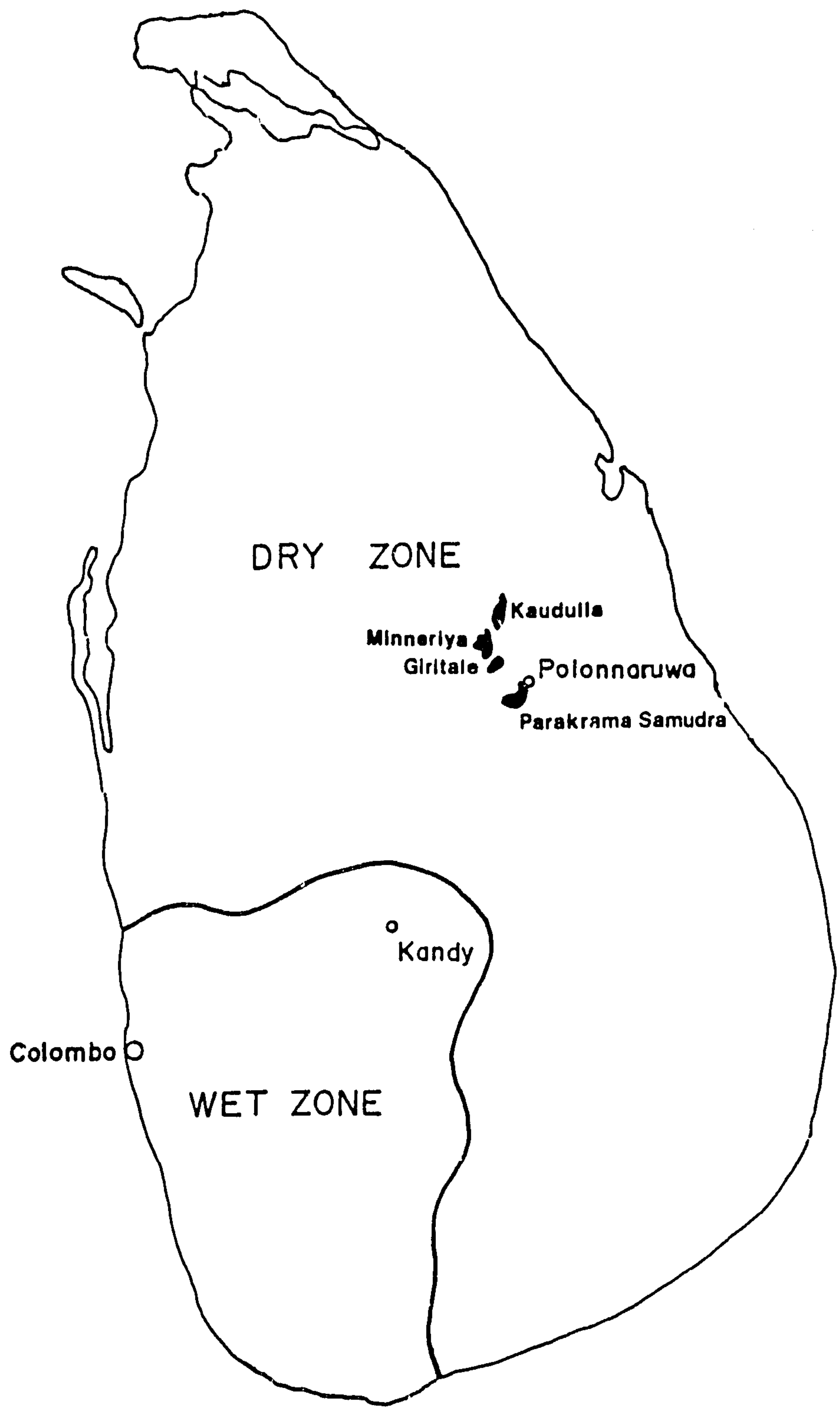

Figure 1. Map of Sri Lanka showing the location of the four irrigation systems.

the extent of canopy removal and the impact of grazing by buffalo and other draught animals. There are also riparian grasses around edges of tanks and adjacent to marsh areas, or villu.

B. IRRIGATION SCHEMES AND LAND USE

The four irrigation systems were originally designed and constructed by ancient, technologically advanced civilizations. The earliest tanks, Minneriya and Kaudulla, were constructed in the 4th century A.D. The Giritale tank, originally built in the 7th century, was restored in the 12th century. At the same time, Parakrama Samudra tank was constructed by King Parakrama Bahu the Great. Following a period of invasion and war, the irrigation systems fell into disrepair and were largely abandoned (Broheir, 1934).

Beginning in the 1940s and continuing through the 1970s, the Government of Sri Lanka restored the ancient irrigation systems in conjunction with colonization and resettlement projects. Irrigation distribution systems were designed in conjunction with settlement plans that included, in addition to irrigation and residential allotments, reservations for communities, parks, schools, forest, and pasture. Within the irrigation command areas were reservations for canal embankments and roads and for surface drainage channels and waterways.

Since restoration of the irrigation systems, rates of in-migration and births have resulted in a great increase in population. As a result of population and associated economic pressures, most all reserved land within the command of an irrigation distribution system has been converted to irrigated paddy. In addition, extensive areas adjacent to the irrigation scheme command areas have been converted to paddy. These areas have been served by tailwater and surface runoff from the major systems.

C. REMOTE SENSING FOR IRRIGATED LAND USE

1. Principles

The basic principles applicable to remote sensing and digital image processing have been presented in a number of sources. One of the most comprehensive and authoritative references for remote sensing is the Manual of Remote Sensing (Colwell, 1983). Comprehensive remote sensing texts include Lillesand and Kiefer (1979) and Campbell (1987) Swain and Davis (1978) and Richards (1986) present outlines for digital analysis of remotely sensed images with discussion of applications in different disciplines.

Satellite-based remote sensing systems measure energy emitted from the surface of the earth in discreet ranges of wavelengths. Satellite images relevant to this study include Landsat and the SPOT imaging systems, which are described in section II.C.3 of this report. For these imaging systems, wavelengths measured correspond with the visible and infrared ranges of the electromagnetic spectrum. Analysis and interpretation of these images is based on the different spectral properties of various earth surface materials. Hoffer (1978) presents a review and discussion of the spectral reflectance characteristics of water, vegetation, soils, and cloud.

Figure 2 depicts the reflectance properties of three basic types of surface material - water, vegetation, and soil - for the visible and infrared range of wavelengths. These materials are actually quite variable in their reflectance characteristics. Water, which shows less than 10 percent reflectance in the blue-green range and no reflectance in the infrared, would have considerably different properties if turbid. The reflectance properties for vegetation are typical for healthy plants: high reflectance in the green relative to the blue and red ranges, and much higher reflectance in the near infrared relative to the visible region. These properties will also differ for various types of vegetation or for healthy plants versus plants under stress. Also, plants can have quite different reflectance properties at different stages of growth.

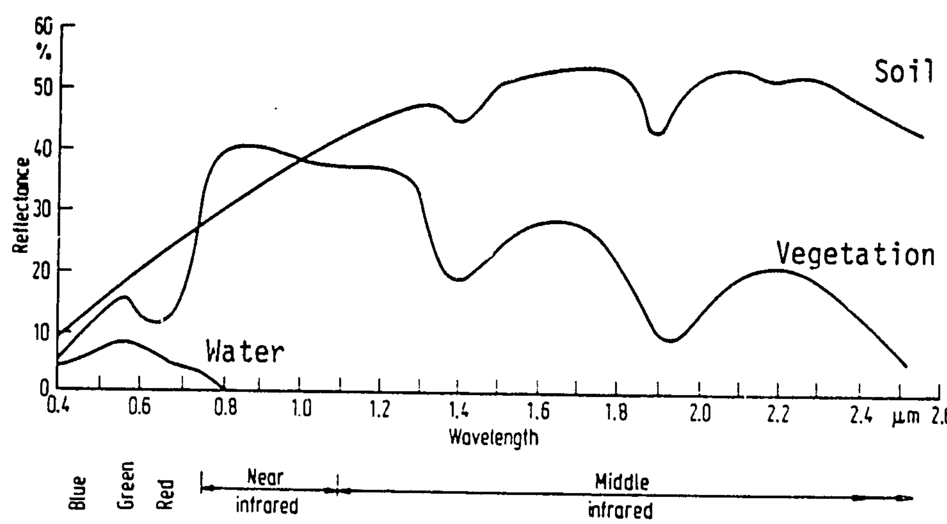

Figure 2. Spectral reflectance characteristics of common earth surface materials in the visible and near infrared to middle infrared range. (Richardson, 1986)

For the visible region of the spectrum, spectral reflectance properties of vegetation are controlled largely by chlorophyll and accessory pigments in the palisade cells of the leaf. In the near infrared range, spectral reflectance of the leaf is controlled by the underlying spongy mesophyll tissue. These controlling factors, and therefore the spectral reflectance characteristics, can vary considerably among plants and also for various stages of growth for most plant species. For example, grass, broadleaf forest, and coniferous forest show reflectance properties somewhat different in the visible wavelengths, but considerably different properties can be seen in the infrared region (Figure 3).

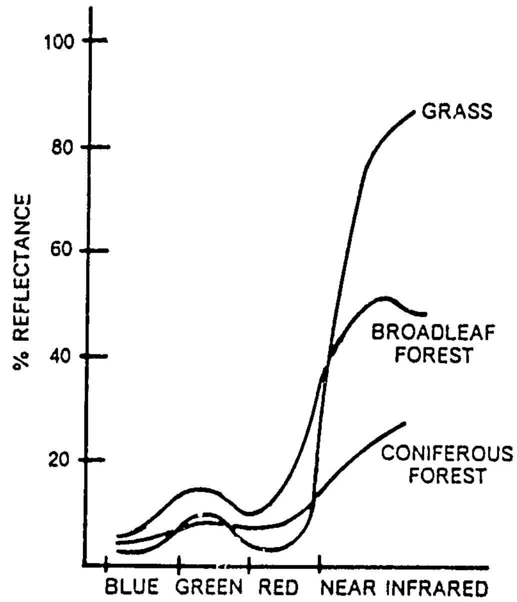

Figure 3. Spectral reflectance differences between vegetation classes. (Campbell, 1987)

A ratio of near infrared to red spectral values is often used in vegetation studies with satellite images. For cultivated crops, this ratio is expected to change considerably over the life of the crop. From Figure 4, the expected near infrared/red ratio is expected to range from near zero at emergence, to a maximum just prior to heading and flowering, and back to a minimum at harvest. This curve represents a general composite of specific curves developed for different varieties of rice paddy (Ayyangar et al., 1980).

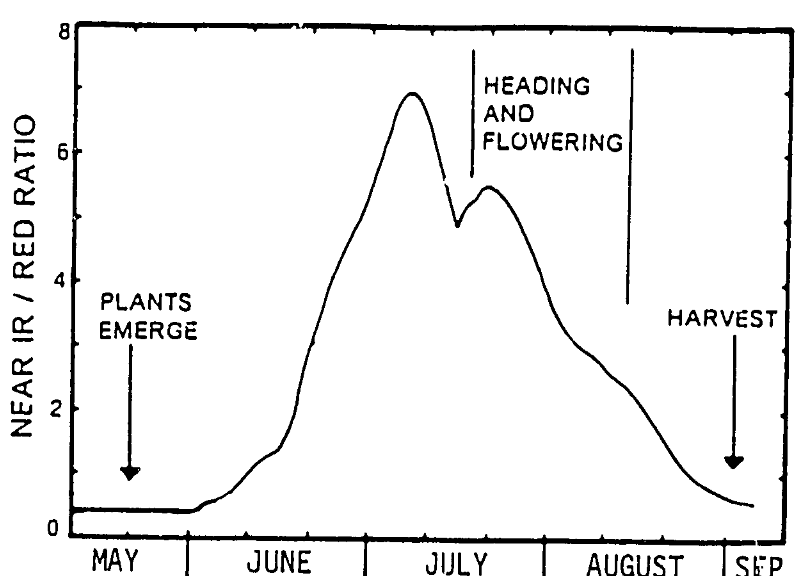

Figure 4. Expected infrared/red ratio for rice paddy throughout the growing season. (Ayyangar et al., 1980)

The earth's surface materials usually do not occur in large, homogeneous areas. In agricultural scenes, individual plants are closely intermingled with the bare soil between plants so that reflectances are mixed, even with fine resolutions. The amount of reflection from the soil depends on the properties of the soil and the amount and type of vegetation canopy.

From Figure 5, soil brightness values for red versus infrared reflectance tend to form a straight line; as a soil reflects more in the red region, it tends to reflect more in the infrared region. Richardson and Wiegand (1977) have defined this relationship as the "soil brightness line". Wet soils are normally dark and reflect low values in both spectral regions (B), whereas dry soils tend to reflect relatively high values in both spectral regions (C).

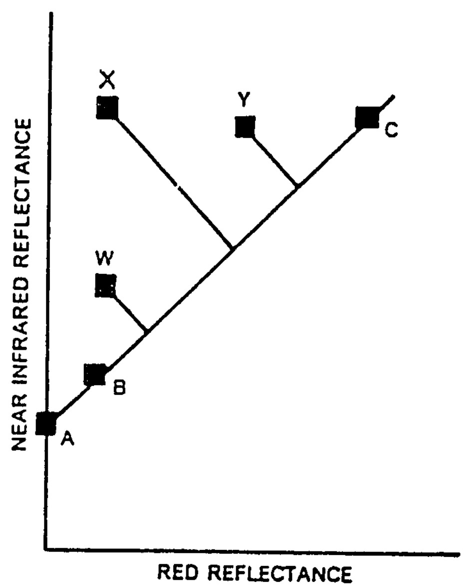

Figure 5. Perpendicular vegetation index. (Richardson and Wiegand, 1977).

The spectral response of vegetation will have a relationship with the soil brightness line, depending on the degree of mixing and the spectral nature of both soil and vegetation. For example, pure vegetation has high infrared reflectance and relatively low red reflectance, and will fall in the upper left of the plot (X). A mixed response of both vegetation and dry soil (Y) has spectral properties like both dry soil and vegetation, and will fall in between (X) and the (C) on the soil line. A mixed response of vegetation and wet soil (W) will fall between (X) and dark end of the soil brightness line (B).

The spectral characteristics of the land cover of most interest to this study, rice paddy, can be expected to have very complex interrelationship among the influencing factors. The spectral response of rice plants depends largely upon factors controlling the density and health of the crop canopy, such as seed variety, stage of growth, soil fertility, influence of pests, weed control, and water management. In addition to the canopy cover, reflectance of the underlying soil depends on physical characteristics of the soil, especially soil color (Cipra et al., 1980) and soil moisture. If water is ponded, reflectance will also be affected by the depth of water and its turbidity.

Factors influencing spectral characteristics of rice paddy were found to be quite variable and complex in the study area. Presence, depth, and turbidity of ponded water were observed as highly variable throughout the study area. Factors which control ponding, and density and health of crop canopy, were studied under the Diagnostic Analysis Project (Fowler and Kilkelly, 1987) in the study area. These factors varied among and within the small, individual paddy allotments, which were less than 5 ac in size. Production inputs (such as fertilizer and water), pest control, and other agronomic practices were highly variable. For the sample sites studied, about half the paddy was transplanted, which reduced the irrigation season up to three weeks, and half was broadcast. Of the broadcast paddy, over half was sown to long-season varieties. The number of days required from the first water issue to the completion of harvest ranged from 120 days to 170 days. Paddy yields ranged from 11 bu/ac to 143 bu/ac.

2. Previous Studies Using Landsat for Mapping Rice Paddy

A study was conducted in a 20 km x 20 km area in Japan (Mukai and Takauchi, 1984). A multitemporal approach was used, with Landsat images from dates early and late in the rice paddy growing season. The early image date was selected to corresponded with standing water in the paddy. Classification methods are unclear, but areas estimated with Landsat were reported to be within 10 percent of areas reported by statistical surveys.

