Iraqi Marshlands Observation System

UNEP Technical Report

UNEP

UNEP Post-Conflict Branch in collaboration with DEWA / GRID - Europe
Implemented under the UNEP "Support for Environmental Management of the Iraqi Marshlands" project, International Environmental Technology Centre (DTIE/IETC)

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Acronyms

CMS	Content Management System
CRIM	Centre for the Restoration of the Iraqi Marshlands
DEWA	Division of Early Warning and Assessment (UNEP)
DTIE	Division of Technology, Industry, and Economics (UNEP)
ETM+	Enhanced Thematic Mapper Plus (Landsat)
GRID	Global Resource Information Database (UNEP)
IMOS	Iraqi Marshlands Observation System
IETC	International Environmental Technology Centre (UNEP)
IRS	Indian Remote Sensing Satellite
MODIS	Moderate Resolution Imaging Spectroradiometer
MIR	Medium Infrared
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIR	Near Infrared
PCoB	Post-Conflict Branch (UNEP)
SLC	Scan Line Corrector (Landsat)
SLCIM	Simplified Land Cover and Inundation Mapping
SVM	Seasonal Vegetation Mapping

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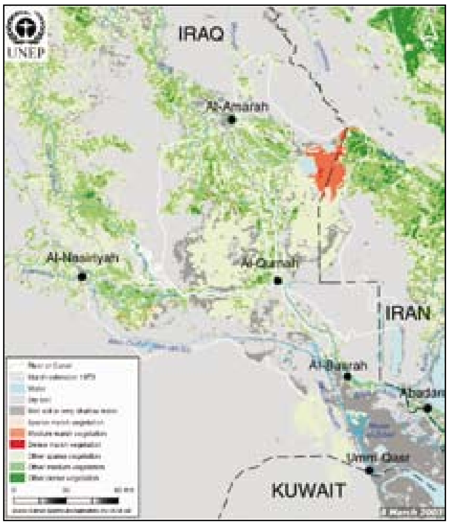
Executive Summary

During the three-year period under observation (January 2003 - December 2005), significant and rapid environmental change has taken place in the Iraqi marshlands. Indeed, after over a decade of precipitous decline – by 2003, the marshlands had dwindled to less than seven per cent of their 1973 extent – a new phase of active and widespread inundation began in the spring of 2003. At the collapse of the former Iraqi regime in March 2003, local communities immediately started to dismantle drainage structures, breaching embankments and dykes, opening flood gates and sealing diversions. The potential for re-flooding was further increased by the end of a three-year drought and good precipitation levels in the Tigris-Euphrates headwater catchment. Re-flooding of the marshes was subsequently officially sanctioned by the Ministry of Water Resources, which established a Centre for the Restoration of the Iraqi Marshlands (CRIM) to manage and coordinate the reinstatement of water and the rehabilitation process.

The inundation of the Iraqi marshlands, which has been continuous since April 2003, is characterized by a high degree of variability, ad-hoc interventions and uncertainty. Speculation about the evolution of the re-flooding has been rampant, with various sources quoting different estimates but offering limited substantiation on how these figures were computed. During this critical and dynamic phase, it became increasingly evident that systematically monitoring environmental change was paramount to gaining a better scientific understanding of the recovery process and to assisting decision-makers to plan and implement appropriate rehabilitation measures. Given the security constraints and vastness of the Iraqi marshlands, as well as cost-effectiveness considerations, satellite remote sensing was the only viable tool to observe the changes taking place on a continuous basis. Accordingly UNEP, in consultation with the Iraqi Ministries of Water Resources and Environment, designed a satellite-based monitoring approach – the Iraqi Marshlands Observation System (IMOS) – to survey the extent and distribution of marshland re-flooding and assess the development of wetland vegetation cover.

The monitoring work revealed that a remarkable and steady recovery process was underway, despite the flow fluctuations typical of such floodplain wetland ecosystems (Plate A). In less than one year since the start of the re-flooding (May 2003-March 2004), more than 20 per cent of the 1973 marshland area had been inundated. By May 2005, almost 50 per cent of the former marshes had been flooded, but this level gradually declined with the high evapotranspiration rates of the hot summer months, stabilizing at approximately 41 per cent by November 2005. Another major finding was the rapid establishment of emergent wetland vegetation, which has been increasing at the significant rate of over 800-900 km^2 per annum since May 2003. To UNEP's knowledge, the results of the satellite-based monitoring represent

Plate A: The progress of marshlands recovery between 2003 and 2005

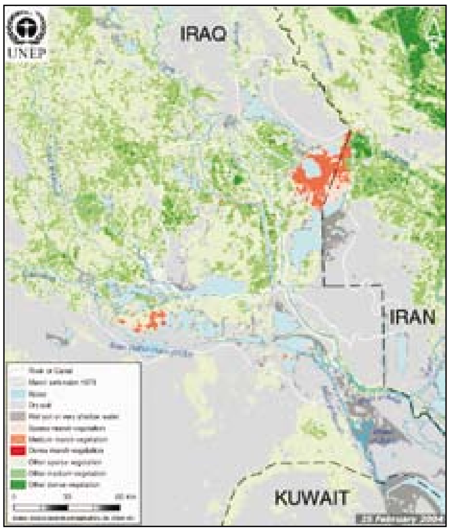


8 March 2003

Only part of the Hawr Al-Hawizeh marsh remains.

Central (Qurnah) and Al-Hammar marshes are virtually totally desiccated.

292 (water) + 593 (marsh. veg.) = 885 km^2
10% of 1973-76 baseline (8,926 km^2)



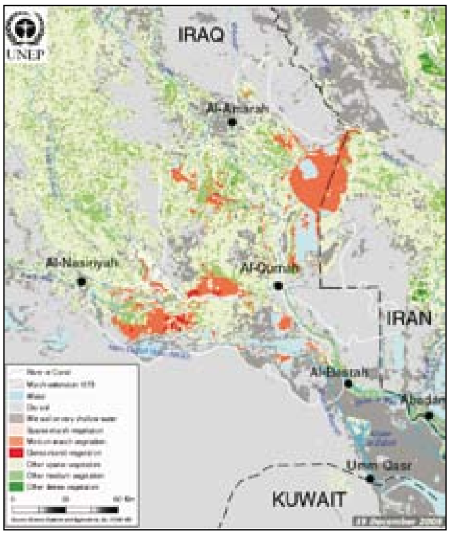
25 February 2004

Al-Hawizeh starts recovering.

Marsh vegetation reappears in western Al-Hammar.

Extensive flooding but overall limited wetland vegetation re-growth.

2,417 (water) + 1,180 (marsh. veg.) = 3,597 km^2
40% of 1973-76 baseline (8,926 km^2)



19 December 2005

Marsh recovery continues in Al-Hawizeh and Al-Hammar. Extensive wetland vegetation recovery.

Marsh vegetation reappears in the Central marshes along the northern bank of the Euphrates and at the riverine fan of Al-Muminah/Butaira.

1,067 (water) + 2,707 (marsh. veg.) = 3,774 km^2
42% of 1973-76 baseline (8,926 km^2)

Plate B: Key phases of marshland recovery as observed by MODIS

the most systematic and accurate mapping of the evolving extent of re-flooding and overall wetland rehabilitation supported with a fully documented scientific methodology.

Despite these positive developments, one should be careful not to equate marshland re-flooding with ecosystem restoration. It is therefore also important to examine whether the change is consistent with desirable states of ecosystem recovery and with the provision of the goods and services on which local populations depend for their livelihood. Such an assessment will require long-term interdisciplinary research and collaboration.

An approach combining satellite sensors to collect data at various scales and multi-temporal analysis was adopted to observe the evolution of marshland re-flooding. A novel methodology using an object-oriented approach, based on initial image segmentation followed by a multi-criteria classification, was developed and applied to MODIS, IRS P6 LISS-III and Landsat ETM+ imagery. The methodology created was considered to be globally satisfactory, and a continuous effort was made to address the remaining uncertainty by studying the anomalies and revising the classification procedures accordingly.

Synoptic maps using a legend to illustrate the temporal distribution of marshland re-flooding and wetland vegetation development were produced on a nominal weekly/bi-weekly basis as of January 2003 (Plate B). In total, 94 map sets were prepared for the three-year period. Surface area statistics of wetland vegetation and water body themes (the two key land cover types in the marshes) were calculated from the synoptic and seasonal vegetation maps. The data was then plotted to analyse the temporal evolution of the entire wetlands, as well as of the three key marshland units of Al-Hammar, Central (Al-Qurnah) and Al-Hawizeh. The comprehensive map collection produced under the IMOS, coupled with the temporal statistical analysis, provides a sound knowledge base to better understand the character and key phases of marshland rehabilitation.

Semi-detailed vegetation mapping of the marshlands was carried out using Landsat 7 ETM+ and IRS satellite imagery, the latter being identified as the most suitable source of medium-resolution imagery currently available. Similar object-based methodologies to the one used for MODIS were developed and applied to both the Landsat 7 ETM+ and IRS satellite data sets (Plate D). In total, seven seasonal vegetation maps were prepared for the spring and autumn, capturing the marshlands at their maximum and minimum extents respectively, on an annual basis for the three-year period. In 2005, Iraqi partners carried out three field data collection campaigns to support and help verify the results of image classification. In addition, field data from the relatively more accessible Iranian part of the marshlands was also used to check the results of the image analysis.

All the results have been placed in the public domain and made available on the IMOS website (http://imos.grid.unep.ch/), which is regularly updated to help ensure timely access for the Iraqi authorities as well as partner organizations and interested stakeholders (Plate C).

Overall, the three main objectives of the IMOS were successfully attained. A fully functional system to monitor marshland re-flooding was developed, providing a synoptic spatial and temporal overview of changes in the marshland environment on a near real-time basis, supplemented with semi-detailed seasonal thematic analysis. Timely accessibility of results (maps and statistics) to Iraqi partners was ensured via the IMOS web portal. Given the scantiness of field data, the analysts' expertise was particularly important in the process. The possibility to log and store the algorithms used, moreover, guaranteed that the results would be fully replicable. In its present form, the core part of IMOS (MODIS-based mapping) can be operated by one full-time geomatician/analyst.

While it would be premature to qualify wetland restoration as "successful", the IMOS shows that an exceptional recovery process is underway. Since early 2003, the marshlands total surface area has expanded from seven per cent to 41 per cent of their maximal extent in the early 1970s. At the risk of making a gross extrapolation, based on the current rate of re-flooding, it would take five to six years for the marshes to be restored to their full 1970s extent. Such a scenario clearly depends on the amount of water available in the Tigris-Euphrates river system and competing water demands from other economic sectors. A more accurate assessment of wetland restoration effectiveness would require additional field data on wetland structure and functions, as well as an assessment of rehabilitated areas with quantitative restoration targets and criteria set by the relevant Iraqi authorities.