The Sri Lanka/Swiss Project mapped land use at 1:100,000 scale (Geiser and Sommer, 1984). Manual interpretation of false color, infrared Landsat images was performed for a variety of land cover types, including paddy. For this study, conducted in the early 1980s, digital classification was not considered appropriate because of the training and expense required for computer operation and because of the expected delays in acquisition of computer-compatible tapes. A multitemporal approach was used to delineate paddy. It was expected that images acquired during flooding but prior to planting would be the key to acreage determination. It was found that water was not standing in all paddy fields on pre-planting dates and that images taken one or two months before harvest worked best for paddy identification.

Remote sensing of tank-irrigated areas in India was performed, using manual interpretation techniques (Thiruvengadachari, 1983). Manual inventory methods were preferable to digital techniques because of the expense of equipment and the training requirements of digital methods. A component of this assessment was the estimation of irrigated cropland. This method was reported as successful, but there were problems with cloud cover and with interpreting images due to the spatial resolution of the Landsat MSS data. The author stressed the need for developing cost effective methods of combining aerial photography with satellite data to establish current baseline conditions of tank-irrigated croplands.

Karunasena (1986) monitored paddy in the Polonnaruwa District. This study included an estimation of irrigated paddy acreage using manual interpretation of Landsat images. The multitemporal approach was used with satellite data from both early season and mid- to late season. Paddy acreage figures were determined for the Parakrama Samudra Scheme by comparing Landsat scenes to topographic maps depicting the location of paddy (Survey Department, 1972) and computing the acreage difference. The total acreage difference was added or subtracted to the Irrigation Department figures for the date of the topographic maps.

3. Satellite-based Systems

Landsat Systems.[1] The series of five Landsat remote-sensing satellites evolved from the photographic observations made during the early manned space flights. Landsat 1 was launched in 1972, the first satellite designed specifically for earth observation. The first three Landsats have been retired: Landsat 4 and 5 are currently in use.

Initially, the primary sensor system used on the Landsats was a television-like, return-beam vidicon (RBV) system consisting of two or three cameras filtered to record three spectral bands. The RBV systems experienced technical problems, and the system was discontinued after Landsat 3. As a result of RBV malfunctions, another sensor, the multispectral scanner (MSS) became the primary Landsat sensor system. The MSS recorded four spectral bands in the visible and near-infrared regions of the electromagnetic spectrum. With a ground resolution of 79 m x 79 m, the MSS system was successful and is currently in operation on Landsats 4 and 5.

An upgraded MSS system, the thematic mapper (TM), is also on board Landsats 4 and 5. The TM is basically an improved MSS, but with a more complex design. The TM provides more detailed spectral and spatial information in narrower spectral regions. As presented in Table 1, the TM system records seven spectral bands: three in the visible region, three in the near and middle infrared, and one in the far infrared (thermal) region. For six spectral bands, the TM has a ground resolution of about 30 m x 30 m. The TM thermal band has a 120 m x 120 m ground resolution. The additional bands and resolution of the TM system add significantly to the data cost, and greatly to data storage and handling requirements.

The first three Landsats covered all areas of the Earth every 18 days. Landsats 4 and 5 orbit in 16-day cycles at an altitude of 705 km. Orbits are sun-synchronous, crossing the equator in the descending node at 9:30 a.m.

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[1]From Colwell (1982), Lillesand and Kiefer (1979), and Campbell (1987).

Table 1. Spectral characteristics and ground resolution of Landsat 4 and 5, and SPOT* satellite sensors.

Sensor	Band Number	Response (micrometers)	Resolution (meters)
Landsat MSS	1	0.5 - 0.6 (green)	80
	2	0.6 - 0.7 (red)	80
	3	0.7 - 0.8 (near infrared)	80
	4	0.8 - 1.1 (near infrared)	80
Landsat TM	1	0.45 - 0.52 (blue-green)	30
	2	0.52 - 0.60 (green)	30
	3	0.63 - 0.69 (red)	30
	4	0.76 - 0.90 (near infrared)	30
	5	1.55 - 1.75 (mid infrared)	30
	7	2.08 - 2.35 (mid infrared)	30
	6	10.4 - 12.4 (far infrared)	120
SPOT	1	0.50 - 0.59 (green)	20
	2	0.61 - 0.68 (red)	20
	3	0.79 - 0.89 (near infrared)	20
	Panchromatic	0.51 - 0.73	10

*Systeme Probatoire d'Observation de la Terre.

Both the TM and MSS systems sense the electromagnetic radiation reflected or emitted from the Earth and record the information in a digital format. The brightness values are recorded on the scanner as a pixel (picture element), with the digital value representing the electromagnetic radiation of a corresponding ground area. Ground area dimensions per pixel are determined by the scanner sample rate and the satellite velocity. Landsat images are formed by aggregating pixel values into a scene. The Landsat scenes represent a ground area of approximately 185 km x 170 km. TM data is also available as a quarter-scene.

Landsat data are available in two formats: digital data on computer-compatible tapes (CCT) and computer-generated composite photographs. The composite photographs are suitable for conventional photo-interpretation applications. The digital data can be analyzed and manipulated on a computer, often adding greatly to the utility of the data. Recent developments in image processing software and computer technology have made computer data analysis much more affordable. Image processing systems are now available for microcomputers such as the IBM-PC/AT.

The Landsat system was sold to the Earth Observation Satellite Company (EOSAT), a private concern, in 1985. EOSAT expects to improve customer service and decrease the lag times in processing orders as experienced by many Landsat data users.

SPOT System.[2] The Systeme Probatoire d'Observation de la Terre (SPOT) program was initiated in 1978 by the French government, and was later joined by Sweden and Belgium and finally, the European Space Agency. The world's first commercial remote sensing satellite, SPOT I, was launched in February 1986. Ground control and commercial marketing is handled by SPOT Image Corporation, headquartered in Toulouse, France.

The SPOT satellite is in orbit at an altitude of 832 km. The orbit is sun-synchronous with the descending node at 10:30 a.m., and a 26-day cycle.

The imaging system consists of two high resolution visible (HRV) imaging instruments that can operate in a three-band, color, multispectral mode or a single band, panchromatic mode. The spectral characteristics of SPOT are shown in Table 1.

SPOT uses a pushbroom scanner that has arrays of 3000 detectors for panchromatic scanning and 6000 detectors for multispectral scanning. The array scanner, as opposed to the mechanical scanner on Landsats, has the advantages of no moving parts, higher geometric fidelity, and longer life expectancy. The disadvantages include the need to calibrate each detector and a wavelength maximum of 1.05 micrometers.

There are two important features of the SPOT system not found with the Landsat system: greater ground resolution and off-nadir viewing. The ground resolution of SPOT I is 10 m x 10 m in panchromatic mode and 20 m x 20 m in multispectral mode. The imaging system has a ± 27 degree, off-nadir viewing capability that permits the sensors to be aimed and also allows the production of stereo images. The ground swath ranges from 60 km at nadir to a maximum of 80 km off-nadir. With the off-nadir viewing capability, the sensors can observe any location within a swath of 950 km with each pass. This allows the acquisition of oblique, successive imagery for a specific location on earth at an average interval of 2-1/2 days.

SPOT I contains two recorders, each capable of storing approximately 300 scenes. Direct readout stations are located in France, Sweden, Canada, and Bangladesh. Stations are under development in India, China, and Saudi Arabia. Additional stations are planned in Australia, Brazil, Iraq, Japan, Pakistan, and the Canary Islands.

4. Availability of Satellite Data for Sri Lanka

Current imagery from both SPOT and Landsat satellites can be acquired for Sri Lanka. The SPOT satellite became operational in 1986, and Landsat MSS data has been available since the early 1970s. The recorders on SPOT 1 enable the acquisition and temporary storage of data over Sri Lanka, before transmitting to a ground receiving station. SPOT data can be purchased from SPOT Image Corporation in Toulouse, France or in Reston, Virginia.

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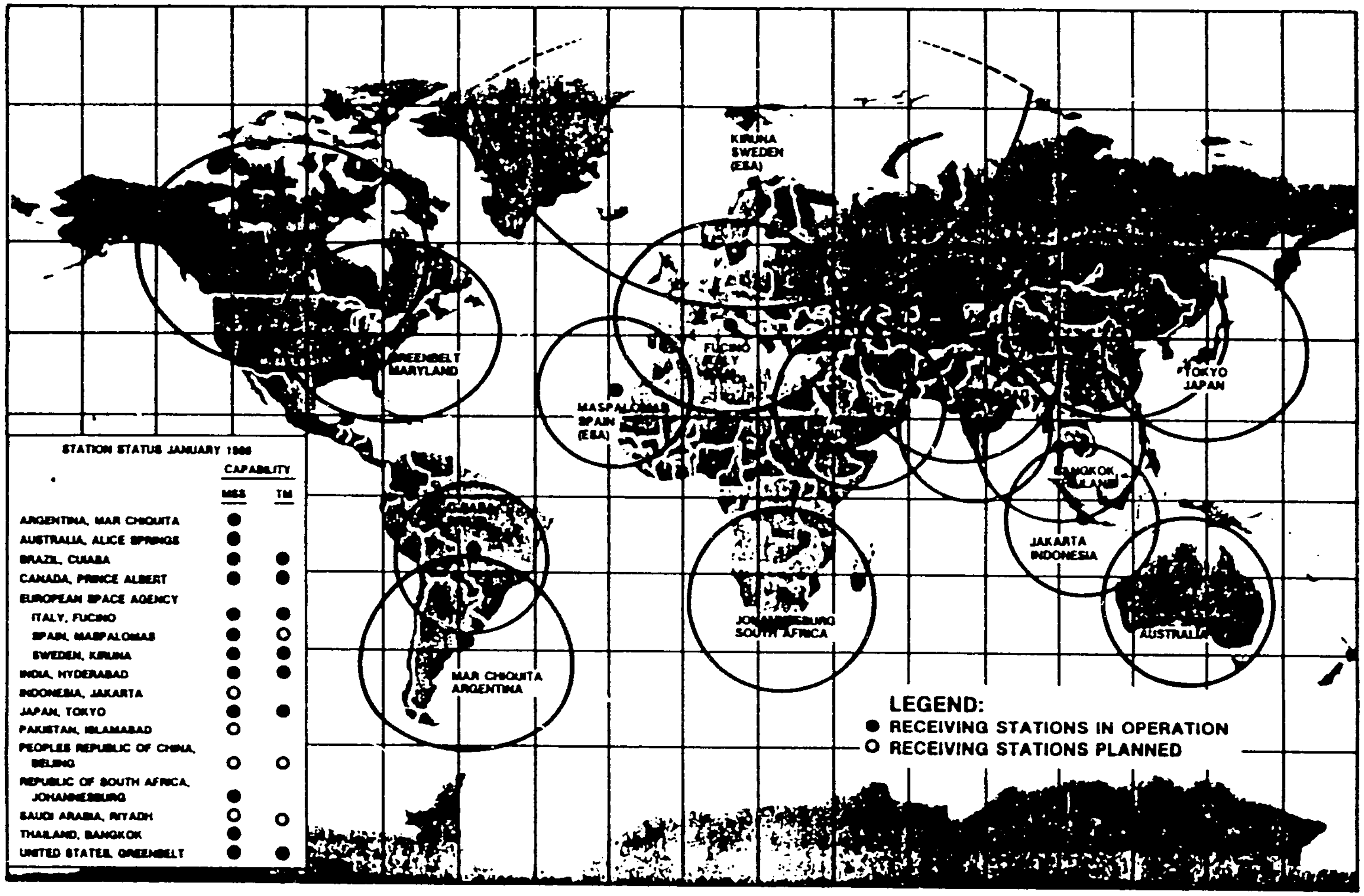
[2] From Courtois and Weill (1985) and SPOT Simulation Handbook (1985).

Landsat MSS data was historically received in the U.S. and archived at EROS Data Center in Sioux Falls, South Dakota. Numerous historical MSS scenes from Sri Lanka are available, but most are prior to 1982. Current images for Sri Lanka are available by special acquisition only.

Sri Lanka is within range of two operating ground receiving stations, located in Thailand and India (Figure 6). The Thailand ground station is currently receiving and archiving Landsat MSS data for South Asia. This station can generate both computer-compatible tapes (CCTs) and photographic products. Data for Sri Lanka is being received and stored on a routine basis, and product quality is good. The ground station in Hyderabad, India also has the capability for receiving and processing Landsat MSS data.

Landsat TM digital data is not currently available for Sri Lanka. The Thailand ground receiving station does not have the necessary equipment for handling TM data. The India station has the capability for processing TM data, but at this writing does not routinely generate CCTs from TM data.

Communication satellites are linked with Landsats 4 and 5, enabling TM data to be relayed directly to a receiving station in the U.S. The communications are through tracking data and relay satellites (TDRSs) in geosynchronous orbits. The TDRSs allow direct transmission of Landsat data to a ground receiving station near White Sands, New Mexico. At present, not all TDRSs are in orbit, and there are certain areas of the world that data relay is not technically feasible. Sri Lanka lies within one such excluded area and, therefore, TM data for Sri Lanka cannot be acquired through the TDRS system until another relay satellite is in place.



EARTH OBSERVATION SATELLITE COMPANY

Figure 6. Map showing the location and approximate range of Landsat Ground Receiving Stations.

III. MATERIALS AND METHODS

Two major activities were undertaken for this study. The first activity included developing and analyzing detailed maps of the irrigation systems from interpretation of large-scale aerial photographs and extensive ground verification. The second activity required computer-based image processing and analyses of two Landsat MSS images. The detailed maps and extensive ground information developed in the first activity were used as ancillary data for the interpretation of Landsat classification and for assessing the accuracy of digital classification methods.

A. IRRIGATED SUBCOMMAND AREAS AND DISTRIBUTION SYSTEM MAPPING

Portions of two yala seasons (1985 and 1986) were required to compile and develop sufficient on-site information to complete mapping of the irrigation distribution systems, irrigated land use, and subcommand area boundaries. Field investigations for Parakrama Samudra, Giritale, and Galamuna (an extension of the Minneriya Scheme) schemes were completed during 1985 yala. The Minneriya and Kaudulla (Stage I) schemes were studied during 1986 yala. Investigations included a search for and assessment of existing maps and agricultural statistics, field investigations and transfer of information to aerial photographs, stereoscopic photo-interpretation and field verification, and interviews with GSL officials. Maps were compiled in the U.S. using the information developed in the field.

1. Assessment of Existing Data

Considerable map and statistics data relevant to this activity were available within various departments of the Government of Sri Lanka. Several sources were assessed which served as valuable references for map compilation. These included various types of maps, blocking out plans, aerial photographs, and statistical data.

Topographic Maps. These Survey Department maps (scale 1:63,360) were revised in 1972 (Survey Department, 1972). Map projection was done using transverse mercator, as well as a metric, local planar coordinate system. General land use classes were depicted on these maps along with major canals of the irrigation distribution systems. These maps were purchased prior to the 1986 suspension of map sales. (Maps could not be obtained without special ministerial approval beginning in 1986.)

Land Use Maps. These maps were produced by the Sri Lanka/Swiss Remote Sensing Project at a scale of 1:100,000 (Survey Department, 1980). Land use included paddy for maha season and acreage figures according to boundaries determined by the assistant government agent.

Blocking Out Plans (BOP). These maps were the original, or copies of original, irrigation systems and resettlement design plans. The BOP maps were produced prior to construction during the 1930s through 1976. Some of these maps were located at the office of the Deputy Director of Irrigation in Polonnaruwa and others were at the irrigation engineers' offices. The BOP maps were compiled at a variety of scales, most commonly 4 chains to the inch (1:3,168). Some plans were complete and in good condition, while other plans were incomplete and/or in poor condition.

Irrigation Scheme Maps. These 1:63,360 scale maps were prepared by the office of the Deputy Director of Irrigation. Major canals and stages of development as defined by the blocking out plans were depicted. Other Irrigation Department documents included water issue schematics for the four distribution systems.