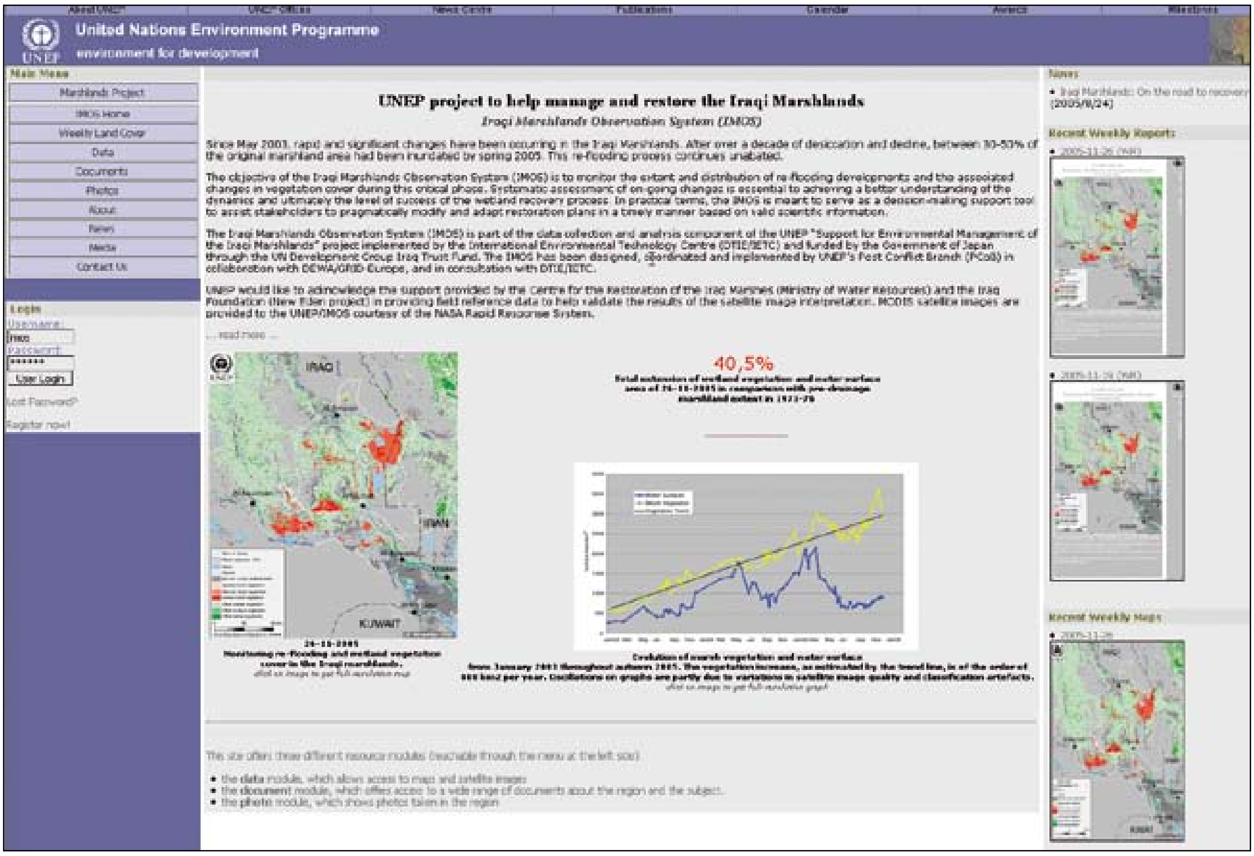


Plate C: IMOS website main page

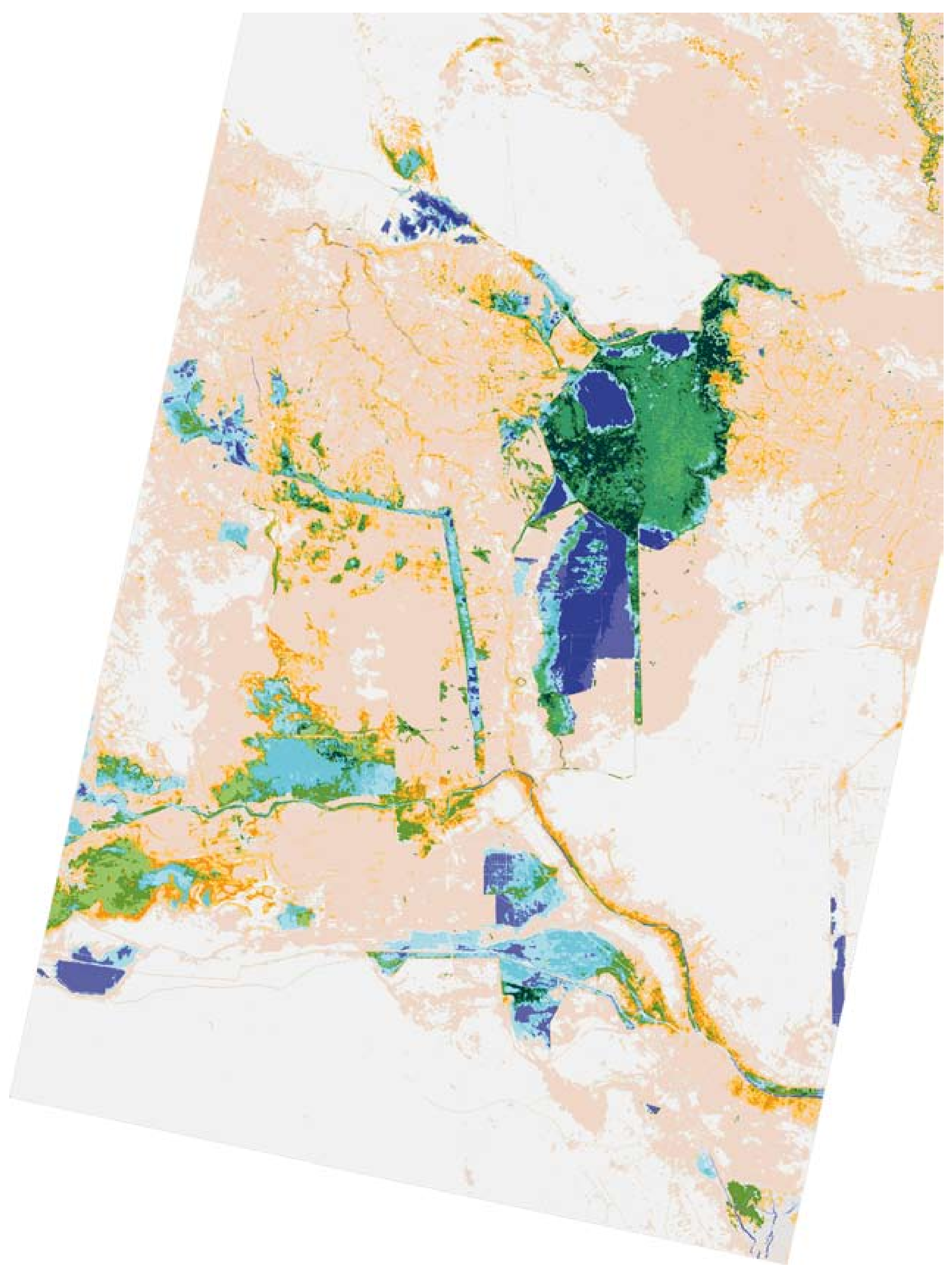


Plate D: Marshlands land cover classification based on IRS imagery taken on 15.06.2005

1. Introduction

1.1. Framework

The Iraqi Marshlands Observation System (IMOS) is part of UNEP's "Support for Environmental Management of the Iraqi Marshlands" project, which is implemented by the International Environmental Technology Centre (DTIE/IETC) and funded by the Government of Japan through the UN Development Group Iraq Trust Fund. The IMOS is designed and coordinated by UNEP's Post-Conflict Branch (PCoB), and implemented in collaboration with DEWA/GRID-Europe.

1.2. Background

Given the limited accessibility and vastness of the Iraqi marshlands, satellite data has proven to be a key source of valuable information on prevailing environmental conditions in the region. In 2001, UNEP relied on hard evidence from satellite imagery to alert the world to the plight of the marshes and place their predicament in the public spotlight (Partow, 2001). The pair of "before" and "after" snapshot images, capturing the scale, speed and severity of environmental degradation, is now a standard bearer of southern Iraq's marshland story.

In the same way that satellite data was used to document the demise of the marshlands, it can play a critical role in tracking and surveying ongoing efforts to re-flood and revive the ecosystem. When control structures were opened and embankments breached by local communities in April and May 2003, satellite images provided a unique perspective of the swollen rivers and canals, as water swept through a landscape that had been desiccated for over a decade. The potential for an accurate assessment of rapidly changing conditions by conventional ground surveys is hindered by the marshlands sheer physical scale and the hazards of navigating across a difficult environment. Due to the current security constraints, moreover, remotely sensed satellite imagery provides an exceptional tool and, in certain cases, the only means to observe the changes taking place on a continuous basis. In addition, benefits of satellite-based surveillance include cost-effectiveness, a global perspective and timeliness, as well as replicable and systematic survey methods.

Since April 2003, rapid and wide-scale inundation has been occurring in the marshlands. Re-flooding, however, is not equivalent to ecosystem restoration. During this critical and dynamic phase, it is therefore important to survey the spatial and temporal distribution of the ongoing re-flooding and associated changes in wetland vegetation cover, to better understand the magnitude and nature of the environmental change taking place.

1.3. Objectives

The overall aim of marshland monitoring is to assess the character and success of the wetland rehabilitation process, and to assist policy- and decision-makers to pragmatically modify and adapt restoration plans in a timely manner, based on valid scientific information. In this context, the goal has been to develop a decision support system that would address the following objectives:

1. Conceive and implement a monitoring concept to systematically acquire, analyse and exchange data and information on the rapid changes taking place in the marshland environment;

2. Develop information products and services based on the gathered data, to support the management of the restoration process;

3. Evaluate the magnitude and character of wetland rehabilitation.

1.4. Acknowledgements

Lead Authors

This project has been carried out through close cooperation between UNEP's Post-Conflict Branch (PCoB) as task leader, and DEWA/GRID-Europe as scientific and technical partner.

H. Partow (PCoB) designed and coordinated the implementation of the Iraqi Marshlands Monitoring

System, and J-M. Jaquet (DEWA/GRID-Europe) was in charge of overall scientific coordination. Data handling, image analysis and interpretation, map production and web design and maintenance were carried out by K. Allenbach, S. Schwarzer and A. Harayama (DEWA/GRID-Europe), and O. Nordbeck (PCoB).

Other Contributors

NASA's Rapid Response System (J. Kendall) provided invaluable support through the provision of good quality MODIS imagery. P. Petrov from the Regional Organization for the Protection of the Marine Environment (ROPME) shared technical insights on MODIS imagery during the initial phase of the project. Y. Hussin from ITC, the Netherlands, reviewed the remote sensing methodology and led the training course on wetland remote sensing for Iraqi experts.

Relevant *in situ* data on water and vegetation was collected by field teams from the Iraqi Ministries of Water Resources (Centre for the Restoration of Iraqi Marshlands) and Environment, in collaboration with staff from Nature Iraq/Iraq Foundation. These include: (i) A. Hashim, F. Haider and O. Natik Nouri (Ministry of Water Resources); (ii) A. Alwash, R. Dayih, and W. Ghanim (Nature Iraq/Iraq Foundation, and (iii) I. Abed (Ministry of Environment). For the Iranian part of the marshlands (Hawr Al-Azim), field data was kindly provided by A. Lotfi and M. Tayab (Inpex Corporation/Pandam Engineers).

Special thanks are also expressed to the following individuals for their valuable support in implementing the IMOS: Monique Barbut, Per Bakken, Chizuru Aoki, Robert Rodriguez, Ali Al-Lami (IETC/DTIE); Edward Maltby (SWIMER, University of Liverpool); Andrea Cattarossi (New Eden Project, Italy); Ron Witt (DEWA/GRID Europe); Jogchum Finnema (UNOPS); Henrik Slotte, Muralee Thummarukudy, Koen Toonen, Elena Orlyk, Matija Potocnik, Rachel Dolores, Firas Abu Taeh and Majeda Ismail (UNEP/PCoB) and Silja Halle for language editing of the report and annexes.

2. The Mesopotamian Marshes

2.1. Geographical Setting

The Iraqi marshlands sit in the heart of the vast floodplain wetlands created by the Tigris-Euphrates river system in the lower Mesopotamian basin. Downstream from Baghdad, approximately 520 km from the head of the Gulf, the very weak longitudinal slope of the land causes the two great rivers to meander and split into multiple branches, creating a chain of almost interconnected shallow freshwater lakes, marshes and seasonally inundated floodplains that typically overflow and merge into larger complexes during periods of high floods. In addition, the perennial Karkheh River as well as a series of seasonal rivers (Wadi Naffath, Al-Tayb/Meymeh, Dawayrij) descending from the Zagros mountains in Iran, drain into the eastern marshes, on the eastern bank of the Tigris River.

The climate of the Mesopotamian floodplain is arid; mean annual rainfall ranges from 100 mm in the west to 150 mm in the east. The very hot summers, when temperatures can reach over 50° Celsius in July and August, induce high evapotranspiration rates of three meters per annum. As a result, the water source nourishing the marshes is almost entirely dependent on the surface run-off generated in the humid Anatolian highlands and Zagros mountains (> 1,000 mm in rainfall) in the north and east, respectively. The extent of the marshes is highly variable, expanding and contracting with seasonal flooding and annual changes in water flows. Prior to dam construction, discharges into the Tigris and Euphrates peaked in April and May, with flow volumes lowest in August and September. This oscillation, generated by snowmelt flood pulses during the spring and gradual water recession over the summer months, plays a critical role in the dynamics of marshland ecology.

The marshes, situated in the geomorphologically complex Mesopotamian floodplain, stretch between a double delta: an inland one produced by the Hindiyah-Hillah on the Euphrates and the Shatt al-Gharaf on the Tigris, and a marine delta system created by the Karun and Marun-Jerrahi river systems. Around the confluence of the two rivers in Qurnah, the Mesopotamian plain becomes extremely narrow as it is almost clogged up by the large conglomeratic alluvial fan of Wadi Batin drawing in from the Nejid in the west, and the Karkheh and Karun river systems descending from the Zagros mountains in the east. By fanning out at the head of the Gulf, the Wadi Batin, the Karkheh and Karun constrict the lower Mesopotamian valley to a width of less than 45 km and prevent the Twin Rivers from directly discharging into the sea. This impediment to the natural drainage of the Tigris and Euphrates results in the creation of the marshlands below the inland delta which connects with the Gulf via the Shatt al-Arab estuary.

Known in Arabic as *Al-Ahwar*, a word of Sumerian origin referring to the white reflection of sheets of open water, the core of the marshes is centred on the confluence of the Tigris and Euphrates (29°55' to 32°45' N and 45°25' to 48°30' E). Below the inland delta, the extreme flatness of the land creates three active fan-deltas: (i) on the Euphrates, the Suq Al-Shuyukh fan divides into many distributaries (Sakha, Akeka, Bani Hassan, Al-Hafar, Umm Nakhla and Qarmat Bani Saeed) which flow into the Al-Hammar marsh and (ii) on the Tigris, the Muminah-Butaira/Majar Al-Kabir and the Kahlah-Musharah fans nourish, respectively, the Central and Hawizeh marshes. In addition, the Karkheh alluvial fan delta substantially contributes to the formation of the eastern Hawizeh marshes.

The marshes are composed of a mosaic of permanent and seasonal fans, shallow and deep water lakes, as well as mudflats and desert landscapes that are regularly inundated during periods of high water levels. Lying over clay soils, the marshes are extensive but shallow. Mean water depth in the permanent marshes ranges from half a meter and two meters during the dry and wet seasons, respectively, and reaches depths of up to six meters in the permanent lakes. The marshes are divided into three major units: (i) Hammar marshes; (ii) Central (Qurnah) marshes and (iii) Hawizeh marshes (Figure 2).

The Hammar marshes are situated almost entirely south of the Euphrates, extending from near Al-Nasiriyah in the west to the outskirts of Al-Basrah on the Shatt-al-Arab in the east. To the south, along their broad mud shoreline, the Al-Hammar marshes are bordered by the sand-dune belt of the Southern Desert. When the Hammar marshes were still intact, their surface area was estimated to range from 2,800 km^2 of contiguous permanent marsh and lake, to a total area of over 4,500 km^2 during periods of seasonal and temporary inundation. The 120 km-long Al-Hammar Lake was formerly the largest water body in the lower Euphrates.

Roughly delimited by the triangle between the towns of Al-Nasiryah, Al-Amarah and Al-Qurnah, the Central marshes are bordered by the Tigris River to the east and the Euphrates River in the south. Prior to marshland drainage, the Al-Musandak wetland complex (Saadiyah, Sanniyah, Nijelah marshes) would typically overflow into the Central marshes, particularly during high floods when emergency flood escapes were made on the western bank of the Tigris to protect human settlements and agricultural fields downstream. Receiving water influxes from an array of Tigris distributaries, most of which branch off from the Shatt-al-Muminah/Butaira and Majar-al-Kabir, as well as the Euphrates, the Central marshes covered an area of about 3,000 km^2 extending to well over 4,000 km^2 during flood periods. Al-Zikri and Umm al-Binni (now dry) were some of the notable permanent lakes located around the centre of the marshes.

The Hawizeh marshes lie to the east of the Tigris River, straddling the Iran-Iraq border. The Iranian section of the marshes is known as Hawr Al-Azim. In the west, they are largely fed by three main distributaries departing from the Tigris River near Al-Amarah; the Musharah, Kahlah and Majriyah. An important water influx also comes from the Karkheh River in Iran. Historically, the Hawizeh covered an approximate area of at least 3,000 km^2, expanding to over 5,000 km^2 during the floods. The northern and central parts of the marshes were permanent but the lower southern sections were mostly seasonal. Large permanent lakes (Umm al Ni'aj) up to six meters deep are still found in the northern part of the marshes. The Hawizeh marshes represent the most intact part of the original Mesopotamian wetland complex and are of major importance as a biodiversity reservoir.

Moving from the interior of the freshwater marshes, the floral zones typically grade outwards from open-water deep lakes with submerged (mainly *Ceratophyllum demersum*) and marginal floating vegetation (water lilies), to permanent marshes dominated by dense stands of *Phragmites* and *Typha,* to seasonal marshes with a prevalence of rushes and sedges, and finally to seasonally flooded mudflats and semi-desertic steppe. The seasonal and shallow, brackish to saline lagoons, have extensive areas of halophytes, such as *Salicornia*.

The waters of the marshes collectively drain into the Shatt Al-Arab estuary at the confluence of the Tigris and Euphrates at Qurnah. In addition, the waters of Al-Hawizeh flow into Shatt Al-Arab via Al-Swaib River (15 km south of Al-Qurnah) and those of Hammar also discharge into Shatt al-Arab at Qarmat Ali near the northern outskirts of Basrah city. Although the Shatt al-Arab estuary is influenced by the strong twice-daily tidal action of the Gulf, which ranges between two and three meters, seawater does not penetrate farther than Abadan. However, the influence of the dynamic tidal action affects the lower reaches of the marshes, particularly the eastern part of the Hammar.

2.2. Biodiversity Features

The Mesopotamian marshlands constitute the largest wetland ecosystem in the Middle East and Western Eurasia and support a rich biota. They provide a key wintering and staging area for migratory waterfowl on the Africa-Europe/Asia flyways. Over 50 per cent of 278 species of birds recorded in the region are dependent on these wetland habitats. The marshes historically provided wintering habitat for some of the largest concentrations of waterfowl in the world, estimated at several million. When the marshlands were drained, at least 66 of these bird species were considered to be at risk, of which at least 10 were considered to be regionally or globally threatened. The marshes have also been singled out as one of the eleven non-marine wetland areas in the world with Endemic Bird Area status, supporting almost the entire global population of two species, the Basrah Reed Warbler (*Acrocephalus griseldis*) and the Iraq Babbler (*Turdoides altirostris*).