Aerial Photography. The most recent, complete aerial photo coverage of the study area was flown during November 1979 by Hunting Surveys. The aerial photos were 9 in x 9 in, black and white, stereo coverage at a scale of about 1:20,000. These aerial photos were purchased prior to the 1986 suspension of map sales. They are currently not available without special ministerial approval.

Statistical Data. Information for irrigation and agriculture in the Polonnaruwa District was compiled by a variety of government agencies including the Department of Irrigation, Department of Agriculture, Agrarian Services and Statistics, and by the Land Commissioner. These data were not consistent among the various sources, primarily due to lack of proper records and unreliable data collection procedures (Elkaduwa, 1984).

To estimate irrigated acreage under field channels, the Irrigation Department relied mainly on previous estimates and on farmer interviews. These methods were not entirely reliable since farmer estimates were uncertain and because farmers illegally irrigated and were not inclined to report that acreage. Also, there were farmers irrigating entirely outside the specified irrigation scheme boundaries. Without records of these irrigators, the Irrigation Department may not have included that acreage in their estimates (Karunaratne, 1986; Senaratna, 1986).

The additional government agent, Polonnaruwa District, collected irrigated acreage figures from all sources and compiled the data as his best estimate. These data, which were considered approximations only, are presented in Table 2.

2. Site Investigations

The 1:20,000 scale aerial photographs served as the primary base for collecting map data. Considerable information was extracted directly from the aerial photographs, and auxiliary information was compiled and transferred to the photos. Irrigation canals and distributary channels were identified on the BOP maps, then delineated on the aerial photographs with identifying symbols. Specified irrigation system boundaries for each canal and major distributary canal were also transferred from BOP maps to aerial photographs. These boundaries often followed natural watercourses and, in most cases, were accurately identified without extensive field investigation.

Table 2. Estimates of irrigated land use by the Government of Sri Lanka (acres). (Source: Elkaduwa, 1984)

Irrigation System	Designed Acreage[1]	Encroachments: Reser-vations[2]	Conver-sions[3]	Adjoining[4]	Other[5]	Total
Parakrama Samudra	19,600	1,960	360	2,922		24,842
Giritale	6,200	620		788		7,608
Minneriya	13,450	1,345	270	2,874		17,939
Galamuma	3,300				793	4,093
Kaudulla	10,400				1,592	11,992
Total	52,950	3,925	630	6,584	2,385	66,474

[1]Source: Irrigation Department.
[2]Reservations within the specified area.
[3]Conversions of highland to paddy.
[4]Encroachments adjoining the scheme using drainage water.
[5]Encroachments not specified.

Preliminary delineation of irrigated acreage was performed by stereoscopic photo-interpretation. Initially, this task required considerable field verification, but was performed with more precision and confidence as experience was incorporated into the interpretation. Since the aerial photography mission was flown during maha, rainfed rice paddy appeared on the photographs in areas not serviced by the distribution system during yala. Segregation of these areas required field verification during yala, but were pre-classified based upon position on the landscape, proximity to irrigation channels, and distinguishing phototone.

Extensive field verification was required for accurate irrigation distribution system mapping and classification of land use. For the distribution system, there were a number of discrepancies between the BOP design, Irrigation Department water issue schematics, and interpretations on the aerial photos: many distribution channels were not aligned as specified, some new channels had been constructed, and some designed channels were actually not constructed.

Field verification was also required for land use mapping. Irrigated land use varies among years and interpretation of the 1979 aerial photographs was not considered entirely reliable. Although encroachment appeared to have stabilized within the older irrigation schemes, minor variation in irrigated acreage occurs from year to year. It appeared that there were more substantial variation and encroachment in the more recently restored irrigation schemes (Kaudulla and recent extensions of Minneriya). Also, encroachment by farmers using drainage water along the exterior boundaries on all the schemes is dynamic and varies between cropping seasons. Apparently, this variability depends on the availability of excess water.

Field verification was performed throughout the Parakrama Samudra, Giritale and Minneriya irrigation command areas. However, mapping of Stage II of the Kaudulla Scheme was not completed because the aerial photography needed for Stage II was not acquired prior to the 1986 suspension of aerial photo sales. Other areas not adequately covered were areas within the irrigation systems' watersheds, but exterior to the specified irrigation system boundaries (along the Periya Aru). These areas had poor roads and incomplete aerial photo coverage. These areas lie outside the recognized irrigation system's boundary and generally were not considered in this analysis.

Field investigations were concentrated on the fringe areas between paddy cultivation and highlands. These areas had been subjected to the most change since the 1979 aerial photographs were collected, and were the most difficult to confidently classify without visual inspection. Areas at the tails of irrigation systems were also examined in greater detail, because of active change and assumed increased encroachment of irrigation.

Transport throughout the irrigation systems was by jeep and by foot. Aerial photo-interpretation was verified and updated, and farmers were questioned as necessary and where possible. Also, interviews were held with numerous Irrigation Department and other government officials to assess the reliability of the various maps and other data sources and to determine the location of recognized irrigation system boundaries.

3. Map Compilation

Field mapping of irrigated land use, irrigation distribution systems, and system boundaries was performed on unrectified aerial photographs of approximate scale 1:20,000. A high level of cartographic accuracy was not required for the final maps, but a reasonable level of accuracy was desirable for analysis of the irrigation systems and for area calculation.

A cost-efficient method of producing final maps with acceptable cartographic accuracy required several steps. To maintain ground control, 1:50,000 topographic maps (Survey Department, 1972) were photographically enlarged and reproduced on mylar at the same scale as the aerial photographs, 1:20,000. The enlarged topographic maps contained major infrastructure features such as roads, main canals and natural drainages. These features were sufficient as ground control for transfer of delineations and symbols from the aerial photographs. From these annotated mylars, final maps were drafted and photographically reduced to two scales, 1:24,000 and 1:40,000.

4. Map Digitizing

Final maps of the irrigated land use and irrigation distribution systems for the PSS were converted to digital data using a tablet digitizer. The digital files were converted to raster-based, geographic information system (GIS) files. The GIS files were rectified using ground control points and a planar transformation matrix. The rectification process was the same as described for geometric preprocessing of Landsat imagery (Preclassification Processing, below). These rectified digital maps were used for a number of operations: computer-based sample extraction and accuracy assessment of classified Landsat images, stratification of the accuracy assessment by areas influenced and not influenced by cloud cover, and rectified area calculation for irrigated land use. The methods used for these operations are described later in this report.

B. DIGITAL ANALYSIS OF LANDSAT DATA FOR MAPPING IRRIGATION COMMAND AREAS

The process of mapping irrigation command areas with satellite imagery required several steps, from acquiring images to digital processing to assessing the accuracy of each digital classification. Major steps in the digital analysis process, presented as a schematic in Figure 7, are discussed below.

1. Acquisition of Satellite Data

The Polonnaruwa District of Sri Lanka is covered by two Landsat scenes: Path 141, Row 54 and Path 141, Row 55. The study area was located along the boundary of the two scenes and, depending on the position of the satellite at the time of data acquisition, it appeared that the entire area could be covered by the northern scene -- Path 141, Row 54. Inquiries regarding scene availability, quality, and percent cloud cover were submitted to the National Research Council of Thailand, Remote Sensing Division. With this information, "quick look" prints - 9 in x 9 in, single band, blank and white prints - were obtained for the scene and date of interest.

The study area was identified and assessed for completeness of coverage and quality of data. The time period of primary interest was for late July and early August, 1985. This period corresponded with fieldwork for ground and aerial photo mapping. Also, these dates were observed to be the period of maximum vegetative growth of rice for the <u>yala</u> season, and were speculated to correspond with maximum spectral reflectance of the rice paddy.

It appeared from the quick look prints that imagery from July 16, 1985, was acceptable. Consideration was given to a multitemporal analysis of Landsat data, and for this purpose another date of imagery was selected. The date selected for the second set of imagery, August 4, 1983, was for the same period of the growing season. Images for <u>yala</u> 1984 were not acceptable due to image quality and percent cloud cover. Orders for Landsat CCTs were placed with the Thailand Remote Sensing Division. Processing and delivery required about six weeks.

2. Preclassification Processing

<u>Selection and Extraction of the Study Area</u>. Entire Landsat scenes represent a ground area of about 185 km x 170 km. The study area, about 40 km x 25 km, was located near the boundary of two Landsat scenes.

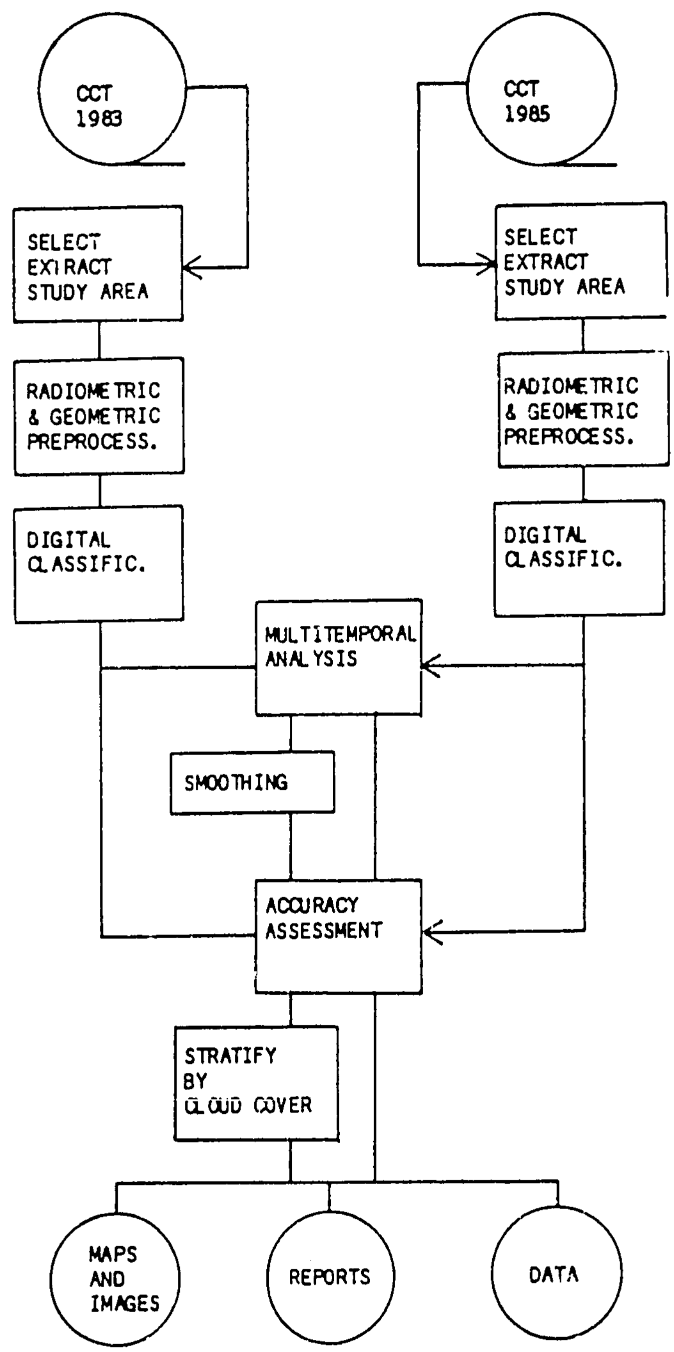


Figure 7. Process used in mapping irrigated command areas with digital Landsat images.

The raw Landsat data, in the band interleaved by line (BIL) format, was displayed by computer onto the color monitor, and pixel coordinates of the approximate study area boundary were determined. Close examination revealed the influence of significant cloud cover for portions of the study area for both dates of imagery. The Parakrama Samudra Scheme (PSS) appeared least influenced by cloud cover and, therefore, classification and analysis of the Landsat images was confined to this area.

The area of both Landsat images corresponding to PSS was extracted and stored as separate digital files. Band 1 was offset 178 pixels relative to the other three bands; this was corrected as the data was loaded from CCT to the computer hard disk. The 1985 imagery required two Landsat scenes for complete coverage of the study area. To ensure radiometric continuity between the two scenes, four single band histograms from both scenes were generated by computer for an overlapping area along the boundary. Since the histograms were exact duplicates, subsets for the two scenes were joined in a mosaic and subsequently handled as a single image file.

Radiometric and Geometric Preprocessing. Prior to classification and analysis, radiometric and geometric preprocessing was performed to improve the Landsat image quality and to bring the images for the two dates into registration with one another and with topographic maps of the area. Radiometric preprocessing was limited to a search for "sixth-line striping," caused by sensitivity differences in the satellite detectors and random line brightness inconsistencies caused by data transmission or processing error. No striping was present, but two lines in the 1983 scene were found in error in a single band. Data values for these lines were corrected by a computer algorithm which recomputes each pixel value by averaging data for the line immediately above and below the faulty line.

Geometric correction was performed by rectifying the 1985 image through a planar transformation and fitting pixel coordinates to a set of map coordinates. The 1983 image was then registered to the 1985 image by the same process, using map coordinates assigned to the 1985 data by image transformation.

The first step in image rectification involved the location of ground control points (GCPs) throughout the scene. Image coordinates were taken from recognizable features on the 1985 Landsat data. Corresponding map coordinates were computed from the 1:50,000 scale topographic maps (Survey Department, 1972) using a digitizing table.

Next, a transformation matrix was computed, using the ERDAS program COORD2, for conversion of the image x,y coordinates to reference (map) x,y coordinates. The coefficients were computed from the GCPs using a least squares regression. The COORD2 program then computed the RMS (root mean square) error for each GCP and compared the sum of RMS errors to the user-defined tolerance value of 1.000 (accurate to within 1 pixel). The sum RMS error for the selected GCP's was 0.941. This value was within the tolerance limit and therefore the transformation matrix was accepted using all GCPs.

The final step involved resampling and coordinate transformation through the ERDAS program, RECTIFY. Image pixels were resampled to a 50 m x 50 m grid cell and transformed by a nearest neighbor algorithm. This method assigned to each output pixel the intensity values, in each of the 4 bands, of the nearest input pixel.

Following image rectification and registration, pixels within the precise boundaries of PSS were extracted and written to a separate file for classification and analysis. This was accomplished by digitizing the system boundaries from the topographic maps and performing a computer overlay of this digital file with the rectified Landsat data. Only Landsat pixels within the system boundaries were retained on the new digital file.

3. Digital Classification

Selection of Classification Method. Digital classification of Landsat imagery is the process of assigning pixels to classes. There are two basic types of classifier methods, the supervised and unsupervised classification. Supervised classification requires the use of sample pixels of known categories to classify pixels of unknown categories. The sample pixels are located as training areas on the Landsat image. Spectral signatures (the brightness values in each band for each pixel in the training area) are extracted and calculations are performed to determine the mean vector and covariance matrix of each signature. In this manner, spectral properties for each informational class of interest are represented. The Landsat image for the entire area of interest is then subjected to a computer classification algorithm, which assigns all pixels to one of the informational classes represented by the spectral signature statistics.

Unsupervised classification involves grouping, or clustering, multispectral data into similar spectral categories. In contrast to supervised classification, unsupervised classification requires minimum initial input from the user. Parameters are typically specified as to the number and size of clusters, and distance between clusters, and the computer calculates the mean vector for each cluster. The cluster data are then considered by a classification algorithm which assigns each pixel to a class represented by one of the clusters. The user is required to interpret the classes established by the unsupervised algorithm.

The unsupervised classification was chosen as the basic classifier for this study for several reasons. First, the class of primary interest, rice paddy, displayed highly diverse spectral characteristics, as supported by field data, field observations, and interpretation of remotely sensed images. Factors considered to contribute most to the spectral properties of rice paddy included plant population, stage of growth, plant vigor, and the presence of ponded water or soil moisture conditions. As reported from research in the study area, paddy farmers conformed to different crop calendars and practiced diverse agronomic practices (Fowler and Kilkelly, 1987). With an average acreage per individual cultivator of less than 3 ac, these factors varied considerably within a few tens of meters.

Second, it appeared from a visual inspection of the Landsat images that some of the rice paddy was quite similar, spectrally, to other classes of land cover. To differentiate these spectrally similar classes with a supervised classification, representative training areas would be required for the variety of land cover conditions. This would have required a field effort that was not possible for this activity.

With an unsupervised classification, such diverse spectral properties of the study area would be recognized by the clustering algorithm. It was speculated that with a general knowledge of the area, the unsupervised classes could be adequately interpreted and identified. Finally, and perhaps of more importance, the main purpose of using a digital classification of Landsat imagery was to test the methodology for rapid and cost-efficient assessments. Since considerably less intensive field efforts are required, the unsupervised method better met this objective.

Unsupervised Classification Procedure. The classification process used an unsupervised classifier as the basic method. A modification of the standard process was used for both the 1983 and 1985 dates of imagery, as illustrated by the schematic diagram in Figure 8. The procedure included an unsupervised classification of the entire image, analysis and interpretation of the classified image, extraction of the image pixels corresponding with unsatisfactory classes, reclassification of unsatisfactory classes, and mosaicing of classes from both classifications.

This process was employed to maximize the efficiency of interpreting the unsupervised clusters and of matching informational classes to spectral clusters. That is, most clusters could be confidently matched with informational classes after the first classification, but some spectrally similar classes could be better separated with a second classification.

Clustering Algorithm

Unsupervised classification utilized an ERDAS clustering algorithm, CLUSTR. This program was derived from software developed by the National Aeronautics and Space Administration (ERDAS, 1987). The CLUSTR program operates by passing twice through the image data; clusters accumulated in the first pass are used in the second pass, a minimum distance classifier. Five parameters control cluster accumulation:

* the maximum number of clusters (NMAX).
* the minimum distance between clusters (C).
* the maximum allowable cluster radius (R1).
* the number of points until cluster merger (M).
* the cluster elimination threshold percentage (P).

Clusters are accumulated by a migrating means algorithm. Each cluster is represented by its centroid (its multispectral mean value), which is used for the minimum distance classifier of the entire image. For each pixel of the image, the minimum distance classifier calculates the multidimensional distance between the pixel and each cluster centroid.

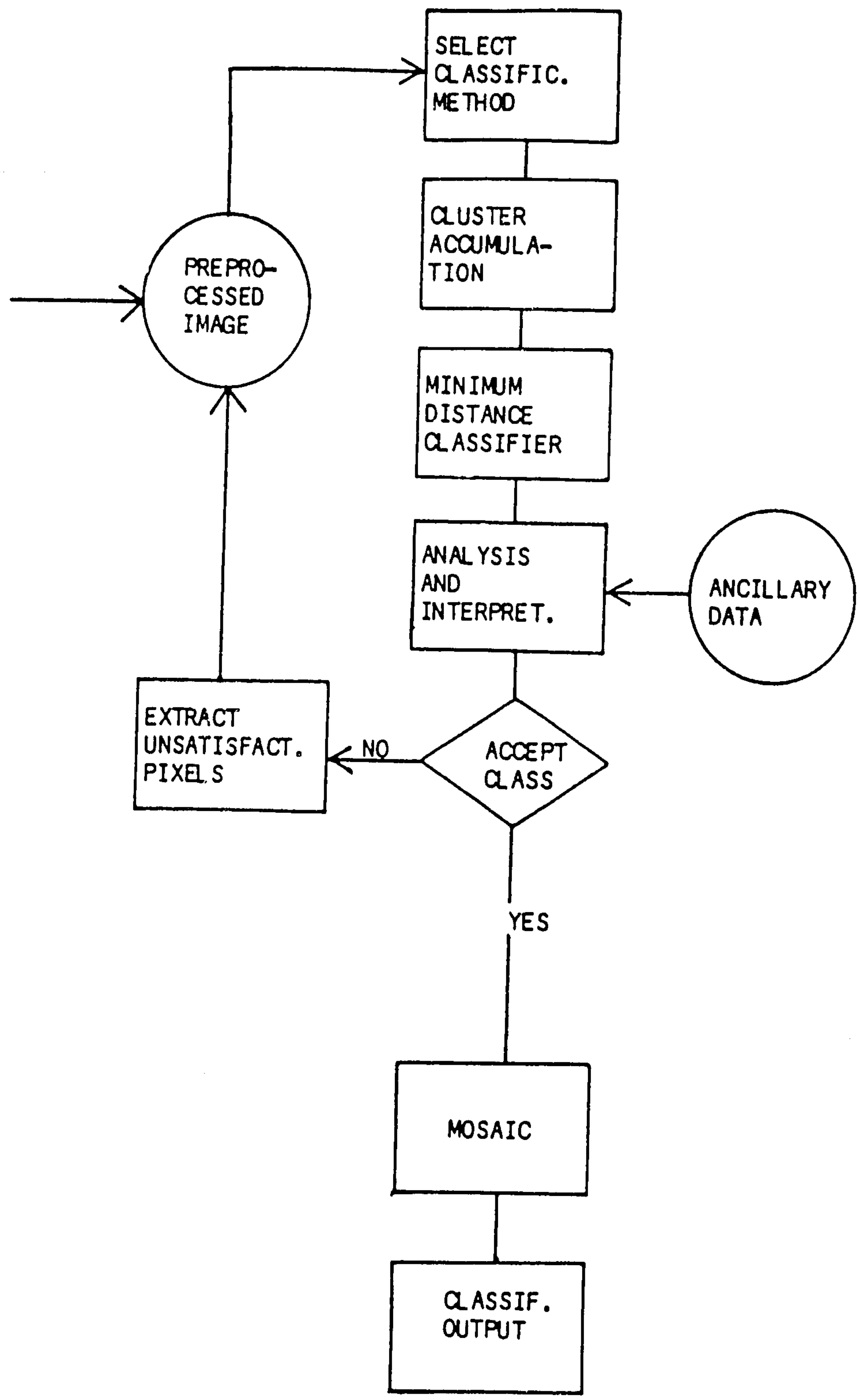


Figure 8. Unsupervised classification procedure.

The pixel is then assigned to the cluster for which the spectral distance is minimized.

Analysis and Interpretation

As shown in Table 3, the number of classes (NMAX) for the initial unsupervised classification of 1983 and 1985 images was 36 and 40, respectively. Interpretation and assessment was performed by visual analysis of a computer display with overlays of each class on the Landsat image. Informational classes were associated with the spectral classes by considering mean values of clusters in each of the four bands, and by ancillary information. Ancillary sources included topographic maps, general irrigation systems maps, field notes, and aerial photographs for specific areas. Informational classes included the following: water, rice paddy, riparian vegetation, forest, highland, and urban.

Table 3. Total number of classes, number of unsatisfactory classes, and associated area for 1983 and 1985 Landsat images.

	Total No. Classes(NMAX)	No. Unsatisfactory Classes	Percent of Area
All Image			
1983	36	4	11
1985	40	3	13
Subset Image*			
1983	15	0	0
1985	10	0	0

*Includes only pixels corresponding to unsatisfactory classes as determined from classification using the entire image.

A qualitative confidence value, scale 1 to 5, was given to each informational class determination. Levels of 3 or more were considered satisfactory. Satisfactory class determinations included most of the water, urban, and highland subclasses and several subclasses of rice paddy and forest land. Pixels placed in satisfactory classes represented 89 percent and 87 percent of the 1983 and 1985 Landsat images, respectively. The unsatisfactory determinations included the riparian class, which was spectrally similar to subclasses of both rice paddy and forest, and subclasses of forest and rice paddy which were spectrally similar to one another.

Pixel Extraction and Reclassification

Pixels corresponding to unsatisfactory classes were extracted by a computer overlay of the classes with the Landsat image. A reclassification by the unsupervised method was performed on these pixels yielding 15 classes and 10 classes for the 1983 and 1985 images, respectively. Informational classes were associated with the reclassified data as described above. For all spectral classes, the information class determination was considered either satisfactory, or it was determined that further spectral segregation of the class, by reclassification, would not improve the interpretation.

Mosaicing

The final steps in the classification procedure involved mosaicing classes from both unsupervised classifications and combining all classes into four major informational classes. Mosaicing was accomplished by a computer overlay of the classes derived from the two unsupervised classification routines. Satisfactory class designations from the second classification were allowed to overwrite unsatisfactory class determinations from the initial classification.

Mosaics from both 1983 and 1985 Landsat data consisted of 47 classes, all of which were considered spectral subclasses of four major informational classes: water, rice paddy, highland, and forest. Accuracy assessment of all 47 classes was not possible with the ancillary data available, and the four informational classes were sufficient for the purposes of this study. Therefore, the 47 classes were combined into four final classes by a computer recode function.

4. Multitemporal Class Combination and Smoothing

From field observation and discussion, it was determined that only minor changes is irrigated land use had occurred between yala seasons of 1983 and 1985. In an effort to improve classification accuracy, classes from unsupervised classifications of both 1983 and 1985 images were combined. This combination was accomplished by the ERDAS program, MATRIX, which utilized the qualitative confidence levels assigned to classes during the unsupervised classification.

Since the 1983 and 1985 Landsat images were geometrically registered, each classified pixel could be compared to its corresponding classified pixel for the other date of imagery. For each pixel, the MATRIX program considered the class assigned for both 1983 and 1985 images. If the classes were the same for both dates, the program simply retained that class for the pixel. If the class was not in agreement between the two dates, the program assigned the pixel to the class with the higher confidence value. For classes in disagreement but with the same confidence value, ancillary data was reconsidered and class assignment was made by the analyst.

Although the average farm size was less than 3 ac, irrigated rice paddy was observed as typically occurring in larger, contiguous blocks. The unsupervised classification maps contained classes, including rice paddy, occurring as single pixels surrounded by pixels of another class. To remove these scattered pixels, a "smoothing" analysis was performed on the map with combined classes from 1983 and 1985 data. All classes were included in the smoothing procedure. With the ERDAS program, SCAN, each pixel was considered as the center element of the nine pixel block. The program determined the class of each of the surrounding eight pixels and reassigned the center pixel to the most frequently occurring class in the block. The smoothed map was retained as a separate file for accuracy assessment and comparison with other digital maps.

5. Accuracy Assessment of Computer Classification

Sample Design and Selection. A meaningful evaluation of the accuracy of Landsat data classification required a sample selection that provided results applicable to the entire map, as well as to the individual categories. To place confidence limits on the accuracy estimates, sampling procedures had to be unbiased and of sufficient size.

Technique

The stratified systematic unaligned procedure (Berry, 1962) has been recommended to the U.S. Geological Survey to test the accuracy of land-use and land-cover maps (Berry and Baker, 1968, pp. 91-100). This sampling method was also considered the most appropriate for similar studies (Rosenfield et al., 1982; Fitzpatrick-Lins, 1981).

The sampling technique chosen was to select the sample from the entire data set by the stratified, systematic, unaligned method; then further stratify this sample according to cloud-influenced and cloud-free areas.

Sample Size

The Landsat data for both 1983 and 1985 had some light cloud cover -- coincidentally in approximately the same areas. It was desirable to stratify the sample by cloud coverage so that some assessment could be made of the accuracy of classification for both cloud-free and cloud-influenced data, and for the overall classification.

The 1985 field verification of irrigated land use was assumed applicable to both the 1983 and 1985 Landsat classifications. Therefore, a sample selected would be applicable to both dates of imagery and to the two cloud cover strata for each data set. The sampling procedure required the sample to be of sufficient size to assess the accuracy of the classification of the cloud-influenced area, which was the smaller of the two strata (40 percent of the total area).

The equation for the approximate sample size was taken from Snedecor and Cochran (1967):

$$N = Z^2pq/E^2, \quad Z = 2 \qquad (1)$$

For this equation, p is the expected percent accuracy; q = 100-p; and E is the allowable error. The value of Z = 2 is taken as the generalized standard normal deviate of 1.96 for the 95 percent, two-sided, confidence level.

For this study, an expected accuracy of 85 percent was assumed with an allowable error of 5 percent. A narrow allowable error was chosen since questionable sample sites (in Sri Lanka) could not be verified in the field. According to the above equation, the number of sample points necessary for a 95 percent, two-sided, confidence level would be

$$N = \frac{4(85 \times 15)}{5^2} = 204 . \qquad (2)$$

Given that 204 sample points were required to assess accuracy on 40 percent of the study area (the cloud-influenced area), it was calculated that 510 sample points would be required to assess accuracy on the entire study area.

Sample Extraction and Analysis. Since several classified images and subsets of classified images were to be assessed for accuracy, an automated method of sampling and analysis was developed using the GIS system.

The sources for all digitally classified data were the 1983 and 1985 Landsat digital data. These images had been rectified and geometrically registered to the same coordinate system and resampled to a 50 m x 50 m pixel size.

A total of 667 sample points were extracted for the PSS study area. As expected for the sampling procedure used, the number of points per category was proportional to the area of each category on the detailed land use map (Table 4).

Table 4. Percentage sample points and land use area by class.

Class	Number of Sample Points	Percent of Sample Points	Percent of Total Mapped Area
Water	64	11	10
Paddy	309	47	46
Other (forest/scrub/ highlands)	294	43	44

Detailed maps of the irrigation distribution system and irrigated land use had been produced at a 1:24,000 scale. These maps had been digitized into the GIS system with a 25 m x 25 m grid cell size and had been rectified to the local coordinate system. For sample extraction and assessment, the digitized map of the PSS irrigation system was resampled by a nearest neighbor algorithm to obtain a 50 m x 50 m pixel size. Then the digitized map was subset to exactly the same file size and dimensions as the Landsat image of the study area. This resampled and rectified digital map could then be used in the GIS system for sampling and accuracy assessment of any digitally classified maps produced from the Landsat data.

The stratified, systematic, unaligned sampling technique as described by Berry et al. (1968) was used to extract a large, unbiased sample from the digitized map of the PSS irrigation system. The entire

PSS was segregated into grids with dimensions of 15 pixels x 15 pixels. A maximum of two samples per grid were extracted. The first sample was selected using the established sampling procedure; then the X coordinate and Y coordinate of the first sample were assigned as the Y and X coordinate, respectively, of the second sample.

Sample pixels corresponding to verified map boundaries between classes were methodically relocated by one pixel toward the interior of the class considered. The direction of relocation to a non-boundary pixel was by the following established priority: north, east, south, west. If non-boundary pixels could not be selected by a one-pixel move, the sample was excluded.

Classes of questionable sample pixels were verified by checking aerial photographs. Samples selected from the villu (swamp) area could not be verified and these 20 samples were discarded. Verification of this area was not possible since the aerial photographs were taken during the monsoon, maha, when the villu is mostly inundated. The maps and Landsat data were for the dry season, yala, when some of this area was under irrigated rice paddy.

Accuracy analysis. Site-specific accuracy was determined by assessing agreement between the classified Landsat images and the digitized, detailed, 1:24,000 scale maps. The standard form for reporting site-specific error is the classification error matrix (Campbell, 1987). The error matrix consisted of an n by n array with both x and y axes labeled with each of the n major informational classes. Errors of omission and commission, and classification accuracy, were computed for each classification method. Identifying a class as 'Class A' when it is determined by verification as 'not Class A' is called an error of commission. Conversely, identifying a class as 'not Class A' when it is verified as 'Class A' is an error of omission.

Overall classification accuracy for each method was described by computing the overall percentage of correct classifications. This was determined by dividing the number of correctly classified pixels in the sample (the diagonal elements in the matrix) by the total number of pixels in the sample.

A classification error matrix was developed by computer for assessing the accuracy of each classified image. The procedure used an ERDAS GIS program, MATRIX, where the verified sample classes were reported in the rows and the classified digital file was reported in the columns of the matrix. A printed report was generated for each matrix overlay. The resulting matrix was then divided according to samples from areas with light cloud cover and samples from areas without cloud cover for separate analysis. With this overlay procedure, separate classification error matrices were easily constructed according to the influence of cloud cover.