New ornithological surveys and waterfowl counts were initiated in 2005, and carried out by the Iraqi Ministry of the Environment, the Iraq Foundation and Iraq Nature Conservation Society under the Canada-Iraq Marshlands Initiative (2005). They recorded 72 species of birds, of which ten were regionally or globally threatened species re-establishing range and/or nesting in the marshes. Particularly dependent on the marshlands are the Dalmatian Pelican (*Pelecanus crispus*), Pygmy Cormorant (*Phalocrocorax pygmeus*), Marbled Teal (*Marmaronetta angustirostris*), White-Tailed Eagle (*Haliaeetus albicilla*), Imperial Eagle (*Aquila heliaca*), the Slender-billed Curlew (*Numenius tenuirostris*) and an endemic sub-species of the Little Grebe (*Tachybaptus ruficollis iraquensis*). Isolated populations of the Goliath Heron, Sacred Ibis, and African Darter are also known to exist in the marshes.

Previously abundant, mammals have been under enormous pressure. Threatened species include the Grey Wolf (*Canis lupus*) and Common Otter (*Lutra perspicillata*). The Smooth-Coated Otter (*Lutra p. maxwelli*) was endangered in 1990 (and may have become extinct by 2005), as well as the Mesopotamian Gerbil (*Gerbillus mesopotamiae*). The marshlands also provide an important habitat for a rich fish fauna, of which several species are endemic and many play a vital economic role. In 1990, the FAO estimated that 60 per cent of Iraq's inland fish catch of 23,500 tons was caught in the marshes. Fish from the carp family (Cyprinidae), which are particularly interesting to scientists who study evolution, are dominant. The marshes also provide important spawning and nursery grounds for a number of marine species, including the Hilsa Shad (*Tenualosa ilisha*) and the Penaeid Shrimp (*Metapenaeus affinis*). Approximately twelve species of fish have been deliberately introduced into the wetlands of Mesopotamia.

2.3. Environmental Change and Recent Developments

Over the course of time, the physical characteristics of the Mesopotamian plain have undergone many changes, continuously evolving during periods of glaciations, sea level oscillations, deltaic progradation and shifts in river courses. The marshlands have invariably been affected by these changes, and the overall proportion of wetlands in the floodplain has been steadily declining since 5,500 BP, as sea levels dropped. Until the mid-twentieth century, however, both the rate and the extent of the change was relatively slow.

The Tigris-Euphrates river system's hydrology and ecology were fundamentally transformed when riparian countries launched the construction of major dams and irrigation projects in the upper part of the basin in the late 1950s. At present, the active storage capacity of the thirty large dams on the Tigris and Euphrates is several times greater than the combined annual flow of both rivers. Moreover, at least twenty more dams are planned or are under construction, including the major Bekhma Dam on the Greater Zab River in Iraq, with a capacity of over 17 billion cubic meters. The resulting alteration in the water flow regime has impacted the downstream marshland ecosystem in two major ways: (i) by substantially reducing the amount of water and sediment reaching the marshlands and (ii) by suppressing the flood pulse driving marshland ecology.

The precipitous destruction of the Mesopotamian marshlands is, however, mainly due to the events that took place within the marshlands in the past 25 years. This decline started with the Iraq-Iran war in the 1980s and reached its zenith with the implementation of massive drainage projects in the wake of the civil unrest that occurred in southern Iraq following the end of the second Gulf War in 1991. Key engineering works included completion of the Main Outfall Drain and "Mother of Battles River", diverting Euphrates flow around the Hammar marshes into the Gulf and the two kilometer-wide and fifty kilometer-long "Glory River", capturing the waters of the Tigris distributaries and preventing any replenishment of the Central marshes. Large areas of the marshes were subsequently partitioned into polders, and the water either pumped out or left to evaporate. As a result, by 2002, the former marshlands had dwindled to less than seven per cent of their surface in 1973.

At the collapse of the previous Iraqi regime in March 2003, a remarkable turn-around in events ushered in a new lease on life for the marshes. Local communities immediately started to breach embankments and dykes, open flood gates and seal diversions. Water rapidly swept over large tracts of the parched marshes for the first time in over a decade. The potential for re-flooding was further increased by the end of a three-year drought and good precipitation levels in the Tigris-Euphrates headwater catchment. Re-flooding of the marshes was subsequently officially sanctioned by the Ministry of Water Resources, which established a Centre for the Restoration of the Iraqi Marshlands.

The inundation of the Iraqi marshlands, which has been continuous since April 2003, is characterized by a high degree of variability, ad-hoc interventions and uncertainty. Marshland re-flooding, however, is not equivalent to ecosystem restoration, and it is important to examine whether this change is consistent with desirable states of ecosystem recovery and with the provision of the goods and services on which local populations depend for their livelihood. Such an assessment will require interdisciplinary research and collaboration. One of the key parameters is the re-establishment of wetland vegetation cover. Over the medium term, it will be necessary to develop a more coordinated water management plan for the marshes, and ensure that timely and adequate water flows are able to sustain the ecological dynamics of this unique ecosystem.

3. The Iraqi Marshlands Observation System

3.1. Concept

As the re-flooding of the desiccated Iraqi marshes lead to a new phase of rapid and significant environmental change, it quickly became clear that a systematic survey of this critical rehabilitation stage would provide an essential information baseline to better understand the direction and character of wetland recovery and help support restorative action planning.

Because of the vast physical extent (15,000-20,000 km^2) and inaccessibility of large parts of the marshlands (due to minefields or lack of transportation infrastructure, for example), remote sensing offered a unique method to monitor, assess and empirically quantify the changes occurring on a near real-time basis. Satellite remote sensing surveillance not only had the advantage of cost-effectiveness, global perspective and timeliness, but also – in the prevailing security context – to be in some cases the only means to observe the rapid environmental change taking place.

With this in mind UNEP, in consultation with the Iraqi Ministries of Water Resources and Environment, designed a satellite-based monitoring approach – the Iraqi Marshlands Observation System (IMOS) – to survey the spatial and temporal distribution of re-flooding and associated changes in wetland vegetation cover. The overall goal of the IMOS is to assess the state of wetland rehabilitation and serve as a decision-making support tool to assist the Iraqi authorities and stakeholders to pragmatically adapt restoration plans in a timely manner based on valid scientific information.

Three key research questions guided the IMOS:

1. What is the spatial distribution of marshland re-flooding ?

2. What is the temporal evolution of marshland re-flooding?

3. What is the wetland vegetation response to the marshland re-flooding?

In order to fulfill the stated objectives, the IMOS was developed with the following practical premises:

- Dependence on multi-resolution /multi-temporal satellite imagery;

- Reliability and low cost of data sources;

- Transparent methodology (fully documented and replicable);

- Complex but solid image analysis methods;

- Legibility of map and statistical outputs;

- Accessible information sharing and distribution through an internet-based web platform.

3.2. Components and outputs

The Iraqi Marshlands Observation System (IMOS) consists of the following components (Figure 1):

1) **Imagery database** compiled from three satellite platforms: Terra-MODIS, IRS-P6/LISS-III and Landsat-ETM;

2) **Field and hydrology database**, containing observations and photos collected by field teams;

3) **Methodologies** for image analysis/ cartography and statistical analysis, detailing the **software** used, **bibliographic** sources and all the steps followed to produce maps, statistics and graphics;

4) **Cartographic products**, consisting of Simplified Landcover/ Inundation Maps (SLCIM, weekly or bi-weekly for 2003-2005) and Seasonal Vegetation Maps (SVM), based on IRS or Landsat images;

5) **Statistical and graphic products**, summarizing the evolution of water and marsh vegetation surfaces between 2003 and 2005, either as a whole, or per marshland unit. Reporting is in the form weekly or bi-weekly bulletins, photographic atlases and posters;

6) **Website**: all the items contained in the yellow frame of Figure 1 are accessible via the IMOS website;

7) **Capacity building**: an introductory training course on wetland remote sensing and field data collection for Iraqi experts was carried out in early 2005. With the documentation of the aforementioned six components of IMOS now completed, the hand-over of the system to the relevant Iraqi institutions will have to be carried out through training sessions and proper technology transfer (in particular software).

In addition to the weekly simplified land cover and seasonal vegetation reports, separate progress reports were produced during the development of the image classification methodology. The present document represents the final compilation of the work and results achieved under the IMOS.

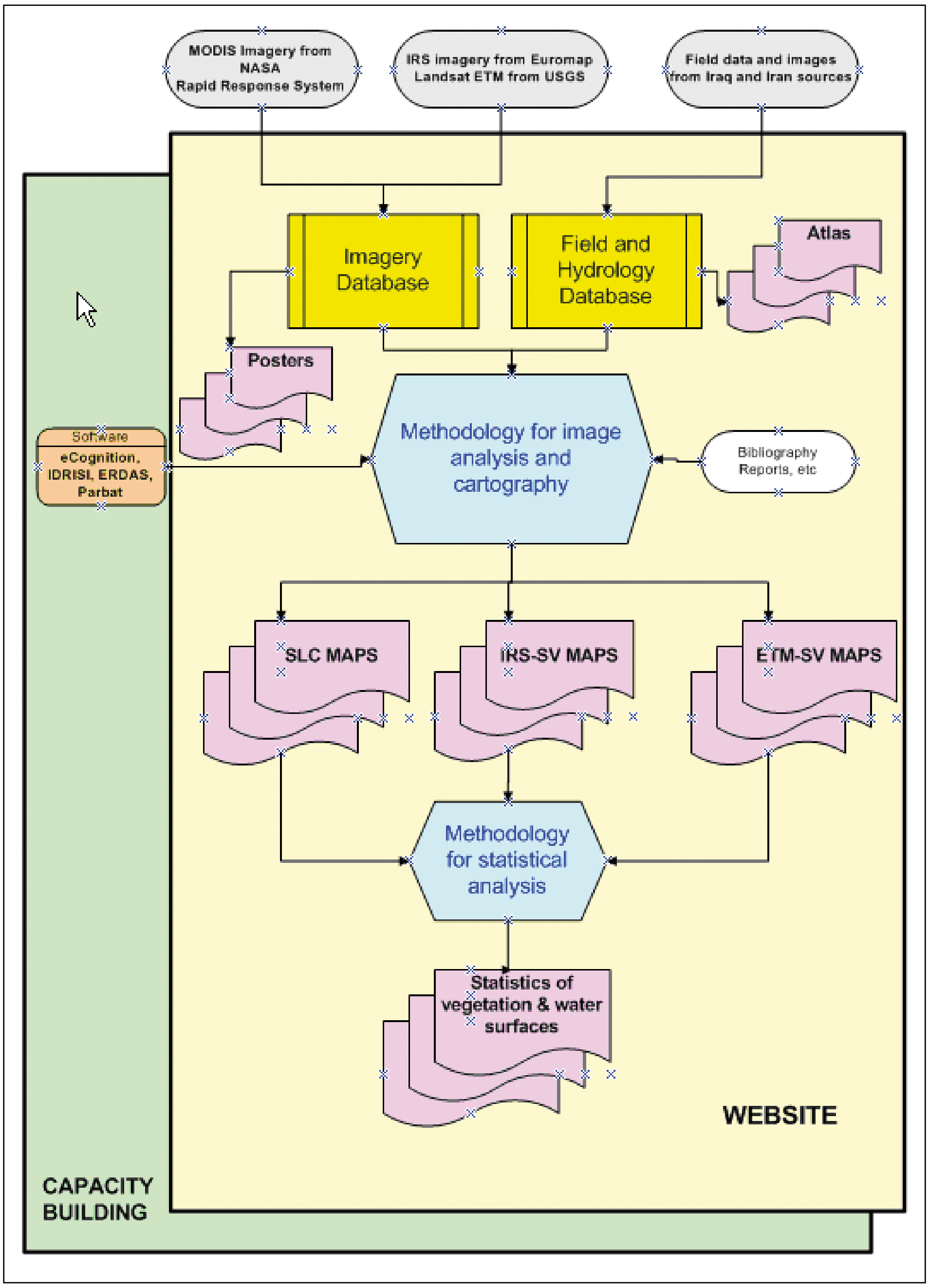


Figure 1: IMOS structure

4. Data

4.1. Satellite imagery

To map the evolution of the marshlands, a multi-stage approach using low- and medium-scale resolution satellite imagery was followed to obtain a more comprehensive coverage and analysis. Three types of satellite sensors were used, as shown in Table 1. In addition, the IMOS database includes some ASTER images and high resolution QuickBird images received from partner organizations. These were used on a selective basis.

The complete list of MODIS images, with characteristics and meta-information is given in Annex H.

4.2. Field information

Because of the security situation in Iraq, UNEP experts were unable to conduct the usual field controls on the image classification results. A collaborative arrangement was therefore made with various partners on the collection and sharing of field observations, namely:

- Iraq: joint field teams from the Iraqi Ministries of Water Resources (Centre for the Restoration of Iraqi Marshlands) and Environment, in collaboration with staff from Nature Iraq/Iraq Foundation have been collecting information on land cover and water quality at 26 sites since the beginning of 2005. UNEP provided training and guidance to these teams on the collection of ground-truthing data and the use of field equipment, survey forms and the selection of target sites. Three field campaigns were carried out in 2005 (in April, June and September), and their results were transmitted to UNEP. Another campaign took place in January 2006, for which the sites were partially revised by UNEP so as to cover areas of particular significance within the marshlands. To date, 53 sites have been photographed and described. The photos are presented in folders following the alphabetical order of the stations[2], and subsequently by date. Each folder consists of two tables: in the first, the top panel provides the meta-information, and the bottom panel offers four views towards the north (upper left), east (upper right), south (lower left) and west (lower right). The second table provides information on land/vegetation cover and water quality.

Type	Source	Spatial resolution (m)	Bands	Units	Nominal time frequency	Number of images used
MODIS	NASA RRS	250	B,G,R,NIR,MIR 3, 4, 1, 2, 7	Reflectance x 10000	Daily	92 (2003-2005)
IRS P6 LISS-III	Euromap	24	V, R, NIR, MIR 2, 3, 4, 5	8bit Digital Number	24 days	15.06.05: Eastern orbit 22.08.05: W.O. 20.09.05: E.O. 09.10.05: W.O.
Landsat ETM[1]	USGS	28	B, V, R, NIR, 2 MIR 1, 2, 3, 4, 5, 7	8bit Digital Number	Fortnightly	1 (06.05.2003) 4 (autumn 2003, spring 04, autumn 04, spring 05)

Table 1: Imagery used in the IMOS project

[1] After May 2003, the imagery is of the SLC-off type
[2] As named by Iraqi partners conducting the field work.