IV. RESULTS AND DISCUSSION

Detailed maps of the irrigation distribution systems and irrigated land use were compiled from aerial photographs, and areas were measured by planimeter. Results and discussion of the findings are presented below. An alternative method using digital classification and analysis of Landsat images for irrigated land use was also investigated. Results of the digital analysis, including a comparison to the detailed maps, are also presented.

A. IRRIGATED SUBCOMMAND AREAS AND DISTRIBUTION SYSTEMS MAPS

Maps of the four irrigation distribution systems were compiled at a scale of 1:24,000. One map included the PSS and Giritale irrigation systems and another map depicted the Minneriya and Kaudulla systems. Copies of these two maps were distributed to USAID and GSL. Reduced copies of the two maps, scale 1:40,000, are enclosed in the attached "envelope" at the back of the report. These maps depict the irrigation distribution systems, including: main canals and distributary canals, irrigated subcommand area boundaries, cultural features, irrigated land use for rice paddy, and major areas of subsidiary crops.

Irrigated land use of each major canal for the four irrigation schemes was measured by planimeter. The acreage was calculated for areas of rice paddy cultivation and larger areas of subsidiary crops, such as found on government farms. Each of the small, shifting, farmer-owned plots of irrigated subsidiary crops occupied an estimated average area of less than 1 ac. Total acreage of these small plots was not determined, and acreage was reported with figures for paddy.

The irrigated land use was reported according to subcommand area boundaries, which were determined from the BOP maps and site investigations. Irrigated acreage was greater than the specified design for each irrigation scheme (Table 5).

The additional irrigated acreage occurred as conversions within the specified design area and as encroachments exterior to the specified area. Conversions included irrigation of areas specified by BOP design as "highlands" and "reservations". Highland areas were designed for uses other than irrigated cropland, such as homesteads, permanent tree crops, garden plots, roads, and community buildings. Reservations included land set aside under the BOP design for village centers, schools, pasture, and forest reserves. Conversions were irrigated by direct diversion from field channels and distributary canals, by farmer-built extensions of watercourses, and by siphon from distributary channels. Encroachments exterior to specified irrigation command areas were mostly irrigated with drainage water from diversions, or <u>anicuts</u>, across natural drainages and were typically farmer-constructed from local materials such as tree branches and mud.

Table 5. Irrigated acreage for major irrigation schemes in the Polonnaruwa District, Sri Lanka, *yala* 1985-1986.

Irrigation Scheme	Measured Irrigated Area (Ac)			Designed Irrigated Area (Ac)[2]	Difference in Measured vs. Design Area (%)
	Paddy	Sc[1]	Total		
Parakrama Samudra	24,218	153	24,371	19,632	+24
Giritale	7,091	14	7,105	6,193	+15
Minneriya					
Main System	16,465	95	16,560	13,434	+23
Galamuna	4,354		4,354	3,305	+32
Kaudulla[3]	—	—	—	—	—
Total	52,128	262	52,390	42,564	+23

[1]Subsidiary crop acreage figures include only large irrigated areas. Small, shifting, farmer-owned plots were included as paddy acreage.
[2]Source: Irrigation Department.
[3]Land use for the Kaudulla Scheme was only partially mapped. Partial acreage not included in these totals.

1. Parakrama Samudra Scheme

Irrigated acreage for PSS as measured during 1985 *yala* is presented in Table 6. Irrigated subcommand areas for the major canals are from 19 to 28 percent more than the acreage specified for irrigation under the blocking out plan design. The inlet channel system, Angamadella Yoda Ela, was irrigated about 8 percent less than the designed 170 ac. Overall, the 1985 measured irrigated acreage for PSS (24,371 ac), is 24 percent above the specified BOP design. Of the total additional acreage, about 83 percent was due to conversions of highland and reservations to rice paddy. The remaining was due to encroachments exterior to the recognized scheme boundary, mostly adjoining and using drainage water from the D1 canal.

Not included in measured acreage for PSS are areas exterior to the Irrigation Department's recognized PSS management area. One such area, near the village of Gallella, is irrigated primarily by drainage water from the D1 and D2 canals. This area measured 445 ac and was not included in the calculated total acreage for PSS.

Table 6. Irrigated acreage for PSS, *yala* 1985.

Subcommand	Measured Irrigated Area (ac) Paddy	Sc[1]	Total	Designed Irrigated Area (Ac)[2]	Difference in Measured vs. Design Area (%)
Angamadella Yoda Ela	157	-	157	170	-8
D1 Canal	18,136	41	18,177		
D1 Canal (adjoining)[3]	1,169	0	1,169		
Subtotal D1	19,305	41	19,346	15,433	+25
D2 Canal	3,590	112	3,702		
D2 Canal (adjoining)[3]	131	-	131		
Subtotal D2	3,721	112	3,833	3,219	+19
D3 Canal	1,035	-	1,035	810	+28
TOTAL PSS	24,218	153	24,371	19,632	+24
Gallela[4]	445	-	445	0	

[1]Subsidiary crop acreage figures include only large irrigated areas. Small, shifting, farmer-owned plots were included as paddy acreage.
[2]Source: Irrigation Department.
[3]Areas adjoining the recognized scheme boundary using tail water from the associated canal.
[4]Gallela area is outside the scheme boundary. Irrigation source is drainage water, much of which is from PSS.

Also not included as measured irrigated acreage were areas adjacent to the Periya Aru (both east and west banks). These areas are not considered part of the managed Parakrama Samudra Scheme. Irrigated acreage varies from year to year, depending on the availability of drainage water (K.W.I. de Silva, personal communication), and since aerial photos were not available for this area, acreage calculations were not reported. Sources of water for the Periya Aru are drainage water from the D1 canal of PSS and the Minneriya Oya and Kahambiliya Oya. These natural watercourses convey drainage water from all four irrigation schemes.

2. Giritale Scheme

Presented in Table 7 is irrigated acreage measured during 1985 *yala* for the Giritale Scheme. Irrigated acreage for this system (7,105 ac) is 15 percent above the specified design. About 13 percent of the irrigated acreage was under the command of the left bank canal, with the remaining acreage under the direct command of the right bank canal or under subcommands of the right bank canal. The measured acreage for the right bank canal included a subsystem, the Divulankadawela system (D6 channel). As separately reported acreage, the Analundewa tank also received water from the Divulankadawela system and some additional water from the Giritale right bank canal. The Kumbukkan Aru system received water from an *anicut* constructed across the Kumbukkan Aru, a natural drainage which conveyed mostly surface drainage water from the right bank command area and from other minor *anicuts*. Most all of the irrigated encrcachment occurred as conversions of highland and reservations to irrigated rice paddy.

Table 7. Irrigated acreage for the Giritale Scheme, *yala* 1985.

Subcommand	Measured Irrigated Area (ac) Paddy	Sc[1]	Total	Designed Irrigated Area (Ac)[2]	Difference in Measured vs. Design Area (%)
Left bank canal	942	7	949	788	+20
Right bank canal	5898	-	5898	5145	+15
Analundewa	135	-	135	130	+ 4
Kumbukkan Aru	116	7	123	130	-5
TOTAL Giritale Scheme	7091	14	7105	6193	+15

[1]Subsidiary crop acreage figures include only large irrigated areas. Small, shifting, farmer-owned plots were included as paddy acreage.
[2]Source: Irrigation Department.

3. Minneriya Scheme

The Minneriya scheme receives irrigation water from the Minneriya Tank and is divided into the main system and the Galamuna system. The Galamuna was constructed as an extension of the Minneriya main system. Spills from the Minneriya Tank are conveyed by the Minneri Oya natural drainage to a major anicut for diversion to and delivery by the Galamuna canal.

Main System. The Minneriya main system was developed in four major stages. Irrigated acreage for each of the four stages, as measured during *yala* 1986, is presented in Table 8. Irrigated acreage for the main system (16,560 ac) is 23 percent above the specified BOP design. Figures for the largest subcommand area, Stage I, indicate an 8 percent decrease in irrigated acreage, while the smaller, adjacent Stage II indicates a 94 percent increase. Stages III and IV show an increase in irrigated acreage of 30 and 54 percent, respectively.

From field observations, an eight percent decrease in irrigated acreage for Stage I is highly suspect, and it is likely that the Irrigation Department design boundaries do not coincide with the subcommand area boundaries determined by this study. Considering Minneriya Stage I and Stage II together, there is a 10 percent increase in measured irrigated acreage over the specified design for the two systems. The same confusion in subcommand may have occurred for Stages III and IV. Most all of the irrigated encroachment for all four stages occurred as conversions of highland and reservations to irrigated rice paddy.

Table 8. Irrigated acreage for the Minneriya Scheme, *yala* 1986.

Subcommand	Measured Irrigated Area (ac) Paddy	Sc[1]	Total	Designed Irrigated (ac[2])	Difference in Measured vs. Design Area (%)
Stage I					
Raja Ela	4678	-	4678		
Stage I, other	1005		1005		
Stage I Subtotal	5683	-	5683	6205	-8[4]
Stage II	2546	95	2641	1358	+94[4]
Stage III	4290	-	4290	3311	+30[4]
Stage IV	3946	-	3946	2560	+54[4]
TOTAL	16465	95	16560	13434	+23
Galamuna	4354	-	4354	3305	+32
TOTAL	20819	95	20914	16739	+25
Area G-1[3]	517	-	517	0	

[1]Subsidiary crop acreage figures include only large irrigated areas. Small, shifting, farmer-owned plots were included as paddy acreage.
[2]Source: Irrigation Department
[3]Area G-1 is exterior to the reorganized Galamuma Scheme boundary. The irrigation source is surface runoff, tail water, and natural drainage water.
[4]The subcommand area boundaries may differ from boundaries used by the Irrigation Department for Stages I through IV. Therefore, measured versus designed area comparisons may not be valid for these Stages.

Galamuna System. Measured irrigated acreage for the Galamuma system as recognized by the Irrigation Department (4,354 ac) was 32 percent above the specified design for irrigated acreage (Table 8). Most all of the irrigation encroachment for the reported acreage for the Galamuna system occurred as conversions of highland and reservation land to irrigated rice paddy.

Exterior to the Galamuna Scheme is a large, irrigated area not actively managed by the Irrigation Department. This area is east of the Galamuna Scheme and is bounded by the Kahambiliya Oya, the Minneri Oya, and Periya Aru. Irrigation water for this area is from diversions of the Minneri Oya and other natural drainages by farmer-constructed anicuts, and from surface drainage water from the Galamuma system. Irrigated area for *yala* 1986 measured 517 ac, but irrigated area varies depending on availability of water. Although this area is not actively managed by the Irrigation Department, some consideration is given to the water supply for the area. At the request of irrigators in the area, if surplus water is available in the Minneriya Tank, extra water is released into the Minneri Oya. The Irrigation Department allows this water to flow through the Galamuna spill, thus increasing the supply in the Minneri Oya for farmer-managed diversions to the water-short areas (S. Senaratna, personal communication).

4. Kaudulla Scheme

Irrigated acreage for the portions of the Kaudulla Scheme, as measured during <u>yala</u> 1986, is presented in Table 9. Acreage irrigated additional to the BOP design included mostly conversions from highland and reservations.

Table 9. Irrigated acreage for the Kaudulla Scheme, <u>yala</u> 1986.

Subcommand	Measured Irrigated Area (ac) Paddy	Sc[1]	Total	Designed Irrigated Area (ac[2])	Difference in Measured vs. Design Area (%)
Stage I	8725	-	8725	4644[3]	
Stage II					
Tract 1	236	-	236	246	-4
Tract 2	622	-	622	490	+27
Tract 3	387	-	387	300	+29

[1]Subsidiary crop acreage figures include only large irrigated areas. Small, shifting, farmer-owned plots were included as paddy acreage.
[2]Source: Irrigation Department.
[3]Acreage figure does not include Tract 1A design. These acres are included in the measured irrigated area for Stage I.

Aerial photographs for most of Stage II of the Kaudulla system were not acquired prior to the suspension of aerial photo sales in 1986. Therefore, the acreage measurements for this irrigation system are not complete.

B. CLASSIFICATION OF LANDSAT IMAGES

1. Digital Images

Computer classification was performed on Landsat images from <u>yala</u> seasons of two years, 1983 and 1985. All classification and assessment of accuracy was performed by computer on digital data, but visual assessment was made for raw images and classified data displayed on the computer monitor. Several of these images were photographed with a 35-mm camera. Displayed as color plates at the end of this chapter are raw Landsat images from both 1983 and 1985 (Plates 1 and 2), combined and smoothed unsupervised classes from both dates of imagery (Plate 4), final land use digital maps (Plates 3, 7 and 8), and subcommand areas (Plate 6).

2. Spectral Characteristics of Final Classes

Due to a software limitation, statistical data for unsupervised spectral clusters consisted only of the mean for each of four image bands. With the CLUSTR program, no other statistics are saved in a signature file. To check the spectral properties of the final four classes, histograms and statistics were generated for the Landsat digital data corresponding to each class. Presented in Table 10 are the spectral characteristics of the 1985 image classification. These data are for the combined, final four classes; each major class is actually a composite of several spectral classes used in the classification and analysis.

Table 10. Spectral characteristics of four major classes from classified Landsat image, Yala 1985.

Class	Band	Min.	Max.	Mean	Std. Dev.	Median	Mode
Water	1	39	72	49.6	5.9	48	49
	2	30	70	41.5	7.3	38	38
	3	26	89	37.2	8.7	35	33
	4	13	84	26.1	8.9	24	23
Paddy	1	41	73	47.8	3.3	48	49
	2	28	77	38.5	4.6	38	38
	3	46	135	92.1	9.4	92	94
	4	39	144	93.2	12.0	94	91
Highland	1	44	95	60.4	5.0	60	58
	2	33	120	65.9	8.6	64	62
	3	34	139	97.3	9.0	98	96
	4	28	128	94.3	10.0	96	97
Forest	1	43	60	53.0	2.9	53	51
	2	33	62	48.5	4.4	48	46
	3	62	115	97.5	6.3	98	99
	4	67	127	98.9	7.0	100	102

A normal distribution for each band indicates spectral continuity for the pixels in the class. Normal distribution for each class is suggested by the similarity of values for mean, median, and mode for each band (Table 10). This was verified by visual observation of histograms.

To better evaluate the spectral separation between classes, a coincident spectral plot was generated (Figure 9) from the data in Table 10. For each of the four bands, this plot illustrates the mean spectral response and the variance of distribution for each of the four classes: water, rice paddy, highland, and forest. The spectral mean of each class is represented by a letter, and the variance (±2 standard deviations) is shown as asterisks. This plot also indicates the spectral overlap between classes and the best bands for discriminating each class.

```
          +--------------+--------------+-------------+--------------+
          I                  **** W ****                             I
Band 1    I                    ** P **                               I
          I                        **** H ****                       I
          I                          ** F **                         I
          +--------------+--------------+-------------+--------------+
          0             30             60            90            120

          +--------------+--------------+-------------+--------------+
          I             ****** W *****                               I
Band 2    I             **** P ****                                  I
          I                       ******* H *******                  I
          I                   ****F****                              I
          +--------------+--------------+-------------+--------------+
          0             30             60            90           -120

          +--------------+--------------+-------------+--------------+
          I        ******** W ********                               I
Band 3    I                                 ******** P *******       I
          I                                    ******* H *******     I
          I                                      ***** F *****       I
          +--------------+--------------+-------------+--------------+
          0             30             60            90            120

          +--------------+--------------+-------------+--------------+
          I   ******** W *******                                     I
Band 4    I                               *********** P ********** I
          I                                 ********* H ********     I
          I                                      ****** F *****      I
          +--------------+--------------+-------------+--------------+
          0             30             60            90            120
```

W=Water   P=Paddy   H=Highland   F=Forest

Figure 9. Coincident spectral plots for 1985 classified Landsat image in four bands.