- Iran: field data was mainly collected in the central and southern desiccated parts of the Hawr al-Azim marshes, as well as along the eastern parameter and several causeways penetrating into the intact core of the marsh. These field campaigns were conducted within the framework of an environmental impact assessment and follow-up monitoring for the development of the Azadegan oil field. An initial campaign was conducted in 2002, and followed by a survey in the winter and spring of 2005, by Pandam Consulting Engineers on behalf of Inpex Corporation. The data was delivered on a CD-ROM, as images linked to a shapefile within an *ArcView 3.2* project, accompanying a report entitled "Vegetation Cover Survey, winter 2005". Although there is no land cover information *per se* in the shapefile table, it is possible to estimate the vegetation type by visual reference to the map. To date, 87 photos are available from the Hawr Al-Azim. Another campaign took place in November 2005.

This photographic and textual field information has been gathered in the Field and Hydrology Database (Figure 1) and is accessible via an *ArcView 3.2* database. It has also been printed as an Atlas (Annex G) of this report.

Figure 2: Location map of the Mesopotamian marshlands

4.3. Other

Some additional information has been collected and stored in the Field and Hydrology Database: hydrological records (water discharge data), Digital Elevation Model (DEM; from SRTM), vectors and topographic maps. Apart from vectors used for map overlays, this data was not extensively used due to time constraints.

The location map of the marshlands, with their subdivisions, is given in Figure 2.

5. Methodology

Satellite imagery was the essential source of primary data available to map and track the evolution of marshland re-flooding. Hence, a considerable amount of time and effort was devoted to developing a methodology that would be efficient, solid and cost-effective.

To this end, two axes of study, corresponding to the products shown in Figure 1, were pursued:

- The extraction of land cover (vegetation and water) from MODIS imagery, with low spatial resolution but high time frequency (Table 1). MODIS imagery is available in the public domain, except for the archive imagery for 2003-2004, which had to be procured. SLCIM maps were thus produced with corresponding statistics;

- The extraction of semi-detailed land cover from Landsat ETM+ (before and after SLC-off) and IRS P6 LISS-III, at higher spatial resolution, but on a seasonal basis only. This imagery, which yielded the various SV maps, had to be purchased at cost.

5.1. Simplified Land Cover and Inundation Mapping (SLCIM)

The methodology to prepare MODIS-based simplified land cover maps is outlined in Figure 3, and detailed in Annex A. Whereas the pre-processing and statistical phases are self-explanatory, the steps followed to extract thematic information from MODIS imagery should be elaborated on.

Instead of the classical image interpretation procedure, whereby each pixel is classified in isolation, a novel object-oriented approach was used, in which the image was first segmented into polygonal objects, based on scale and homogeneity criteria (Song et al., 2005), with a possibility to assign weights to various layers. Fuzzy logics, and spectral, textural, shape or contextual criteria could then be applied to interactively classify the pre-defined objects. The procedure went through a decision tree, and produced a well-structured class hierarchy.

In the scientific community, the object-oriented approach has so far essentially been applied to high-resolution image classification[3]. The decision to use the object-oriented approach on low-resolution MODIS imagery as well as medium-resolution Landsat and IRS data sets, was made on the following grounds:

- Possibility to define a logical, hierarchical and well-structured legend;

- Feasibility of segmenting the imagery into objects at several levels of detail;

- Cartographic themes mapped in a more compact way (less salt-and-pepper effect) than when working on a pixel basis;

- Large choice of criteria for the classification of segmented objects;

- Unified procedures applicable to all imagery types;

- The eCognition software (Professional version 4.0) used to develop IMOS mapping products, provides the analyst with numerous possibilities to interactively supervise the classification process (Definiens, 2005).

In total, 94 MODIS images were segmented according to the criteria shown on Table 2, and subsequently classified following the hierarchy on Figure 10, using the bands and indices shown in Table 3. The segmentation criteria were chosen after numerous trials.

The class hierarchy and labelling were developed in relative detail because of the necessity to separate and map marsh vegetation and water surfaces in priority. The procedure was designed to be as simple and robust as possible, but sufficiently accurate to minimize omission and commission errors.

[3] See examples on Definiens website (www.definiens-imaging.com) and in Harayama and Jaquet, 2004.

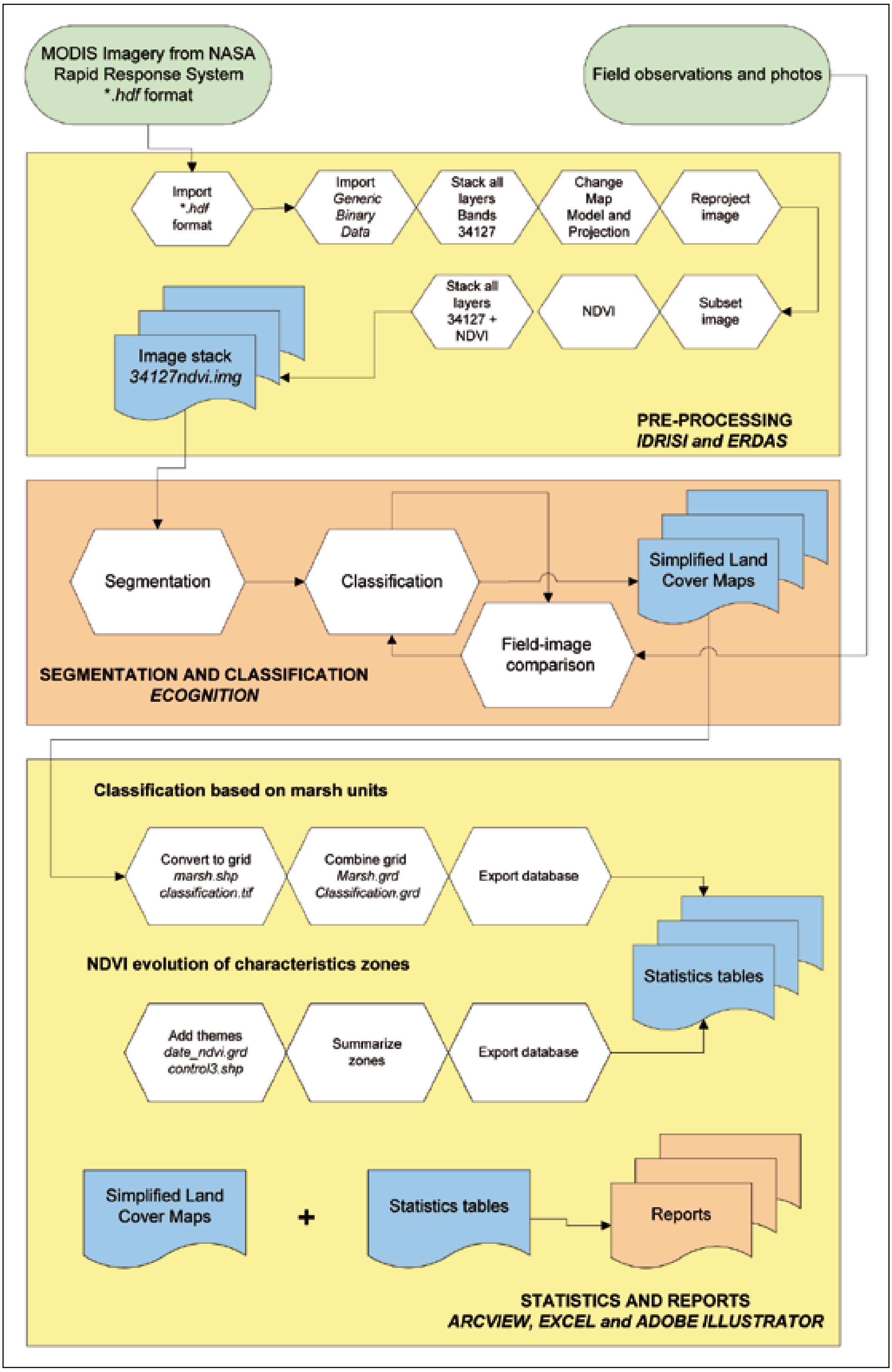


Figure 3: MODIS-based SLCIM methodology

The classification criteria shown in Table 3 were chosen to optimize separation and discrimination of categories on the basis of a structured class hierarchy.

- Vegetation is separated from non-vegetation using the Normalized Difference Vegetation Index (NDVI<0.125) (Fleming, 2000);

- Separation between soil and water is done using medium infrared (MIR). Dark soil may be, at times, equivalent to wet soil. Other criteria are under study (NDWI; McFeeters, 1996; Huggel et al., 2002);

- In the vegetation category, the density criterion comes into play before the distinction between marsh and land vegetation. Density is a function of (a) number of stands per unit surface; (b) vegetation height; (c) vegetative state (greenness) and (d) type of substrate (water vs soil). This parameter is expressed as sparse (NDVI<0.125), medium (0.25 ≤NDVI ≤0.50) and dense (NDVI >0.5);

- Discrimination between marsh and non-marsh vegetation rests on the **simplified assumption that the former essentially consists of** *green emergent hydrophytes* (Phragmites sp). Inclusion of other categories such as dry hydrophytes, xerohalophytes and halophytes is attempted only in the classification of higher-resolution imagery (IRS and Landsat).

Owing to variations in MODIS scene geometry and atmospheric conditions, the criteria in Table 3 had to be interactively ajusted by the analyst, according to the following steps:

- Visual comparison of the current SLCI map with previous ones (previous week);

- Examination of the water and vegetation surface statistics and graphs;

- Consultation of ancillary information on precipitation episodes, river discharge records, reports of dyke breaches and opening of flood gates and escapes;

- Consultation of the field database (Annex G);

- In the event of, for example, a large increase or decrease in water surface in a specific area without any likely link to ancillary information, it is postulated that a classification error occurred, and the image is reclassified based on adjusted thresholds;

- In the case of, for example, a large increase or decrease in vegetation surface in a specific area within a time span of a week, a classification error is postulated and the image is reclassified with adjusted thresholds.

In spite of these precautions, and due to the lack of complete field records on hydrological events, the computed surfaces graphs (Figure 38) display some unexplained irregularities. Whether these are the result of classification imperfections or show actual variations on the ground will have to be confirmed in follow-up studies. The upward trend in marshland extent and wetland vegetation development, however, is unequivocal.

MODIS bands	3	4	1	2	7	NDVI	Reason
Domain	B	G	R	NIR	MIR	-	Spectrally complete
Weight	1	1	1	1	1	0	*A priori* equality of influence. Avoid NDVI redundancy
Scale	10						Optimum for object identification
Shape - Spectral	0.1 – 0.9						Low spatial resolution
Compactness - smoothness	0.5 – 0.5						Negligible role because of small influence of shape

Table 2: MODIS imagery segmentation criteria

Theme	Layer	Criterion range	Ct / Var[4]	Remarks
Vegetation	NDVI	> 0.125	ct	
Non vegetation		*not* veg		
Water	MIR	*not* veg *and* MIR<1000	v	
Soil		*not* veg *and* *not* water		
Dark soil	Red	*not* veg *and* *not* water *and* R<2000	ct	
Light soil		*not* veg *and* *not* water *and* *not* dark soil		
Sparse (veg)	NDVI	veg *and* NDVI<0.25	ct	
Medium (veg)	NDVI	veg *and* 0.25<NDVI<0.5	ct	
Dense (veg)	NDVI	veg *and* *not* medium veg *and* *not* sparse veg		
Dense marsh vegetation	NDVI marsh_1973_iran.shp B+G+R MIR PIR (GREEN)	veg *and* *not* medium veg *and* *not* sparse veg *and* *within* marsh pot.lim. *and* brightness <1100 *and* MIR<900 and PIR<3600 GREEN<800	v v v v	both MIR and NIR G only used in winter images
Medium marsh vegetation	NDVI marsh_1973_iran.shp B+G+R MIR PIR (GREEN)	veg *and* medium veg *and* *within* marsh pot.lim. *and* brightness <1100 *and* MIR<900 PIR<3600 GREEN<800	v v v v	both MIR and PIR G only used in winter images
Sparse marsh vegetation	NDVI marsh_1973_iran.shp B+G+R MIR PIR (GREEN)	veg *and* sparse veg *and* *within* marsh pot.lim. *and* brightness <1100 *and* MIR<900 PIR<3600 GREEN<800	v v v v	both MIR and PIR G only used in winter images
Dense vegetation		veg *and* *not* medium veg *and* *not* sparse veg *and* *not* dense marsh veg		
Medium vegetation		veg *and* medium veg *and* *not* medium marsh veg		
Sparse vegetation		veg *and* sparse veg *and* *not* sparse marsh veg		

Table 3: MODIS imagery classification criteria

[4] See Annex I for list of thresholds

5.2. IRS-based Seasonal Vegetation Mapping

The methodology to prepare IRS-based seasonal land cover maps is outlined in Figure 4, and detailed in Annex B. Based on an object-oriented approach, its rationale is similar to that of SLCIM, with the difference that a spectral analysis is performed prior to segmentation and classification. This additional step was necessary to decipher the spectral properties of the various themes known to occur in and around the marshes. By means of feature-space plots (Figure 5), parallel-piped class limits were defined in the various visible and infrared bands, as well as in terms of NDVI. Research is ongoing to replace parallel-piped thresholds by class limits that are closer to statistical distributions.

The four IRS images were segmented according to the criteria given in Table 4. Since the focus here was primarily on vegetation cover, the near infrared band was privileged by setting its weight to 100. The middle infrared was used to distinguish water surface from other land cover types. As this theme was the second in importance after vegetation, its weight was set to 50. The NDVI, with a very small standard deviation, was given a strong weight to be appropriately factored in the analysis. As trials showed that neither the red nor green bands were of significance to the classification, they were given a low weight.

The scale parameter[5] was set to 10 (and not less) because of computing processing limitations. The spectral information was the most important source of information for the delineation of vegetation, soil and water. Thus the weight for the geometric information ("shape") was set to 0.2, which by inference meant that the spectral "influence" for the segmentation ("colour") was set to 0.8. The smoothness criterion was privileged (0.8) over compactness because of the small influence of shape in natural morphologies.

The objects resulting from segmentation were classified following the hierarchy in Figure 16 and Figure 17, using the bands and thresholds shown in Annex B (Table B1).

A dichotomous strategy to create the class hierarchy was pursued: the first class was defined using certain bands and thresholds; the second encompassed everything excluding the first class. Using this technique, it was possible to: (a) set up a simple but structured class hierarchy and (b) avoid unclassified areas falling somewhere between classes, which would have been grouped on the same level using different features.

Finding the right thresholds for building a valuable classification was an iterative process of trial-and-error, using the feature plots generated in a previous step (Figure 4, middle panel; Figure 5). The step-by-step subdivision of classes did not necessarily follow a grouping logic, that is, a grouping of thematic classes and a separation of different but familiar sub-classes on the next level. In fact, the separation process of the analysed IRS images started at the highest level of land cover type, as that was the easiest to distinguish and separate.

When using the functionality offered by *eCognition software*, the analyst should be aware that there is no single way of (i) building a class hierarchy and (ii) using features and thresholds: .different analysts could develop different methodologies and generate similar results.

5.3. Landsat ETM-based Seasonal Vegetation Mapping

The methodology to prepare Landsat ETM-based seasonal landcover maps is outlined in Figure 6, and detailed in Annex C. It is very similar to that of IRS (see 5.2). The only image classified, from 6 May 2003, is of standard quality (prior to the SLC-off breakdown).

The image was segmented according to the same criteria used for IRS (Table 4), and then classified according to the class hierarchy of Figure 26, following the criteria of Table 6.

[5] Proportional to the size of the objects and therefore inversely proportional to their number.

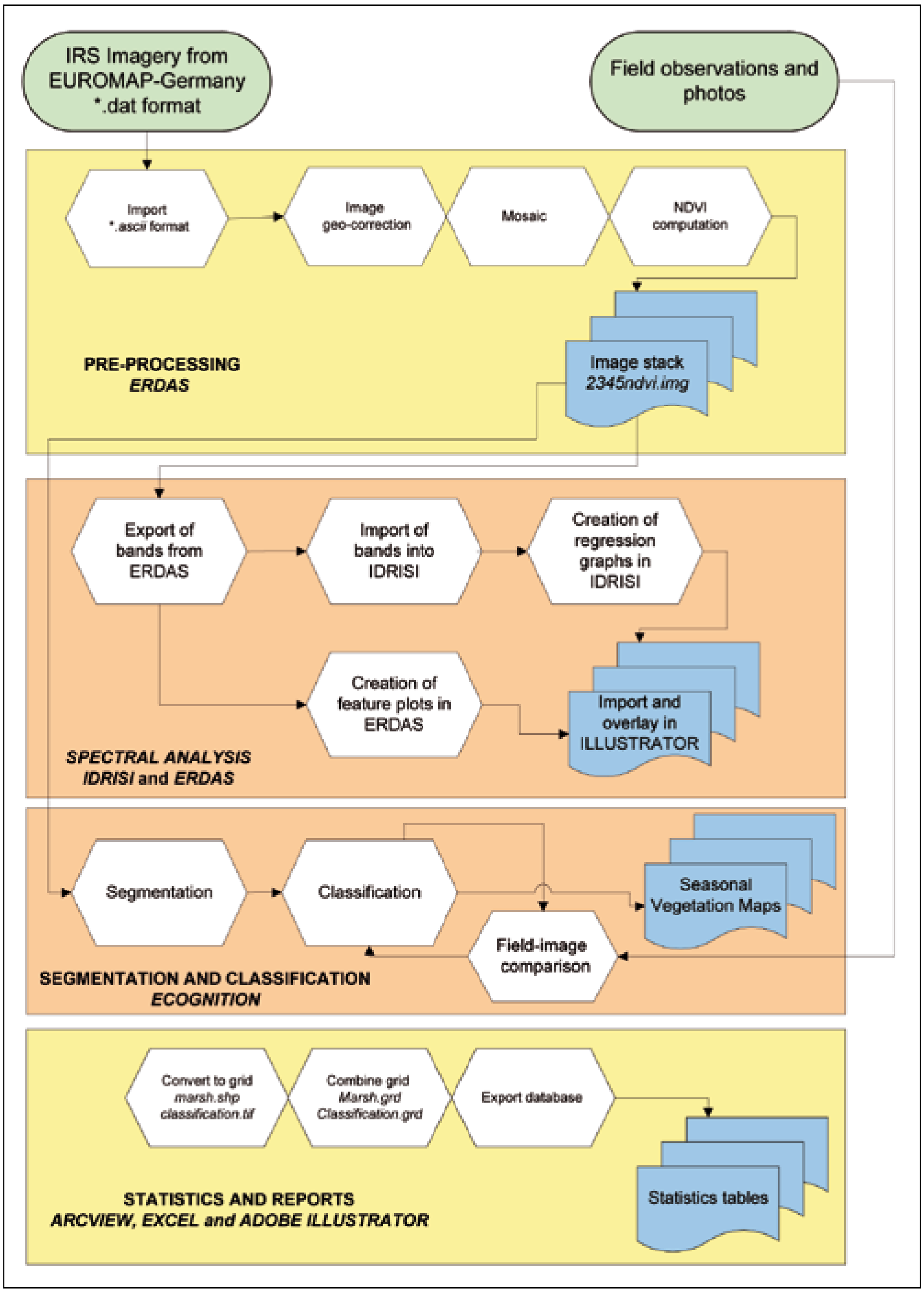


Figure 4: IRS-based SVM methodology

IRS bands	2	3	4	5	NDVI	Reason
Domain	G	R	NIR	MIR	-	Spectrally complete
Weight	1	1	100	50	100	To enhance role of vegetation
Scale	10					Computing reasons
Shape - Spectral	0.2 – 0.8					Colour information predominant
Compactness - smoothness	0.2 – 0.8					Negligible role because of small influence of shape

Table 4: IRS imagery segmentation criteria

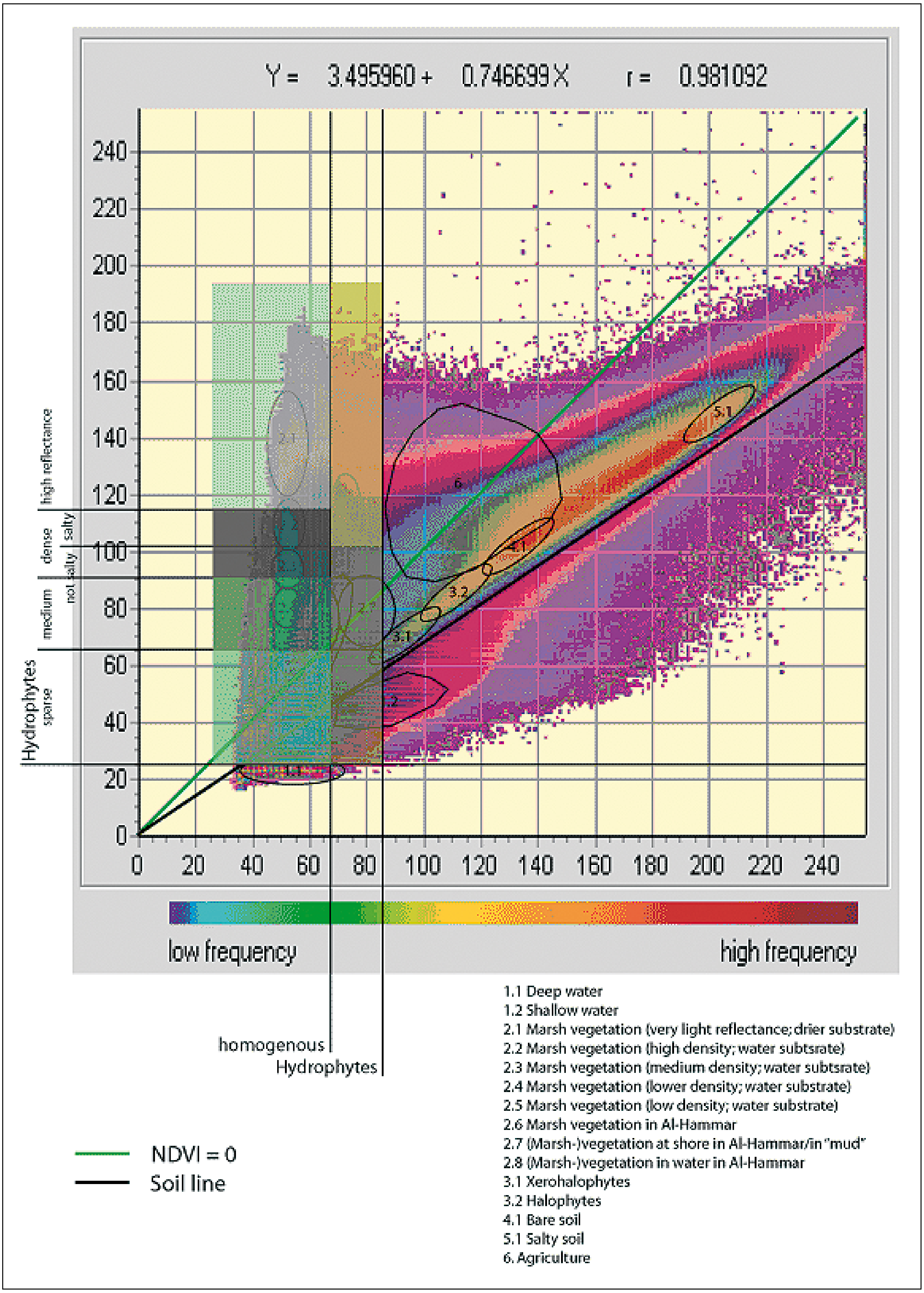


Figure 5: Position of various themes in IRS Red (horizontal) and NIR (vertical) spectral space

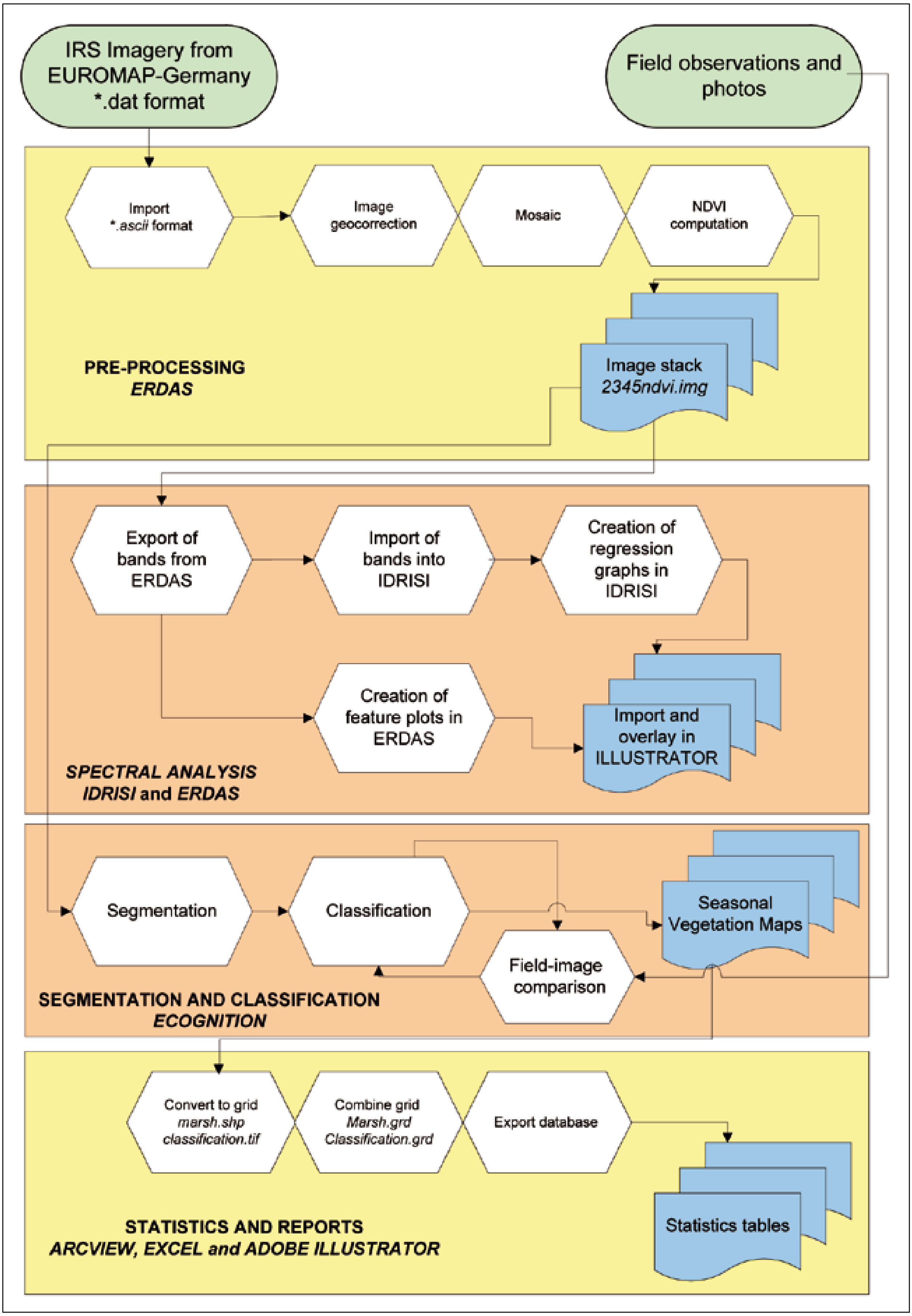


Figure 6: Landsat ETM-based SVM methodology

5.4. Landsat SLC-off based Seasonal Vegetation Mapping

The methodology to prepare Landsat ETM/SLC-off-based seasonal land cover maps is outlined in Figure 8, and detailed in Annex D. It is very similar to that of IRS (see 5.2). The classified images are from the second half of 2003, the first half of 2004, the second half of 2004 and the first half of 2005 (see Annex D for details on compositing).

On 31 May 2003, Landsat 7 experienced an anomaly which caused the Scan Line Corrector to stop functioning properly. Since then, all the ETM+ images have been collected in SLC-off mode[6]. Line scan gaps in the original images are filled in with images from other dates, which introduces artificial heterogeneities in the final product. Given that there is no alternative Landsat imagery at the moment, a methodology to produce land cover maps from SLC-off data was devised. Their quality is not expected to equal that of the other products (ETM- and IRS-based).

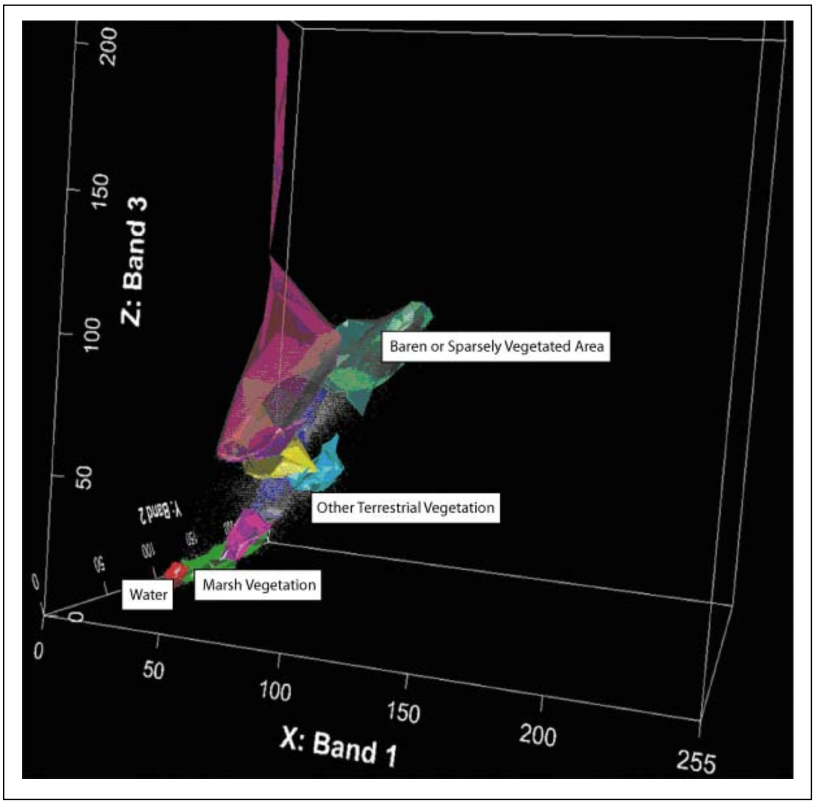


Figure 7: 3D feature space representation in PARBAT

The images were segmented according to the criteria shown in Table 5, and then classified according the class hierarchy of Figure 29, following the criteria of Table 7.

For logistical reasons, the spectral analysis was performed by the ENVI software instead of ERDAS. In addition, an improvement was introduced by using the PARBAT[7] software, which made possible the display of 3-dimensional feature spaces (Figure 7).