For example, water is best separated in bands 3 and 4, and paddy is best separated from highland and forest in bands 1 and 2. The spectral means for forest and highland are best separated in band 2, but considering the variance, there is overlap between these two classes in all bands.

Although highland and forest are not spectrally distinct in a single band, the classification algorithm considered spectral values for each of four bands. To illustrate the multivariate spectral distribution of the four classes, two-dimensional ellipse plots were created for each combination of the four bands (Plates 9 and 10). The ellipse plots represent equal probability curves of each class, for each two-band combination, with a standard deviation of 2. In order to create the ellipse plots, about 300 pixels from each class were extracted from the Landsat image by three or more samples, and the ERDAS program, ELLIPSE, generated statistics and a visual display of the plots.

Observations of class samples in two-band combinations support, but may also significantly add to, observations of the single-band spectral plots. These observations can provide the analyst with knowledge of class discrimination and indications of the correlations between bands. For example, as expected from the coincident spectral plots, the ellipse plots show the water class as spectrally separate from all other classes in each two-band combination except for the combination of bands 1 and 2. Also, the rice paddy class shows overlap with forest in all combinations, but is nearly distinct for combinations of bands 2 and 4, and for bands 2 and 3. For the overlapping highland and forest classes, the ellipse plots show best discrimination for combinations of band 2 with any other band. Finally, it can be observed from either plot that bands 3 and 4 are highly correlated for all classes except water, which is distinct for several other band combinations. This suggests that the inclusion of both bands 3 and 4 in digital classification may not be necessary for discriminating these four classes.

3. Classification Results

Digital Processes. Subsets of 1983 and 1985 Landsat MSS images corresponding to the PSS boundaries were classified for land use. For further analysis, the 1983 and 1985 classifications were combined in an effort to improve the classification results. This multitemporal class combination was further processed by digital smoothing. Classification results were reported for each of the four digital operations:

* 1983 Landsat image classification
* 1985 Landsat image classification
* 1983 and 1985 Landsat image classifications, combined
* 1983 and 1985 Landsat image classifications, combined and smoothed.

Both dates of Landsat imagery, 1983 and 1985, had an apparent influence of clouds corresponding to the northern portion of the PSS command area. Because cloud cover directly influences brightness values for each affected pixel, digital classification results for the area influenced by clouds were expected to differ from results for the cloud-free area. For this reason, all classification results were stratified by cloud cover influence and reported for each of three alternatives:

* all of the PSS command area
* areas without significant cloud cover influence
* areas with significant cloud cover

Comparison of Results with Detailed Maps from Ground Classification. Table 11 presents irrigated acreage figures for each of the four digital operations. The acreage figures are compared to results obtained by planimeter of the final maps, which were developed by ground classification using aerial photography and field verification. These results are also stratified according to the influence of cloud cover. However, the degree of cloud influence and its effect on spectral properties of ground cover was not quantified or assessed in this study. This comparison of total acreage is indicative of classification accuracy but it does not constitute an accuracy assessment; site-specific accuracy assessment for each digital classification is presented in the next section of this report.

The digital classification, with total irrigated acreage nearest to ground classification results, is for the 1985 Landsat image of areas without cloud cover. The Landsat classification acreage of 14,659 is very near the ground classification acreage of 14,489, a difference of 1.1 percent. For the same area, the 1983 image classification differs by 11.1 percent.

Irrigated acreage figures for the combined (and combined and smoothed) 1983 and 1985 classes are only slightly nearer to ground classification figures than 1985 classes only. This is likely due to the inaccuracy of the 1983 classification relative to the 1985 classification.

With exception of the 1983 classification, acreage figures for all digital operations are consistently nearer ground classification figures (within a range of 1 to 3 percent of ground figures) for the areas without cloud cover. Acreage for cloud-affected areas differ by about 8 percent.

4. Accuracy Assessment by Method

Classification error matrices present results of the accuracy assessment of sampled points for each Landsat classification (Tables 12 - 15). The sample representing the entire Parakrama Samudra Scheme was stratified into sampled points from cloud-affected areas (about 40% of the total) and sampled points unaffected by cloud cover. Using this stratification, Landsat classification was assessed for accuracy by digital overlay of the sample with the classified images.

All classes developed in the unsupervised classifications were combined into four basic classes: water, rice paddy, highland and forest. During the sample verification process it became apparent that verification of both forest and highland classes was not possible using the ancillary information available. Since the focus of this study was to identify irrigated land, the forest and highland classes were combined to one class, "other", for assessment of accuracy.

Table 11. Comparison of ground classification and classified Landsat data for all of PSS -- areas without cloud cover and areas with cloud cover.

	Irrigated Acres*		Landsat Acreage (Percent of Ground Classified Acreage)
	Ground Classification	Classification of Landsat Data	
PSS -- All			
Ground classification	24,371	-	-
1983 Landsat	-	26,766	109.8
1985 Landsat	-	23,746	97.4
1983 & 1985 Landsat, combined	-	23,922	98.1
1983 & 1985 Landsat, combined & smoothed	-	23,823	97.7
PSS -- Areas Without Cloud Cover			
Ground classification	14,489	-	-
1983 Landsat	-	16,097	111.1
1985 Landsat	-	14,659	101.1
1983 & 1985 Landsat, combined	-	14,844	102.4
1983 & 1985 Landsat, combined & smoothed	-	14,755	101.8
PSS -- Areas with Cloud Cover			
Ground classification	9,882	-	-
1983 Landsat	-	10,669	107.9
1985 Landsat	-	9,087	91.9
1983 & 1985 Landsat, combined	-	9,077	91.9
1983 & 1985 Landsat, combined & smoothed	-	9,069	91.8

*Includes rice paddy and subsidiary crops.

Table 12. Accuracy evaluation for classification of 1983 Landsat data -- all of PSS, areas without cloud cover, and areas with cloud cover.

	MSS Classification Results					
	Water	Rice Paddy	Other*	Total	% Accuracy	% Omission
Verified All of PSS						
Water	51	4	9	64	80	20
Rice paddy	0	234	75	309	76	24
Other	3	112	179	294	61	39
Total	54	350	263	667		
% Commission		6	33	32		
Overall % Correct				69		
Verified Area Without Cloud Cover						
Water	51	4	9	64	80	20
Rice paddy	0	149	29	178	84	16
Other	1	67	98	166	59	41
Total	52	220	136	408		
% Commission	2	32	28			
Overall % Correct				73		
Verified With Cloud Cover						
Water	0	0	0	0	-	
Rice paddy	0	85	46	131	65	35
Other	2	45	81	128	63	37
Total	2	130	127	259		
% Commission	100	35	36			
Overall % Correct				64		

*Highland and forest combined.

Table 13. Accuracy evaluation for classification of 1985 Landsat data -- all of PSS, areas without cloud cover, and areas with cloud cover.

	MSS Classification Results					
	Water	Rice Paddy	Other*	Total	% Accuracy	% Omission
Verified All of PSS						
Water	63	1	0	64	98	2
Rice paddy	2	247	60	309	80	20
Other	2	36	256	294	87	13
Total	67	284	316	667		
% Commission	6	13	19			
Overall % Correct				85		
Verified Area Without Cloud Cover						
Water	63	1	0	64	98	2
Rice paddy	0	154	24	178	87	13
Other	1	29	136	166	82	18
Total	64	184	160	408		
% Commission	2	16	15			
Overall % Correct				87		
Verified With Cloud Cover						
Water	0	0	0	0	-	
Rice paddy	2	93	36	131	80	20
Other	1	7	120	128	93	7
Total	3	100	156	259		
% Commission	100	7	13			
Overall % Correct				82		

*Highland and forest combined.

Table 14. Accuracy evaluation for classification of combined 1983 and 1985 Landsat data -- all of PSS, areas without cloud cover, and areas with cloud cover.

	MSS Classification Results					
	Water	Rice Paddy	Other*	Total	% Accuracy	% Omission
Verified All of PSS						
Water	61	1	2	64	95	5
Rice paddy	1	252	56	309	82	18
Other	3	35	256	294	87	13
Total	65	288	314	667		
% Commission	6	12	18			
Overall % Correct				85		
Verified Area Without Cloud Cover						
Water	61	1	2	64	95	5
Rice paddy	0	158	20	178	89	11
Other	2	28	136	166	82	18
Total	63	187	158	408		
% Commission	3	15	14			
Overall % Correct				87		
Verified With Cloud Cover						
Water	0	0	0	0	-	
Rice paddy	1	94	36	131	72	28
Other	1	7	120	128	93	7
Total	2	101	156	259		
% Commission	100	7	23			
Overall % Correct				83		

*Highland and forest combined.

Table 15. Accuracy evaluation for classification of combined and smoothed 1983 and 1985 Landsat data -- all of PSS, areas without cloud cover, and areas with cloud cover.

	MSS Classification Results					
	Water	Rice Paddy	Other*	Total	% Accuracy	% Omission
Verified All of PSS						
Water	62	0	2	64	97	3
Rice paddy	2	261	46	309	85	15
Other	2	30	262	294	89	11
Total	66	291	310	667		
% Commission	6	9	13			
Overall % Correct				89		
Verified Area Without Cloud Cover						
Water	62	0	2	64	97	3
Rice paddy	1	161	16	178	90	10
Other	2	22	142	166	86	14
Total	65	183	160	408		
% Commission	5	10	11			
Overall % Correct				90		
Verified With Cloud Cover						
Water	0	0	0	0	-	
Rice paddy	1	100	30	131	76	24
Other	0	8	120	128	93	7
Total	1	108	153	259		
% Commission	100	7	20			
Overall % Correct				85		

*Highland and forest combined.

A synopsis of accuracy information from Tables 12 - 15 was tabulated and includes the rice paddy classes and overall classification accuracies (Table 16). The accuracy levels of rice paddy are generally similar to, and display the same trend as, the overall accuracies for each operation. The overall accuracy for each classification or digital operation is consistently improved according to the following order: areas with cloud cover, all areas, areas without cloud cover. The magnitude of overall accuracy improvement for areas without cloud cover relative to areas with cloud cover is 8 percent for 1983 classification and about 5 percent for each of the other methods.

Table 16. Accuracy of classification of Landsat data for rice paddy and overall classification for all of PSS, areas without cloud cover, and areas with cloud cover (synopsis of Tables 12 - 15).

	Rice Paddy			Overall
	% Accuracy	% Omission	% Commission	% Correct
PSS -- All				
1983 Landsat	76	24	33	70
1985 Landsat	80	20	23	85
1983 & 1985 Landsat, combined	82	18	12	85
1983 & 1985 Landsat, combined & smoothed	85	15	9	89
PSS -- Areas Without Cloud Cover				
1983 Landsat	84	16	32	73
1985 Landsat	87	13	16	87
1983 & 1985 Landsat, combined	89	11	15	87
1983 & 1985 Landsat, combined & smoothed	90	10	10	90
PSS -- Areas With Cloud Cover				
1983 Landsat	65	35	35	65
1985 Landsat	80	20	7	82
1983 & 1985 Landsat, combined	72	28	7	83
1983 & 1985 Landsat, combined & smoothed	76	24	7	85

Except for areas with cloud cover, the overall accuracy for all but the 1983 classification is 85 percent or greater. This compares favorably with requirements of Anderson et al. (1976) that satisfactory U.S. Geological Survey land use maps should have an accuracy of at least 85 percent. The highest overall accuracy, 90 percent, is for the smoothed and combined 1983 and 1985 classes for areas without cloud cover.

The accuracy for classes and for overall classification is significantly less for the 1983 classification. The reason is not clear, but it is suspected that the August 4 date of the image may have corresponded with unusual field conditions not observed during the 1985 and 1986 dates of field study. No field observations or quantitative information was obtained for the 1983 yala season, but it was generally known to be a relatively dry and early season (P. Elkaduwa, personal communication). From Table 12, there is a high error of omission for the water class (20 percent) compared to errors of 5 percent or less for the other classifications (Table 13 - Table 15). If irrigation tank water levels were unusually low, certain pixels in the 1983 image may have been correctly placed in a class other than water, such as bare soil or highland. Incorrect interpretation of accuracy for such pixels would result in high errors of omission for the water class.

Errors for the other 1983 image classes may be due to assumptions which would have been incorrect under unusual field conditions. Analysis and interpretation of unsupervised spectral clusters was based on the assumption that rice paddy was at a stage of development corresponding with high infrared reflectance. This assumption would be incorrect if rice paddy had flowered and was in senescence. Under such conditions rice paddy would be more likely to be confused with certain forest and highland classes.

Relative to the 1985 classification, there is a only a slight improvement, or no improvement, in accuracy of both rice paddy class and overall classification for the combined 1983 and 1985 classes (Table 16). Relative to the 1983 classification, the improvement in accuracy of both rice paddy and overall classification is more significant. Rice paddy cultivation is improved by 5 to 7 percent (absolute) and overall accuracy is improved by 14 to 16 percent. This was not unexpected, considering the relative accuracies of the 1983 and 1985 classifications.

Smoothing of the 1983 and 1985 combined classes improved overall accuracies somewhat. The overall accuracy improvement is about 2 percent for areas with cloud cover, 3 percent for areas without cloud cover, and 4 percent for all areas. From interpretation of the individual error matrices, much of the overall accuracy improvement is from reducing errors of commission for the rice paddy and "other" classes. These errors likely corresponded to smoothing of isolated pixels or boundary pixels.

Plate

1 1983 Landsat MSS image for the study area. Image is displayed as false color infrared. The upper portion of the image is influenced by cloud cover.

2 1985 Landsat MSS image for the study area. Image is displayed as false color infrared. The upper portion of the image is influenced by cloud cover.

3 Digitized 1:24,000 scale map of the PSS irrigation distribution system and irrigated land use. The source map was based on interpretation of aerial photographs and extensive ground verification. The color scheme is similar to the classified Landsat image, for visual comparison. Water is displayed in blue, rice paddy is green, subsistence crops are bright yellow and all other land use is displayed in dark yellow.

4 Classified Landsat data of the PSS from 1983 and 1985 classes, combined and smoothed. Water is displayed in blue, rice paddy is green, highland is dark yellow, and forest is displayed in brown.

5 Digitized 1:24,000 scale map was used for sample point and extraction. The location of sample points is displayed with a 15 pixel by 15 pixel grid used in the sampling procedure.

6 Digital map showing subcommand area boundaries of the PSS.

7 Digitized 1:24,000 scale map of the PSS irrigation distribution system and irrigated land use. Grid cell size 25 m x 25 m. Image is displayed as a 2x reduction.

8 Subset of digitized 1:24,000 scale map of the PSS irrigation distribution system and irrigated land use. Grid cell size is 25 m x 25 m. Image is displayed as a 1x magnification.

9 2-Dimensional ellipse plots for signatures of four landcover classes. Bands displayed as x versus y are from lower left, respectively: band 1 versus band 4, band 1 versus band 2, band 1 versus band 3.

10 2-Dimensional ellipse plots for signatures of four landcover classes. Bands displayed as x versus y are from lower left, respectively: band 3 versus band 4, band 1 versus band 3, band 2 versus band 4.