ETM bands	3	4	7	Reason
Domain	R	NIR	MIR2	Spectrally complete
Weight	1	1	1	To enhance role of vegetation
Scale	10			Computing reasons
Shape - Spectral	0.2 - 0.8			Colour information predominant
Compactness - smoothness	0.2 - 0.8			Negligible role because of small influence of shape

Table 5: Landsat SLC-off imagery segmentation criteria

[6] http://landsat.usgs.gov/slc_off.html

[7] http://www.parbat.net/

Sub-class 1	Sub-class 2	Sub-class 3	Sub-class 4	Sub-class 5	Sub-class 6	Criterion	Threshold
Data						Inv (not data)	
	Water					MeanMIR1	<36
		Submerged vegetation				MeanNDVI	-0.25 to -0.17
		Vegetation in Water				MeanNDVI	>-0.19
		Water without vegetation				Inv (VegetInWater) ^ Inv (WaterWithoutVeg)	
	Not water					Inv(Water)	
		Marsh				MeanMIR2	<40
			Hydrophytes			MeanRed	<46
				H Dense		MeanNDVI	>0.4
				H Medium		MeanNDVI	0.2-0.4
				H Sparse		MeanNDVI	<0.2
			Not hydrophyte			Inv(Hydrophytes)	
				Xerophytes		MeanNDVI	>-0.09
				Not vegetation		Inv(Xerophytes)	
					Marsh dry soil	MeanGreen ^ Albedo	>108 >112
					Mars wet soil	Inv(Marsh Dry Soil)	
		Not marsh				Inv(Marsh)	
			Terrestrial vegetation			MeanNDVI	>-0.07
			Bare soil			Inv(Terrestrial Veg)	
				Light/salty soil		MeanGreen ^ Albedo	>108 >112
				Red/desert soil		Inv(Light/Salty Soil)	
No data						MeanBlue ^	=0
						MeanGreen ^	=0
						MeanRed ^	=0
						MeanNIR ^	=0
						MeanMIR1 ^	=0
						MeanMIR2 ^	=0

Table 6: Landsat ETM classification criteria and thresholds **The ^ sign means "AND"**

Sub-cl. 1	Sub-cl. 2	Sub-cl. 3	Sub-cl. 4	Criterion	Threshold
Emergent marsh water (1)				Mean-Inverted NDVI^	< -0.46
				MeanRed^	< 50 (< 55)
				Agriculture Mask^	Not agriculture
	Marsh (1.1)			MeanNDVI	> -0.1
		High density (1.1.1)		MeanNDVI	> 0.2 (> 0.15)
		Intermed. dens. (1.1.2)		MeanNDVI	0.1-0.2 (0.08-0.15)
		Low density (1.1.1)		MeanNDVI	< 0.1 (< 0.08)
	Water (1.2)			MeanNDVI	< 0.1
		Deep_water (1.2.1)		MeanRed	< 52.5
		Shallow_water (1.2.2)		MeanRed^	52.5 - 78
				MeanNIR^	< 40
		Water with subm. vegetation (1.2.2)		Not deep_water (1.2.1) ^	
				Not shallow_water (1.2.2) ^	
	Water/subm. veg/marsh (1.3)			MeanNDVI	-0.1 - 0
		Low density marsh vegetation (1.3.1)		MeanRed	<- 45
		Water with subm. vegetation (1.3.2)		Not water with subm. vegetation(1.3.2)	
Marginal marsh (2)				Not emerg. marsh water(1)	
	Soil_water (2.1)			MeanNDVI	<-0.1
		Bare or sparse veget. area (2.1.2)		Not shall_water(2.1.1) ^	
				Not wet_soil(2.1.2) ^	
		Shallow_water (2.1.1)		MeanNDVI	< -0.3
		Wet_soil (2.1.2)		MeanConstRed-mIR	-0.3 - -0.2 (-0.3 – -0.15)
	Terrestrial veg (2.2)			MeanNDVI	> -0.1
		Marginal_marsh (2.2.1)		MeanConstRed-mIR	< -0.1 (< 0)
			Marginal_marsh (2.2.1.2)	Agriculture mask	Not agriculture
			Terrestrial (2.2.1.1)	Agriculture mask	Agriculture
		Terrestrial (2.2.2)		Not marg_marsh (2.2.1)	Agriculture
Soil (3)				Mean-Invert NDVI^	-0.3 - 0.8
	Bare or sparsely veget. area (3.1)			Not terrestrial(3.2)	
	Terrestrial (3.2)			MeanNDVI	> -0.1

Table 7: Landsat ETM/SLC-off classification criteria and thresholds

The ^ sign means "AND".
Inverted NDVI: -(nIR – 240 + Red) / (nIR - 240 – Red).
MeanConstantRed-mIR: (mIR + Red) / (mIR – Red).
The thresholds in black fonts are valid for the images of autumn 2003, spring 2004 and autumn 2004.
The thresholds in red are valid for spring 2005.

5.5. Field validation

The time correspondence between the classified images and the available field information (see 4.2) is shown in Table 8. There are a number of good matches for MODIS in 2005. IRS images, too, coincide closely or approximately with field observations. In addition there is an approximate match for the May SLC-off image.

When available, the field information was included in the classification process by means of a visual comparison, as indicated in the flowcharts of Figure 4, Figure 6 and Figure 8.

Year	Period	Field data	Classified imagery			
			MODIS	IRS	ETM	SLC-off
2003	Spring		X		06.05.03	
	Summer		X			
	Autumn		X			
2004	Winter		X			
	Spring		X			
	Summer		X			
	Autumn		X			
2005	January	Iran (Azadegan)	X			
	February	Iran (Azadegan)	X			
	March		X			
	April	Iraq	X			
	May		X			xxx
	June	Iraq	X	15.06.05		?
	July		X			?
	August		X	22.08.05		?
	September	Iraq	X	22.09.05		?
	October		X	09.10.05		?
	November	Iran, Iraq?	X			?
	December		x			?
						?

Table 8: Correspondence between field data and imagery

Yellow indicates a close match; green indicates an approximate match.

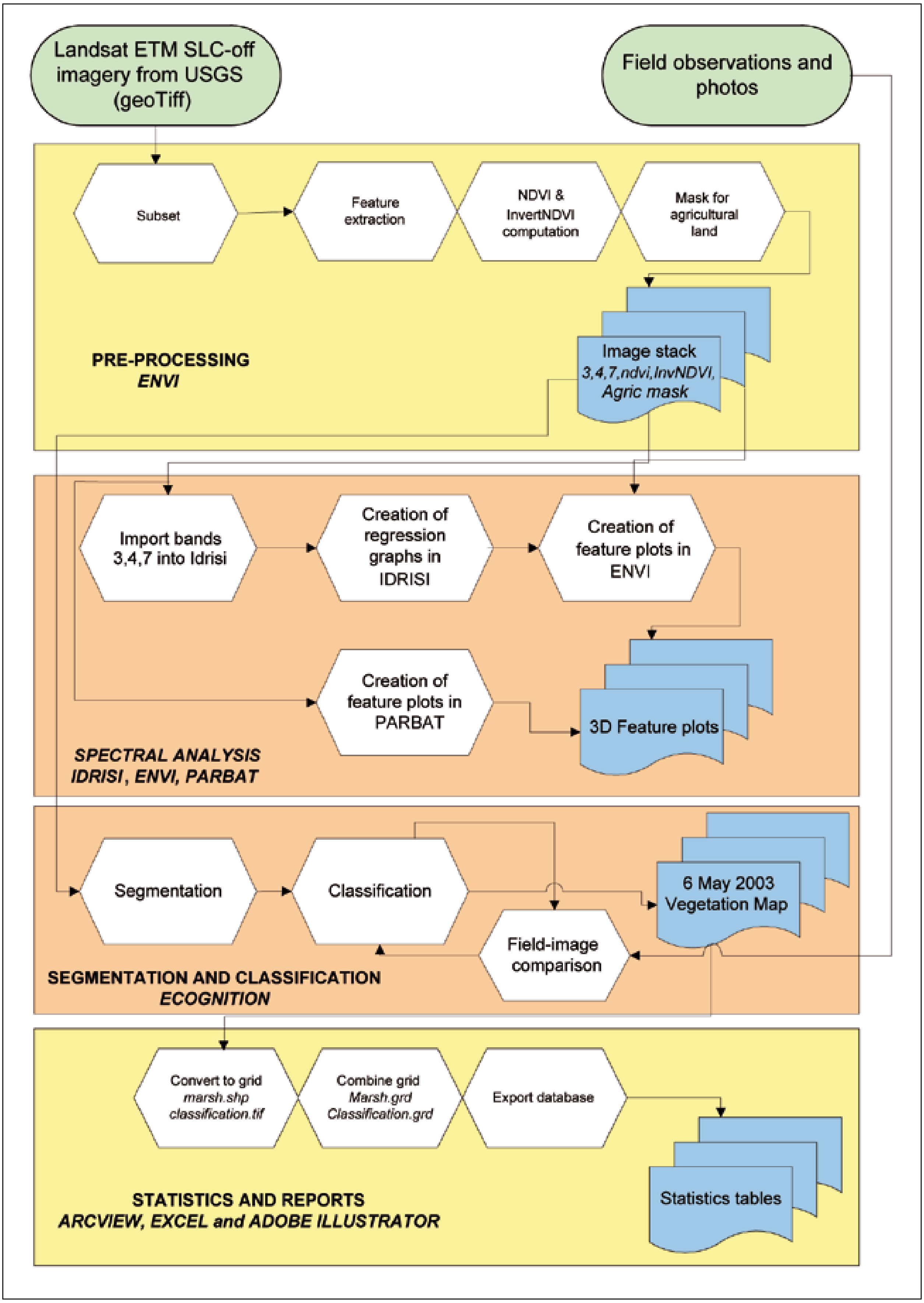


Figure 8: Landsat SLC-off-based SVM methodology

5.6. Website

The backbone of the website is a **Content Management System** (CMS), a computer software system for organizing and facilitating collaborative creation of documents and other content. The content provider thus does not need extensive programming knowledge to insert information into the website. The CMS used in this project is *XOOPS* (http://www.xoops.org/), a widely used and highly modular system written in PHP. We strongly encourage reading the *XOOPS* manual to better understand the system, its functionality and customization.

The CMS was set up on a Linux server, but it can run on other systems as well (Windows/Macintosh OS). It needs an Apache web server and MySQL database to function properly. As limited computer processing is needed, the server operates relatively well.

Another component of the website, which is external to the CMS, is the Internet Map Server (IMS). The IMS enables easy and efficient access, display and download of satellite data and GIS data layers (e.g. zoom, pan, scale, coordinates, etc). In order to display the satellite images, the Minnesota MapServer engine (open source) was installed. A technical description of the IMOS website is included in Annex E, and the main page layout is shown in Figure 9.

The IMOS website has been loaded with the relevant map and satellite data sets and is now fully functional. It is updated at regular intervals with weekly products, and has been the principal means of disseminating findings to the Iraqi authorities and other partners.

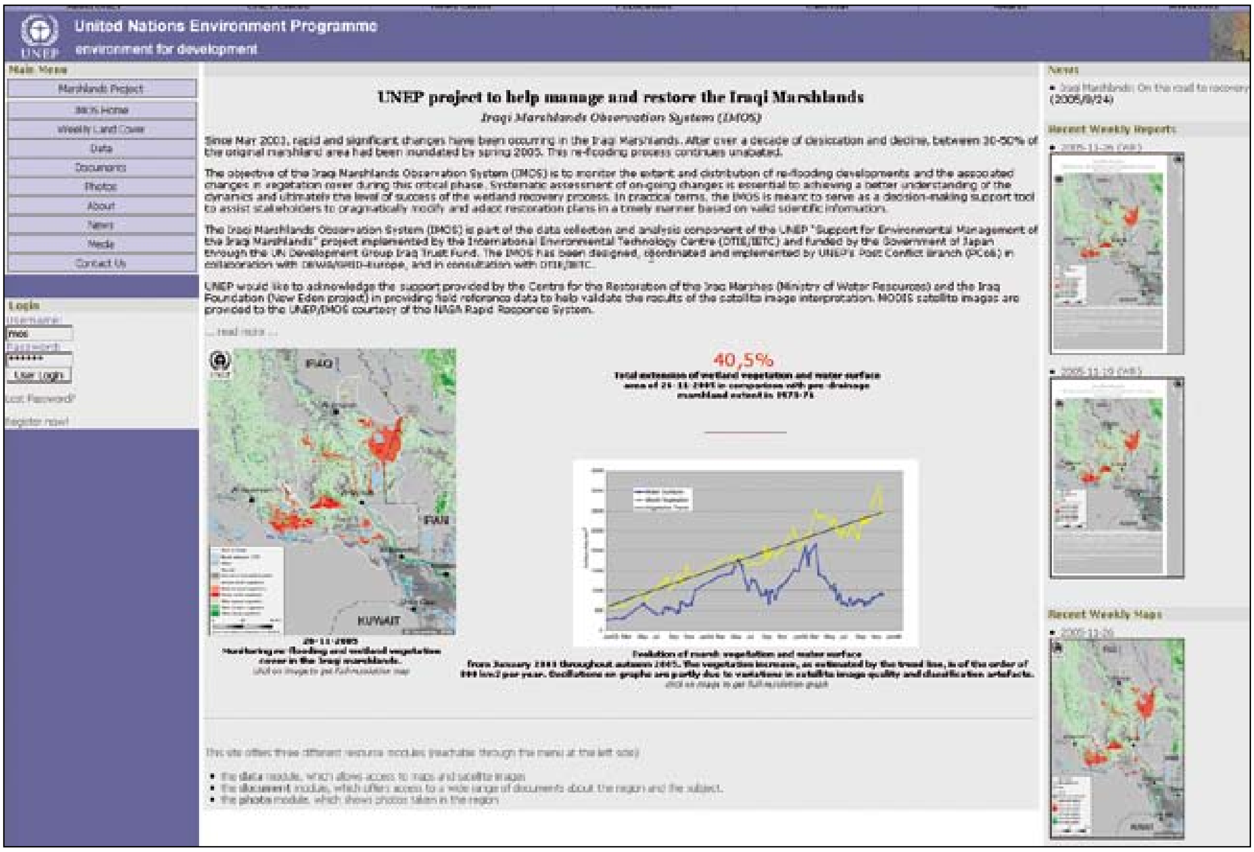


Figure 9: IMOS website main page

6. Outputs

6.1. Simplified Land Cover and Inundation Maps

A total of 94 simplified land cover and inundation maps were produced, at an approximate bi-weekly frequency in 2003-2004, and weekly in 2005 (depending on atmospheric conditions and image quality). The classified maps were incorporated in 83 reports, which included statistical analysis of water and marsh vegetation surfaces and Normalized Difference Vegetation Index (NDVI) time series. These reports are available on the IMOS website[8], and are compiled in Annex F.

6.1.1. Land cover themes definition

The class hierarchy derived from eCognition classification is illustrated in Figure 10, and its interpretation demonstrated in Table 9. Figure 11 (p.36) shows a standard map product. The water and soil themes are globally reliable, even though the distinction between darker/dry soils and wet soils should be further improved.