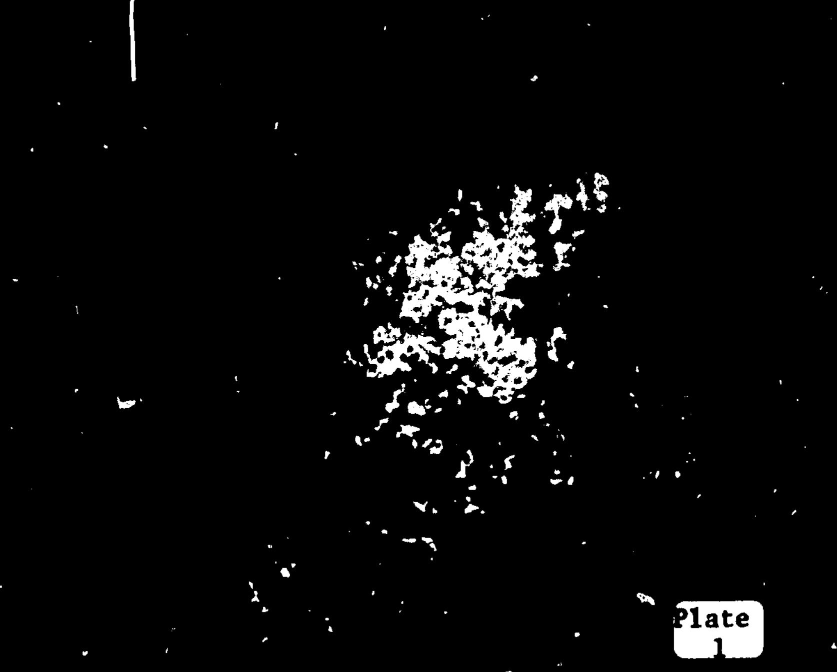


Plate 1

Plate 2

Plate 3

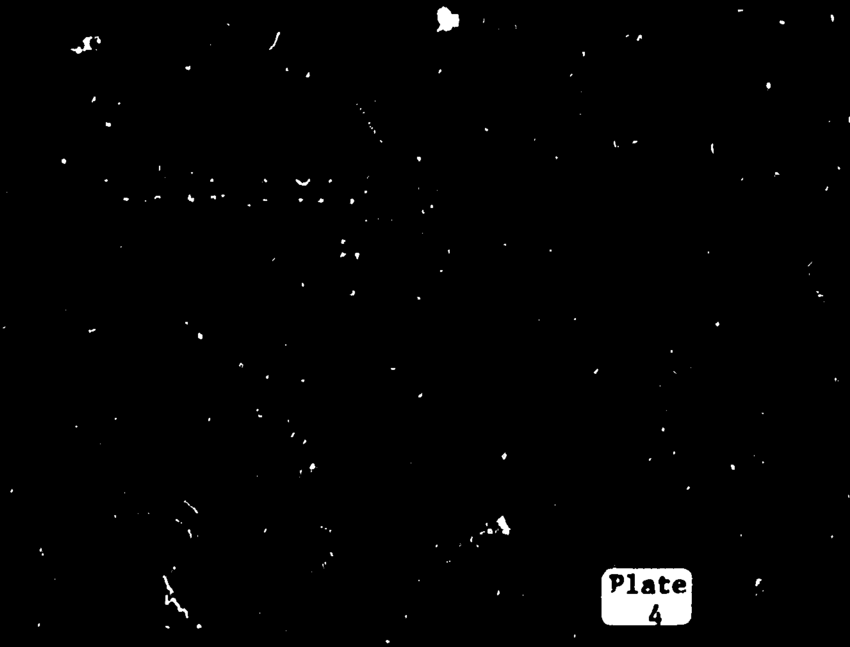


Plate 4

Plate 5

Plate 6

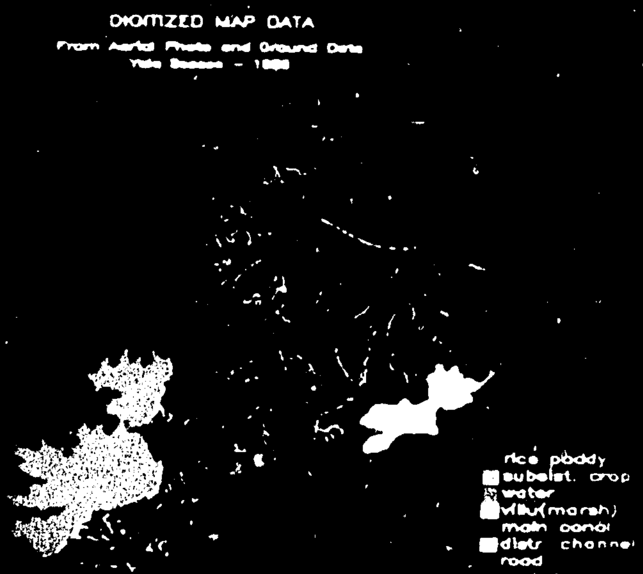


Plate 7

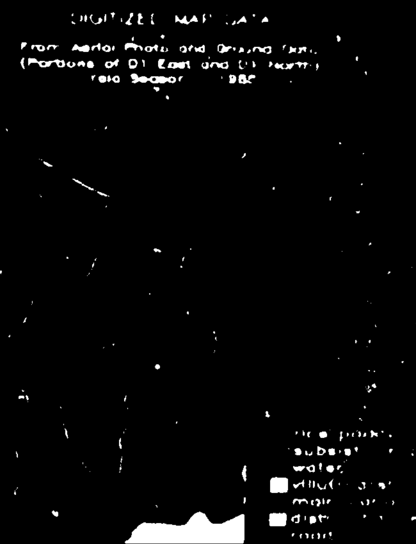


Plate 8

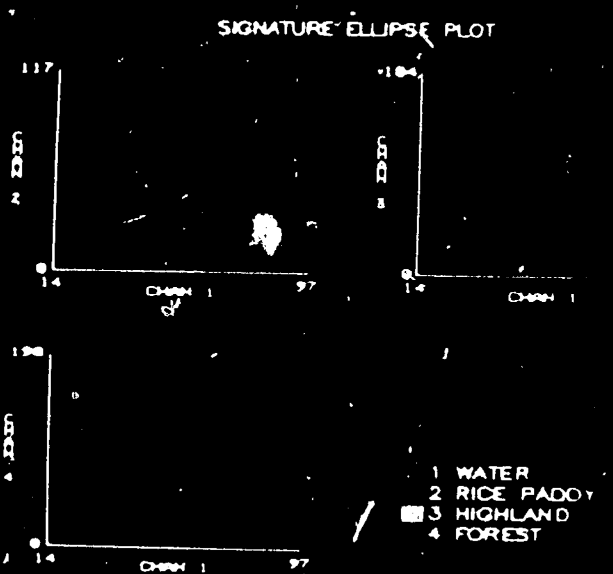


Plate 9

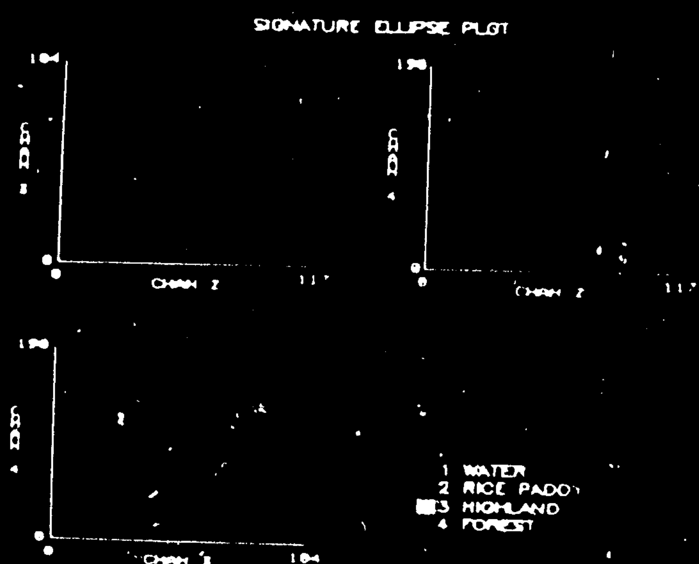


Plate 10

V. SUMMARY

A primary objective of this study was to provide the Government of Sri Lanka, the Diagnostic Analysis Project, and the ISM Project with detailed maps of the four irrigation systems, including irrigated acreage figures, for subcommand areas within the systems. A second objective was to determine the utility of satellite image processing for rapidly assessing the irrigation systems. Because of the effort required for detailed mapping, rapid assessment was limited to mapping irrigated land use.

A. IRRIGATED SUBCOMMAND AREAS AND DISTRIBUTION SYSTEM MAPPING

Preliminary delineation of irrigated acreage was performed by stereoscopic photo interpretation. Initially, this task required considerable field verification, but was performed with more precision and confidence as experience was incorporated into the interpretation. Field verification was required because of changes in land use since the date of the aerial photography. (Aerial photos are currently available for Sri Lanka only with ministerial approval.)

Field verification was required to accurately map the irrigation distribution system. There were a number of discrepancies between the BOP design, Irrigation Department water issue schematics, and interpretations of aerial photos.

Sets of two maps each covering the four irrigation systems were produced at two scales: 1:24,000 and 1:40,000. A cost-efficient, manual method was used to compile final maps with acceptable cartographic accuracy.

Acreage figures were compiled for the irrigated command areas recognized and managed by the Irrigation Department. However, there was extensive irrigated area exterior to these boundaries that depends on tail water and runoff from the four major schemes.

Current irrigated acreage for each of the four irrigation schemes was measured to be greater than the specified design. The additional irrigated acreage occurred in areas specified as highlands or as reservations, and was also due to encroachments exterior to the designed command area. Converted highlands and reservations were irrigated by direct diversion from field channels and distributary canals, by farmer-built extensions of field channels, and by siphon from distributary channels. Encroachments exterior to the specified system were mostly irrigated with drainage water from farmer-built anicuts.

Irrigated acreage was measured for the command area of PSS as recognized by the Irrigation Department. The acreage measured 24,371 ac: 24 percent above the specified BOP design. Most of the additional irrigated acreage was due to conversions of highland and reservations.

Extensive irrigated acreage exterior to PSS was not considered part of the command area. The source of irrigation water for these areas, near Gallella village and along the Periya Aru, is mainly tail water and runoff from the four major irrigation schemes.

The Giritale Scheme's irrigated acreage measured 7,105 ac: 15 percent above the specified design. Most of the additional irrigated area occurred as conversions of highland and reservations.

Irrigated acreage for the Minneriya main system, 16,560 ac, measured 23 percent above the specified BOP design. Most of the additional irrigated area occurred as conversions of highland and reservations to rice paddy.

Measured irrigated acreage for the Minneriya-Galamuma system as recognized by the Irrigation Department, 4,354 ac, was 32 percent above the specified design for irrigated acreage. Most of the addition in the reported acreage occurred as conversions of highland and reservations to irrigated rice paddy.

Exterior to the recognized Galamuna Scheme is a large, irrigated area not actively managed by the Irrigation Department. Irrigation water for this area is from diversions of the Minneri Oya and other natural drainages via farmer-constructed anicuts, and from tail water of the Galamuma system.

Aerial photographs for most of Stage II of the Kaudulla system were not acquired prior to the government suspension of aerial photo sales in 1986. Therefore, the acreage measurements for this irrigation system were not complete.

B. LANDSAT IMAGE CLASSIFICATION

Only Landsat MSS data were available for Sri Lanka when this study was initiated. Data were acquired from the Thailand receiving station. The ground resolution of Landsat MSS is about 79 m x 79 m in four spectral bands. SPOT satellite data is currently available for Sri Lanka. Ground resolution of SPOT images, 0.1 ac (0.04 ha), is 15 times greater than Landsat MSS images.

Landsat TM digital data is not currently available for Sri Lanka. This data will be available from the U.S. when a satellite relay system is operational or when the receiving station in India becomes fully operational. The ground resolution of Landsat TM is about 30 m x 30 m in six spectral bands and 120 m x 120 m in the thermal band.

The unsupervised method was successfully used as the basic classifier for this study. Because of highly variable agronomic practices and small landholdings, rice paddy displayed highly diverse spectral characteristics. The supervised method of obtaining representative training samples from paddy, and from other types of landcover, would have required considerably more extensive field work than could be done. With the unsupervised method, the diverse spectral properties of paddy and similar landcover were generally recognized by the clustering algorithm.

The conversion of irrigated land use and irrigation distribution system maps to digital data was quite useful to the Landsat classification. These digital maps were rectified and used in sample extraction and to assess the accuracy of the classified Landsat images.

The stratified, systematic, unaligned sampling technique was used to extract a large, unbiased sample from the digitized map of PSS. The computer sample extraction method used in this study allowed for rapid sampling and assessment of any geometrically-registered digital file.

Cloud-free images covering all four irrigation schemes could not be found for the desired period during the growing season. Accuracy of image classification was acceptable for cloud-free areas, but not acceptable for areas with cloud cover.

Classification error matrices were used to estimate the agreement between classified Landsat images and digitized maps. The digital sample files were stratified and separately assessed according to the influence of cloud cover in the study area. Overall accuracy for areas without cloud cover was 5 percent to 8 percent better than accuracy for areas with cloud cover.

The highest overall accuracy, 90 percent, was for the smoothed and combined 1983 and 1985 classes for areas without cloud cover. Except for areas with cloud cover, the overall accuracy for all but the 1983 classification was 85 percent or greater.

The gross irrigated acreage for Landsat classification of the cloud-free portion of the 1985 image is 14,659 ac. This figure is very near the ground classification acreage of 14,489, a difference of 1.1 percent. With exception of the 1983 classification, acreage figures for all digital operations were consistently nearer ground classification figures for the areas without cloud cover. For areas without cloud cover, acreage figures were within a range of 1 percent to 3 percent of ground figures, whereas acreage for cloud-affected areas differed by about 8 percent.

Relative to the 1985 classification, combining classifications of 1983 and 1985 resulted in no improvement in classification accuracy. Digital smoothing of classes improved overall accuracies by 2 percent to 4 percent.

The 1983 image classification accuracy is significantly less than the accuracy of the 1985 image classification. Field work was conducted in 1985 and 1986; no field observations or data were collected in 1983. The lower accuracy may be due to incorrect assumptions about 1983 field conditions.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. IRRIGATED SUBCOMMAND AREAS AND DISTRIBUTION SYSTEM MAPPING

Current irrigated acreage was 15 percent to 32 percent greater than the specified design for the four irrigation systems.

The detailed mapping methods were effective for supplying all data needs. Considering the detail level of final irrigation distribution system and land use maps, the methods used were both time and cost efficient.

If accessible, aerial photography is recommended as the primary information source for detailed mapping of irrigation distribution systems. For land use mapping in areas with more than one distinct cropping season, photography should correspond with the season of interest.

Computer-assisted drafting would have added to the efficiency of map compilation and to the quality of the results. This method is recommended for similar mapping projects in the future.

There are irrigated areas exterior to the command area actively managed by the Irrigation Department. Changes affecting water management of the main systems apparently would affect these irrigators. It is recommended that irrigated acreage and irrigation water sources be determined for these areas prior to irrigation system improvement. With this accurate information, management decisions could be made more effectively.

B. LANDSAT IMAGE CLASSIFICATION

Digital classification of cloud-free Landsat images was a successful method for determining irrigated acreage of major subcommands. Overall classification accuracy was 85 percent to 90 percent. Irrigated acreage was determined to within 1 percent to 3 percent of other, ground-intensive methods.

High resolution SPOT satellite data are currently available for Sri Lanka. These data are recommended for use in similar studies where higher resolution is required, such as mapping distribution systems and assessing specific field conditions. For determining gross irrigated acreage, it is uncertain that higher ground resolution would result in area estimates more accurate than obtained with Landsat MSS, but site-specific accuracy may be improved.

Once a digital data base is established within a geographic information system, it can used for further analysis of baseline conditions and for monitoring and evaluating irrigation system improvements. With the database developed in this study, for example, irrigated acreage for individual distributary channels or field channels could be quickly computed by a digital overlay of the service area boundaries. Water requirements could also be determined by another overlay with soils, cropping patterns, and other related spatial data.

A computer-based, automated sampling procedure was used successfully in this study. This method is recommended for similar studies using digital land use classification techniques.

The influence of cloud cover in satellite imagery is an important consideration for Sri Lanka.

For classification of remotely sensed images it is important that the analyst is aware of specific field conditions at the time of image collection. The validity of assumptions about the 1983 field season used in this study are uncertain.

Smoothing is a quick and simple digital operation and resulted in improved accuracy of Landsat classification.

VII. LIST OF REFERENCES

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VIII. APPENDICES

APPENDIX A

GLOSSARY OF ABBREVIATIONS AND TERMS

ac	acre
BIL	band interleaved by line
BOP	blocking out plan
bu	bushel
CCT	computer-compatible tapes
EOSAT	Earth Observation Satellite Company
ERDAS	Earth Resources Data Analysis System
ft	feet
GCP	ground control point
GIS	geographic information system
GSL	Government of Sri Lanka
ISM	Irrigation Systems Management Project (Sri Lanka)
km	kilometer
m	meter
maha	wet season; October to March
MSS	multi-spectral scanner
pixel	picture element
PSS	Parakrama Samudra Scheme
RBV	return-beam vidicon
RMS	root mean square
SPOT	Systeme Probatoire d'Observation de la Terre
TDRS	tracking data and relay satellite
TM	thematic mapper

USAID	United States Agency for International Development
villu	marsh areas
yala	dry season; April to September

APPENDIX B

LIST OF WATER MANAGEMENT SYNTHESIS II PROJECT REPORTS

WMS 1 Irrigation Projects Document Review

Executive Summary
Appendix A: The Indian Subcontinent
Appendix B: East Asia
Appendix C: Near East and Africa
Appendix D: Central and South America

WMS 2 Nepal/USAID: Irrigation Development Options and Investment Strategies for the 1980s

WMS 3 Bangladesh/USAID: Irrigation Development Options and Investment Strategies for the 1980s

WMS 4 Pakistan/USAID: Irrigation Development Options and Investment Strategies for the 1980s

WMS 5 Thailand/USAID: Irrigation Development Options and Investment Strategies for the 1980s

WMS 6 India/USAID: Irrigation Development Options and Investment Strategies for the 1980s

WMS 7 General Asian Overview

WMS 8 Command Area Development Authorities for Improved Water Management

WMS 9 Senegal/USAID: Project Review for Bakel Small Irrigated Perimeters Project No. 685-0208.

WMS 10 Sri Lanka/USAID: Evaluation Review of the Water Management Project No. 383-0057.

WMS 11 Sri Lanka/USAID: Irrigation Development Options and Investment Strategies for the 1980s

WMS 12 Ecuador/USAID: Irrigation Sector Review

WMS 13 Maintenance Plan for the Lam Nam Oon Irrigation System in Northeast Thailand

WMS 14 Peru/USAID: Irrigation Development Options and Investment Strategies for the 1980s

WMS 15 Diagnostic Analysis of Five Deep Tubewell Irrigation Systems in Joydebpur, Bangladesh

WMS 16 System H of the Mahaweli Development Project, Sri Lanka: 1982 Diagnostic Analysis

WMS 17 Diagnostic Analysis of Farm Irrigation Systems on the Gambhiri Irrigation Project, Rajasthan, India: Volumes I-V

WMS 18 Diagnostic Analysis of Farm Irrigation in the Mahi-Kadana Irrigation Project, Gujarat, India

WMS 19 The Rajangana Irrigation Scheme, Sri Lanka: 1982 Diagnostic Analysis

WMS 20 System H of the Mahaweli Development Project, Sri Lanka: 1983 Diagnostic Analysis

WMS 21 Haiti/USAID: Evaluation of the Irrigation Component of the Integrated Agricultural Development Project No. 521-0078.

WMS 22 Synthesis of Lessons Learned for Rapid Appraisal of Irrigation Strategies

WMS 23 Tanzania/USAID: Rapid Mini Appraisal of Irrigation Development Options and Investment Strategies

WMS 24 Tanzania/USAID: Assessment of Rift Valley Pilot Rice Project and Recommendations for Follow-On Activities

WMS 25 Interdisciplinary Diagnostic Analysis of and Workplan for the Dahod Tank Irrigation Project, Madhya Pradesh, India

WMS 26 Prospects for Small-Scale Irrigation Development in the Sahel

WMS 27 Improving Policies and Programs for the Development of Small-Scale Irrigation Systems

WMS 28 Selected Alternatives for Irrigated Agricultural Development in Azua Valley, Dominican Republic

WMS 29 Evaluation of Project No. 519-0184, USAID/El Salvador, Office of Small-Scale Irrigation -- Small Farm Irrigation Systems Project

WMS 30 Review of Irrigation Facilities, Operation and Maintenance for Jordan Valley Authority

WMS 31 Training Consultancy Report: Irrigation Management and Training Program

WMS 32 Small-Scale Development: Indonesia/USAID

WMS 33 Irrigation Systems Management Project Design Report: Sri Lanka

WMS 34 Community Participation and Local Organization for Small-Scale Irrigation

WMS 35 Irrigation Sector Strategy Review: USAID/India; with Appendices, Volumes I and II (3 volumes)

WMS 36 Irrigation Sector Assessment: USAID/Haiti

WMS 37 African Irrigation Overview: Summary; Main Report; An Annotated Bibliography (3 volumes)

WMS 38 Diagnostic Analysis of Sirsia Irrigation System, Nepal

WMS 39 Small-Scale Irrigation: Design Issues and Government-Assisted Systems

WMS 40 Watering the Shamba: Current Public and Private Sector Activities for Small-Scale Irrigation Development

WMS 41 Strategies for Irrigation Development: Chad/USAID

WMS 42 Strategies for Irrigation Development: Egypt/USAID

WMS 43 Rapid Appraisal of Nepal Irrigation Systems

WMS 44 Direction, Inducement, and Schemes: Investment Strategies for Small-Scale Irrigation Systems

WMS 45 Post 1987 Strategy for Irrigation: Pakistan/USAID

WMS 46 Irrigation Rehab: User's Manual

WMS 47 Relay Adapter Card: User's Manual

WMS 48 Small-Scale and Smallholder Irrigation in Zimbabwe: Analysis of Opportunities for Improvement

WMS 49 Design Guidance for Shebelli Water Management Project (USAID Project No. 649-0129) Somalia/USAID

WMS 50 Farmer Irrigation Participation Project in Lam Chamuak, Thailand: Initiation Report

WMS 51 Pre-Feasibility Study of Irrigation Development in Mauritania: Mauritania/USAID

WMS 52 Command Water Management -- Punjab Pre-Rehabilitation Diagnostic Analysis of the Niazbeg Subproject

WMS 53 Pre-Rehabilitation Diagnostic Study of Sehra Irrigation System, Sind, Pakistan

WMS 54 Framework for the Management Plan: Niazbeg Subproject Area

WMS 55 Framework for the Management Plan: Sehra Subproject Area

WMS 56 Review of Jordan Valley Authority Irrigation Facilities

WMS 57 Diagnostic Analysis of Parakrama Samudra Scheme, Sri Lanka: 1985 Yala Discipline Report

WMS 58 Diagnostic Analysis of Giritale Scheme, Sri Lanka: 1985 Yala Discipline Report

WMS 59 Diagnostic Analysis of Minneriya Scheme, Sri Lanka: 1986 Yala Discipline Report

WMS 60 Diagnostic Analysis of Kaudulla Scheme, Sri Lanka: 1986 Yala Discipline Report

WMS 61 Diagnostic Analysis of Four Irrigation Schemes in Polonnaruwa District, Sri Lanka: Interdisciplinary Analysis

WMS 62 Workshops for Developing Policy and Strategy for Nationwide Irrigation and Management Training. USAID/India

WMS 63 Research on Irrigation in Africa

WMS 64 Irrigation Rehab: Africa Version

WMS 65 Revised Management Plan for the Warsak Lift Canal, Command Water Management Project, Northwest Frontier Province, Pakistan

WMS 66 Small-Scale Irrigation -- A Foundation for Rural Growth in Zimbabwe

WMS 67 Variations in Irrigation Management Intensity: Farmer-Managed Hill Irrigation Systems in Nepal

WMS 68 Experience with Small-Scale Sprinkler System Development in Guatemala: An Evaluation of Program Benefits

WMS 69 Linking Main and Farm Irrigation Systems in Order to Control Water

Volume 1: Designing Local Organizations for Reconciling Supply and Demand
Volume 2: A Case Study of the Niazbeg Distributary in Punjab, Pakistan
Volume 3: A Tank System in Madhya Pradesh, India
Volume 4: The Case of Lam Chamuak, Thailand
Volume 5: Two Tank Systems in Polonnaruwa District, Sri Lanka

1 MAP

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2 OF 3

FOR

FIGURE(S):

MINNERIYA AND

KAUDULLA

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FOR

FIGURE(S):

PARAKRAMA SAMUDRA and GIRITALE

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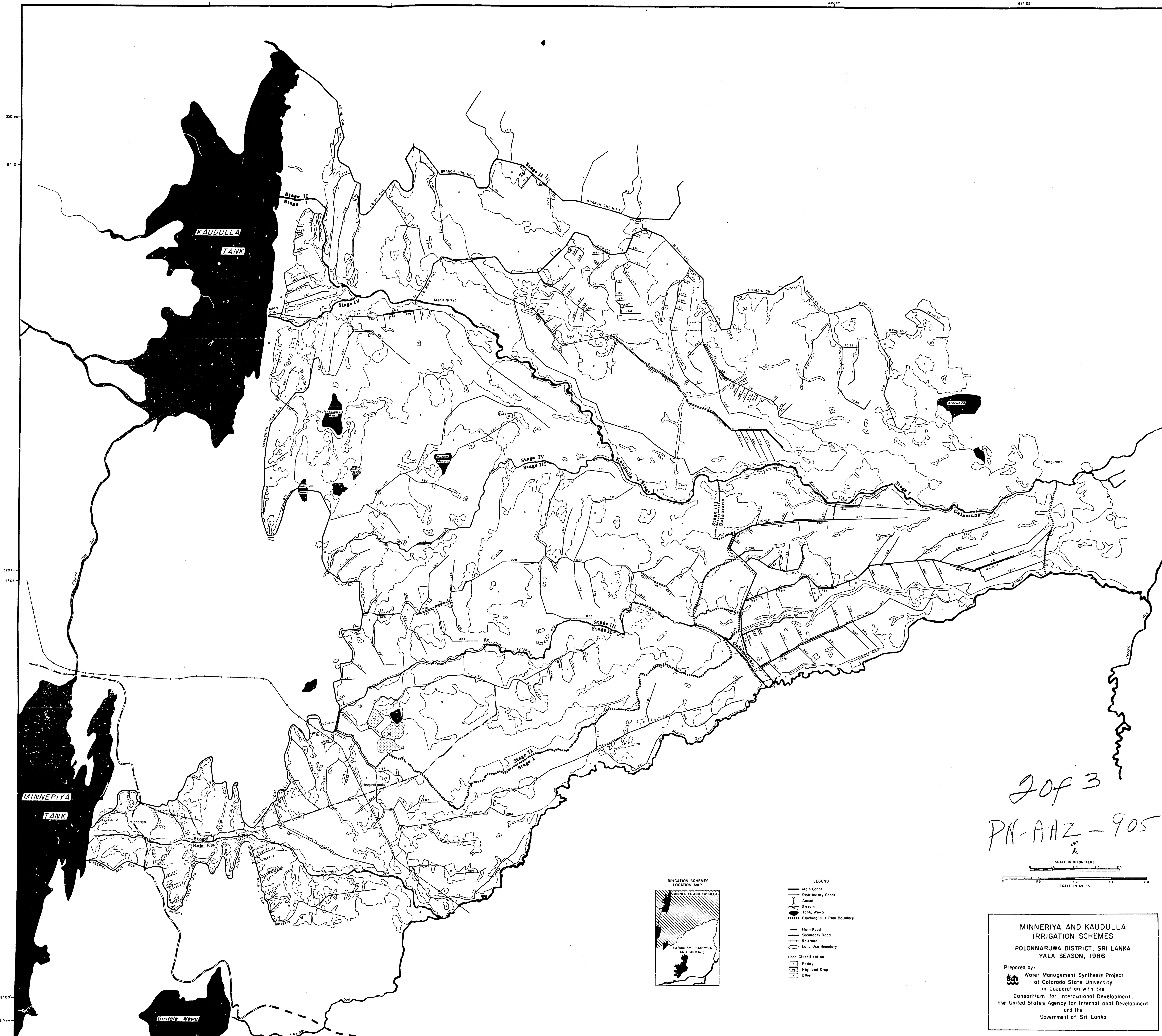

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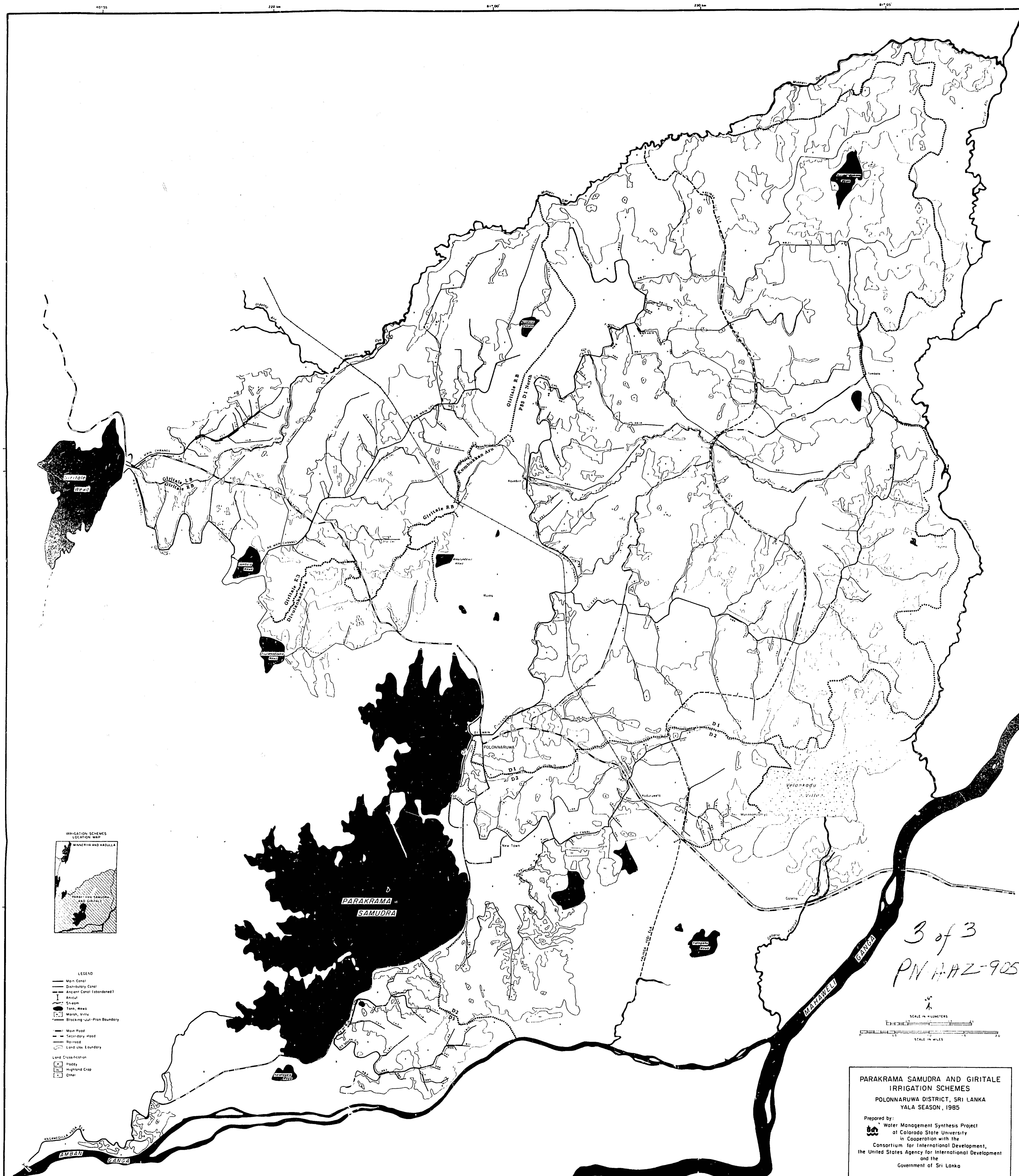

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