Vegetation could only be classified following spectral criteria, because contextual or textural information was not readily discernible at the MODIS resolution of 250-500 m. Hence, the marsh vegetation theme was restricted to easily distinguishable green hydrophytes (essentially Phragmites and Typha). Sub-themes were defined on the basis of marshland vegetation density, combined with the degree of appearance of water between the reed stands (visible on IRS imagery; see Figure 19).

The “other vegetation” class represents the terrestrial vegetation sensu stricto, such as grasslands, shrubs, trees and agriculture, as well as marginal marsh vegetation, such as halophytes and xero-halophytes. These last categories are known to exist at least in the Iranian part of the marshlands (Hawr Al-Azim), where they have been mapped in situ (Inpex, 2005).

[8] http://imos.grid.unep.ch/

Adjusted thresholds for classification criteria are given in each weekly report (see Table 10 for an example).

This classification scheme is satisfactory when the reeds are in a vegetative stage (green). During the winter season, the perennial reeds go into dormancy and become dry (brown), making their spectral identification on images difficult. Hence, it is possible that part of the dry reed beds were mapped as soil, so that the winter decrease in marsh vegetation could be an artefact (Figure 12, top, January 2005).

6.1.2. Surface statistics and trends

The chronological evolution of surface area for the following elements is presented in the weekly reports (Annex F):

- Marsh vegetation: per marshland unit (Al-Hammar, Al-Qurnah, Al-Hawizeh) and for all marshes;
- Water surfaces: per marshland unit (Al-Hammar, Al-Qurnah, Al-Hawizeh) and for all marshes;
- Total marsh extension (= vegetation + water).

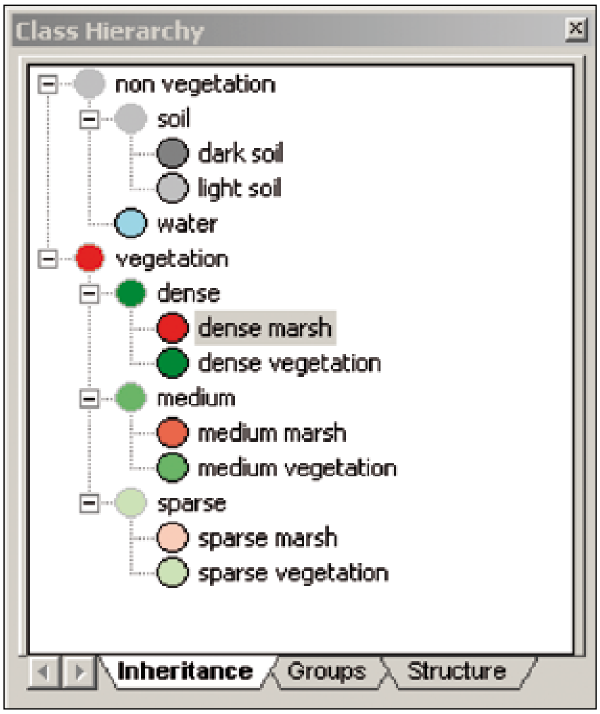


Figure 10: Class hierarchy of MODIS classification

Theme	Sub-theme	Interpretation	Comments
Water		All types	Trustworthy
Soil	Dark soil	Dark soil *sensu stricto* or wet soil	Wet soil in depressions or close to water bodies
	Light soil	Desert soil and sand	
Marsh vegetation	Sparse MV	*Phragmites* and *Typha* of varying density and degree of mixing with water	Green hydrophytes only. Does not include dry reeds, halophytes and xero-halophytes
	Medium MV		
	Dense MV		
Other vegetation	Sparse OV	Terrestrial vegetation of varying types and density, plus marginal marsh vegetation (halophytes, xero-halophytes)	Agriculture generally corresponds to dense OV
	Medium OV		
	Dense OV		

Table 9: SLCI maps themes (legend)

Class	Criterion threshold
Non-vegetation	NDVI < 0.125
Water	MIR < 500
Soil	MIR > 500
Dry soil	Red > 2000
Wet soil or very shallow water	Red < 2000
Vegetation	NDVI > 0.125
Sparse vegetation	NDVI < 0.25
Medium vegetation	0.25 < NDVI < 0.50
Dense	NDVI > 0.50
Marsh vegetation	Albedo < 800 and MIR < 1200 and NIR < 3050

Table 10: SLCIM adjustable classification criteria (example of situation on 26.11.05)

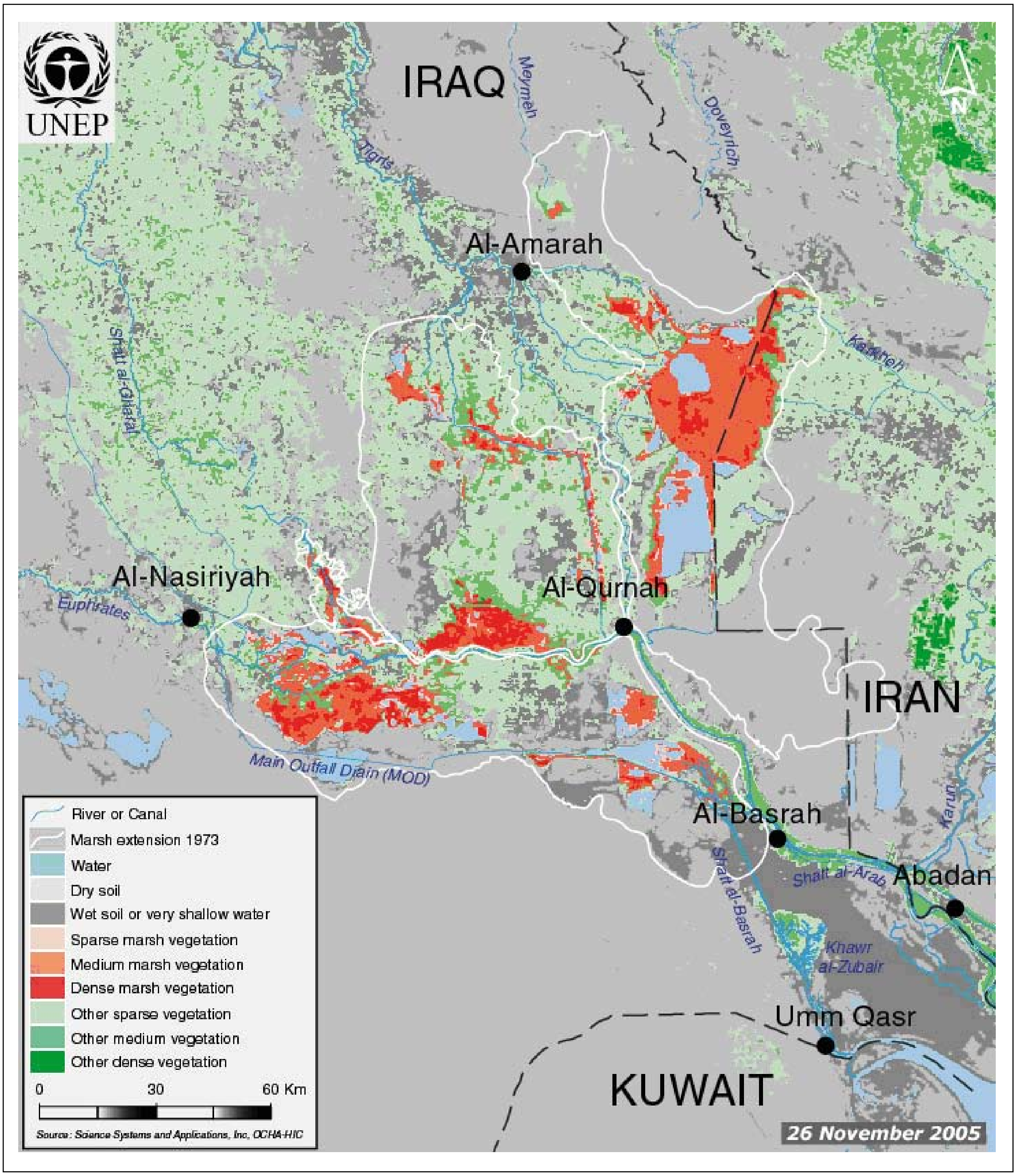
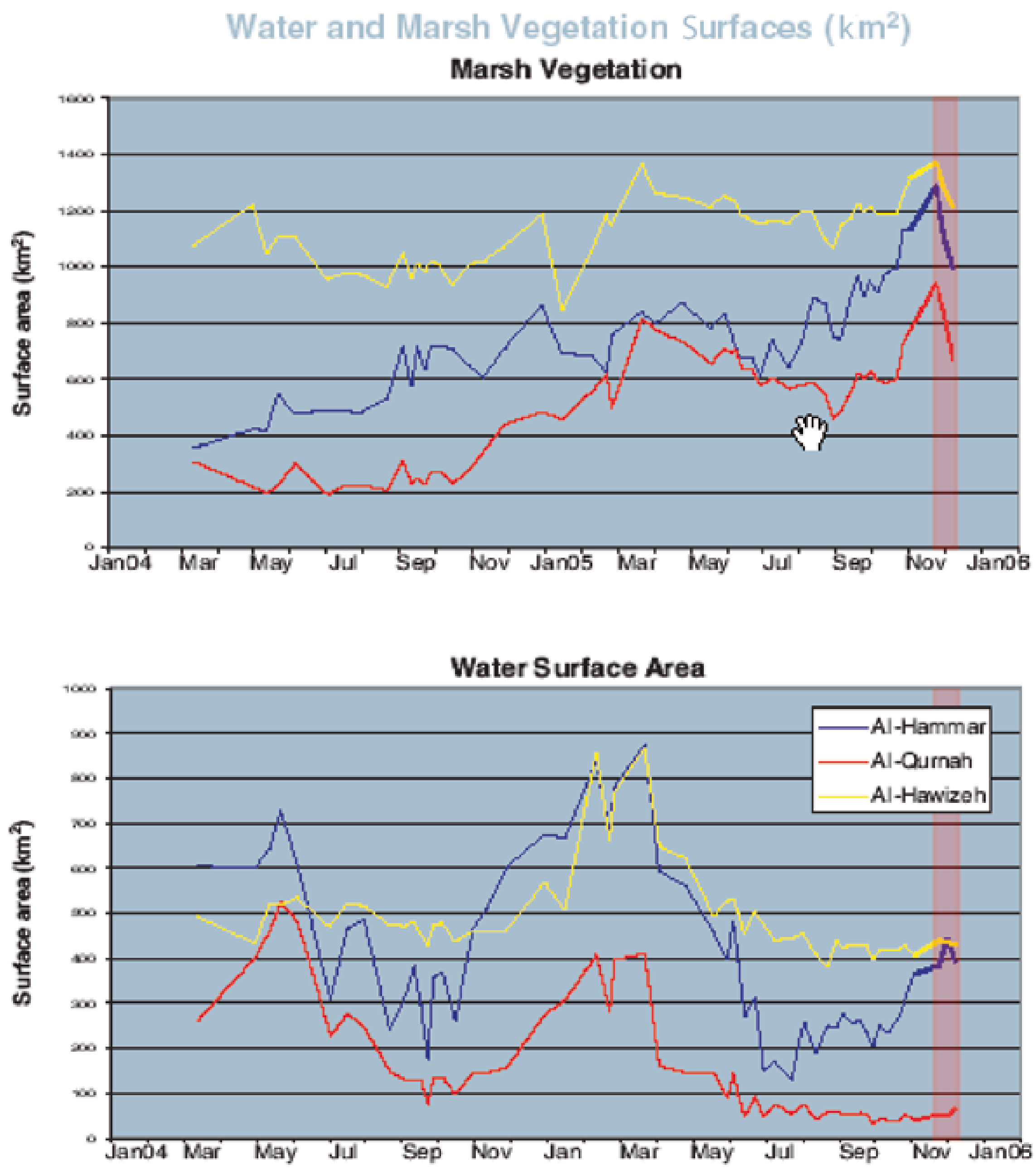


Figure 11: SLCI maps for 26 November 2005



Land cover	Water		Marsh vegetation		Marsh Ext. (Water + Veg.)		Potential extension
26/11/05	km^2	%*	km^2	%*	km^2	%*	km^2
Al-Hammar	394	8	999	20	1393	28	4951
Al-Qurnah	65	1	676	14	741	15	4840
Al-Hawizeh*	431	7	1218	20	1649	28	5947
Total	890	6	2893	18	3783	24	15738

** as % of potential extension*

** Al Hawizeh marsh: includes the Iranian extension where it is known as Hawr Al-Azim*

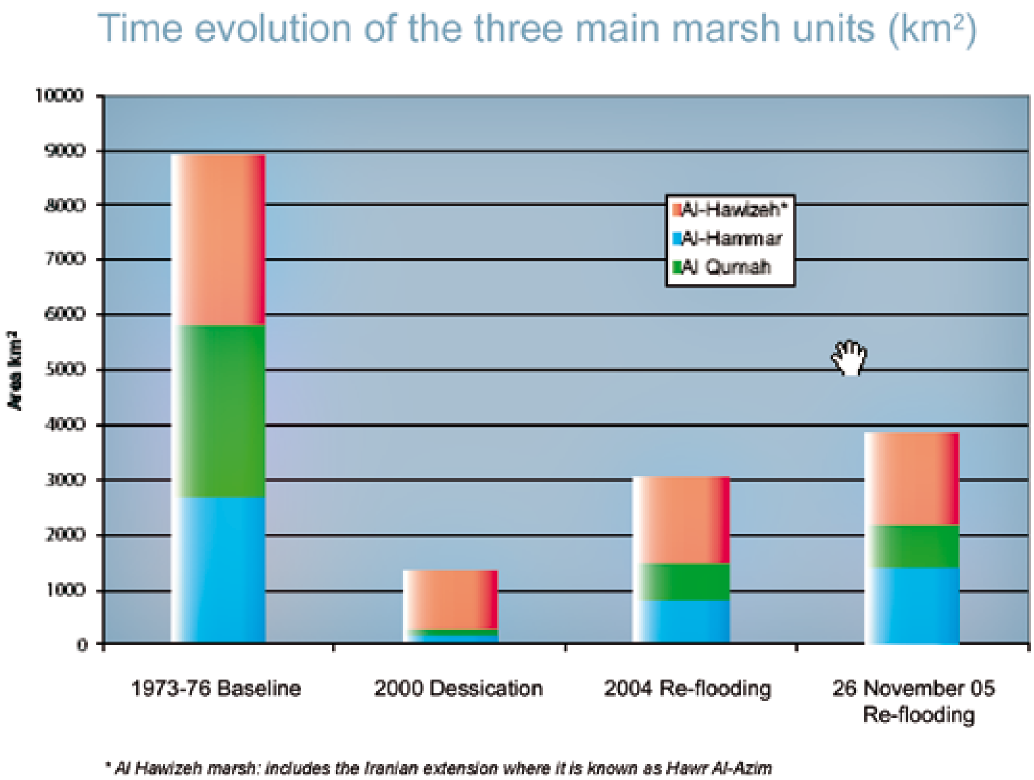
Figure 12: Water and marsh vegetation surface statistics

An example of the statistical analysis is shown in Figure 12. A temporal comparison between the 1973-76 baseline, the 2000 desiccation, the 2004 re-flooding and recent marsh extension is shown in Figure 13.

To gain a better understanding of the general vegetation evolution, the NDVI was monitored over time in a number of representative areas (marshes, agriculture, desert, palm trees), as shown in Figure 14.

Finally, Figure 15 is a compilation of the overall evolution of marshland vegetation and water surfaces between 2003 and 2005. The vegetation surface graph exhibits irregularities of the order of 100-300 km^2. Likewise, the irregularities of the water surface graph reach an amplitude of 500 km^2, superimposed on a clear seasonal periodicity.

A linear trend line was manually adjusted on the vegetation graph. It clearly shows a steady increase of marshland extent (from 500 km^2 in early 2003 to 3,000 km^2 at the end of 2005).



Marshland (Vegetation + Water)	Baseline 1973-76	Dessication 2000		Re-flooding 2004		Re-flooding 26-11-05	
	km^2	km^2	%*	km^2	%*	km^2	%*
Al-Hammar	2729	174	6	824	30	1393	51
Al-Qurnah	3121	98	3	654	21	741	24
Al-Hawizeh/Al-Azim	3076	1084	35	1540	50	1649	54
Total	*8926*	*1356*	*15*	*3018*	*34*	*3783*	*42*

** as % of baseline 1973-76*

Figure 13: Comparison between the 1973-76 baseline, the 2000 desiccation, the 2004 start of the re-flooding and the latest marsh extension (26 November 2005)

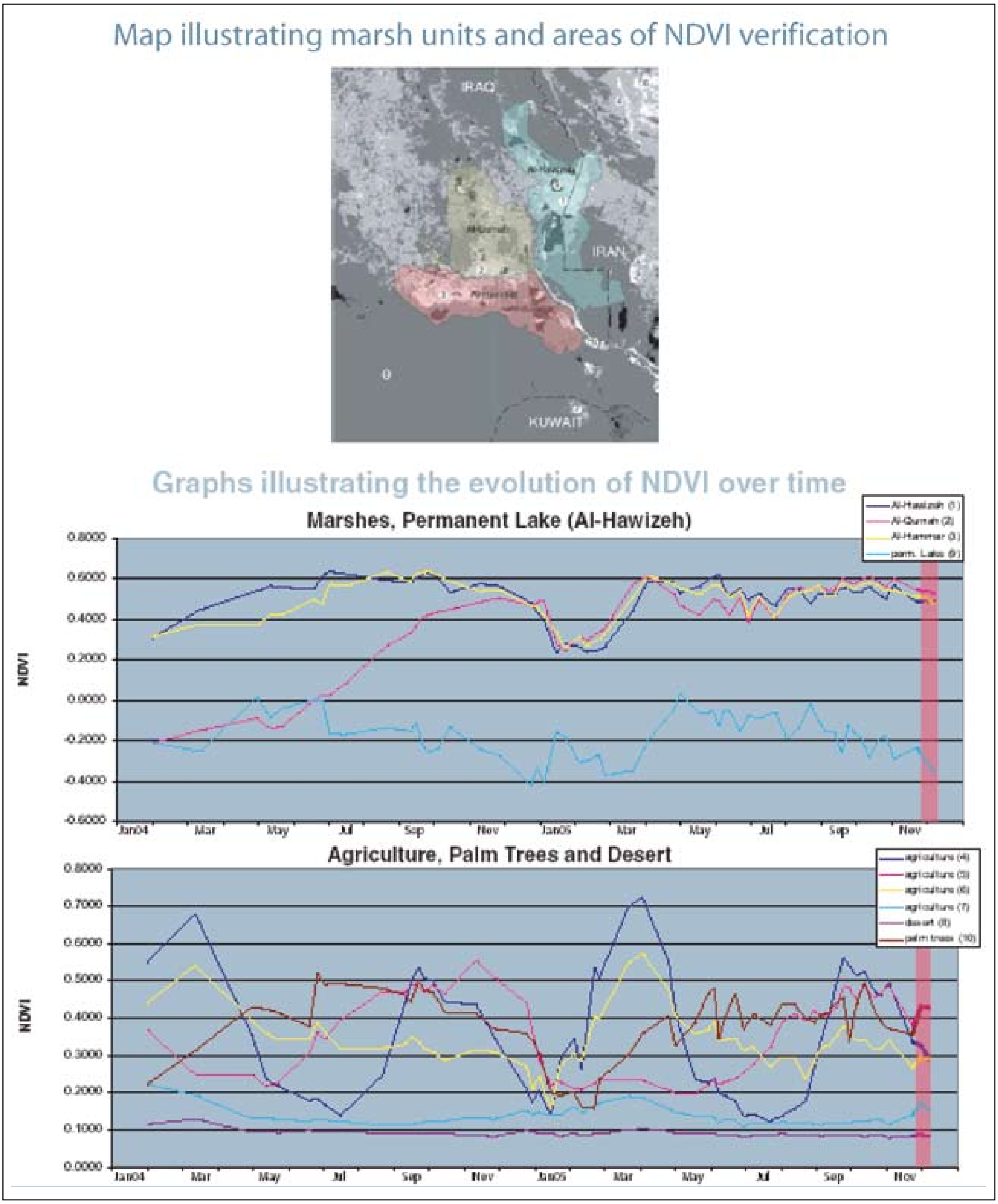


Figure 14: Evolution of NDVI over time

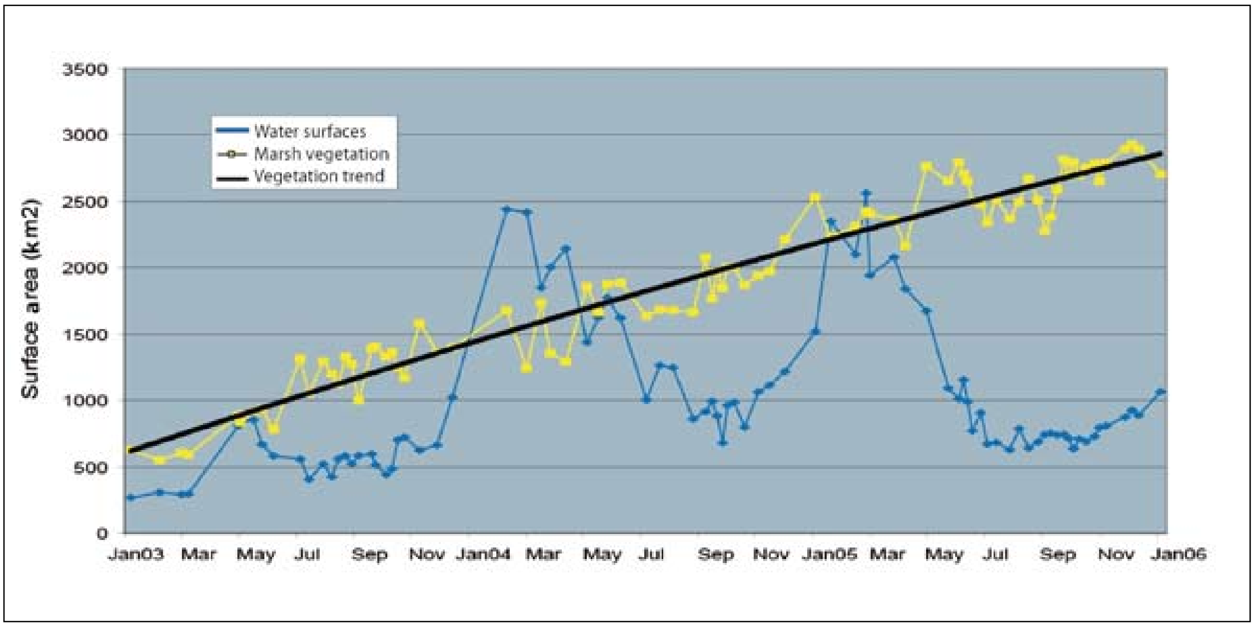


Figure 15: Progress of marshlands recovery between 2003 and 2005

6.2. IRS-based Seasonal Vegetation Maps

Medium resolution land cover maps were produced by the classification of IRS images on the following dates:

15.06.05: eastern path (067/048+067/049);
22.08.05: western path (066/048+066/049);
20.09.05: eastern path;
09.10.05: western path (floating scene).

Due to the time difference in satellite image capture between the paths, mosaicking was not attempted, and four separate maps were produced (Figure 20-Figure 23).

6.2.1. Land cover themes definition

The class hierarchies derived from *eCognition* classification are shown in Figure 16 and Figure 17. They are similar, with the exception of the "hydrophytes with less water" sub-class that was only distinguishable in June 2005. The first step was to separate water from the rest of the image. Repeated trials were made to distinguish "real" water surfaces from other land cover themes. Particularly complex was the classification of the "water with vegetation" sub-class under the "hydrophytes" or "water" class. By varying parameters and thresholds, it was concluded that optimum separation was to include the "water with vegetation" sub-class in the water class, and to separate both types in the next step, using NDVI as the functional criterion (Table B1, Annex B).

The justification for the two slightly different class hierarchies between June 2005 and the other months stems from the two different red – NIR feature plots depicted in Figure 18: only the June image shows a distinct population in the feature plot, shifted slightly towards higher Red values than the usual hydrophytic vegetation. This class, called "hydrophytes with less water", is found almost only in the western part of Al-Hammar (Figure 19). It is suspected that this difference is due to the fact that the vegetation in this region is dominated by Typha as opposed to Phragmites.

On the 15 June 2005 IRS image (Figure 20), a bright green vegetation signature is visible, especially at the north-eastern edge of Al-Hawizeh in Iran (Hawr Al-Azim). This signature is most likely due to the fact that vegetation in this region is denser and grows on more elevated and relatively "drier" land. The bright green signature seems to occur only in the May image, as the August image does not show this condition. These feature characteristics can clearly be distinguished from other hydrophytes, not only on the satellite image but also on the feature plot (Figure 19, top). They occupy the same range of red values as the other *Phragmites* classes, which were confirmed by preliminary field observations. Available field data validates the postulation made, but further ground-truthing is required to verify and establish the causes of observed variations.

Due to variations in atmospheric conditions, the criteria to classify objects into the classes indicated on Figure 16 and Figure 17 had to be interactively changed by the analyst, as indicated in Table B1 in Annex B.

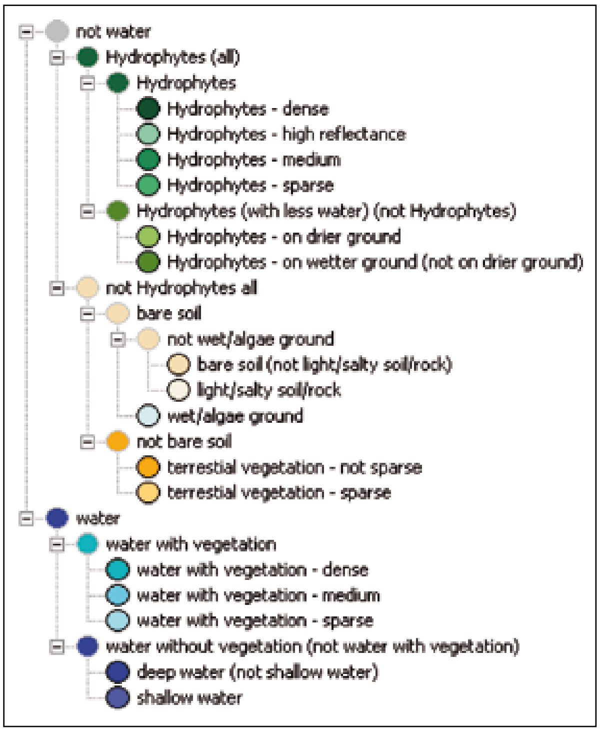


Figure 16: IRS-based class hierarchy for 15-06-2005

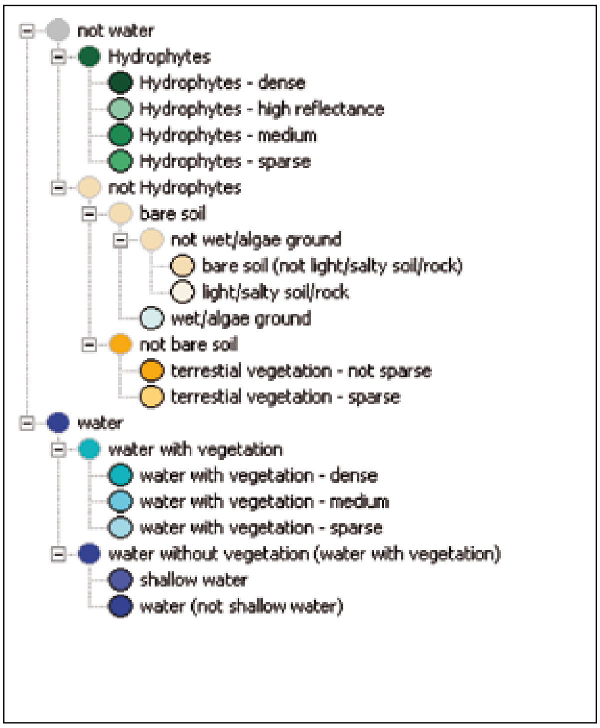


Figure 17: IRS-based class hierarchy for all other dates

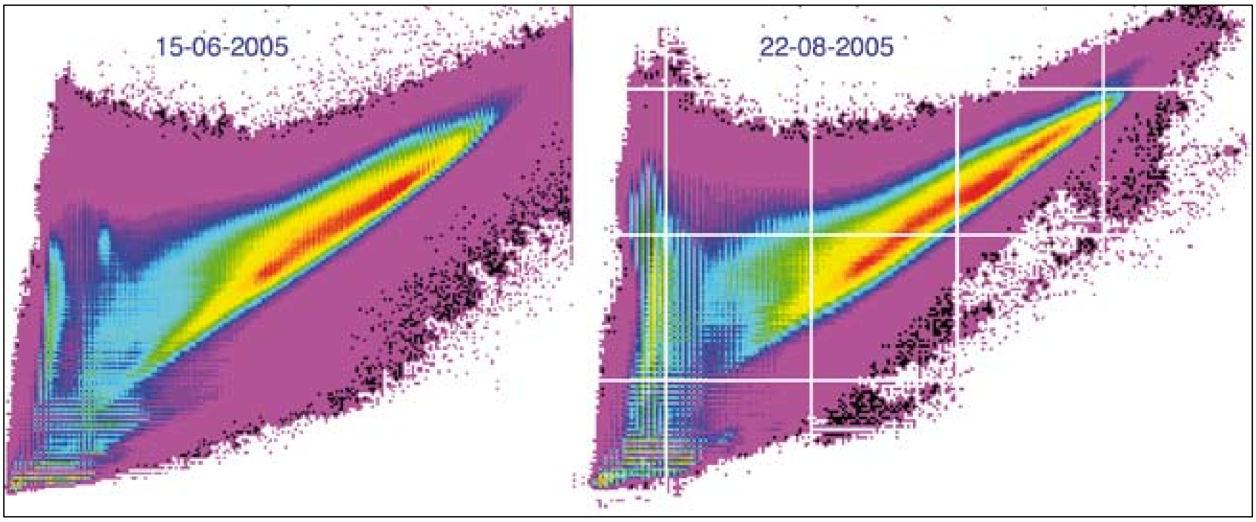


Figure 18: Red – NIR feature space plots of IRS images of 15.06.05 (left) and 22.08.05 (right). The rectangle represents the "Hydrophytes with less water"

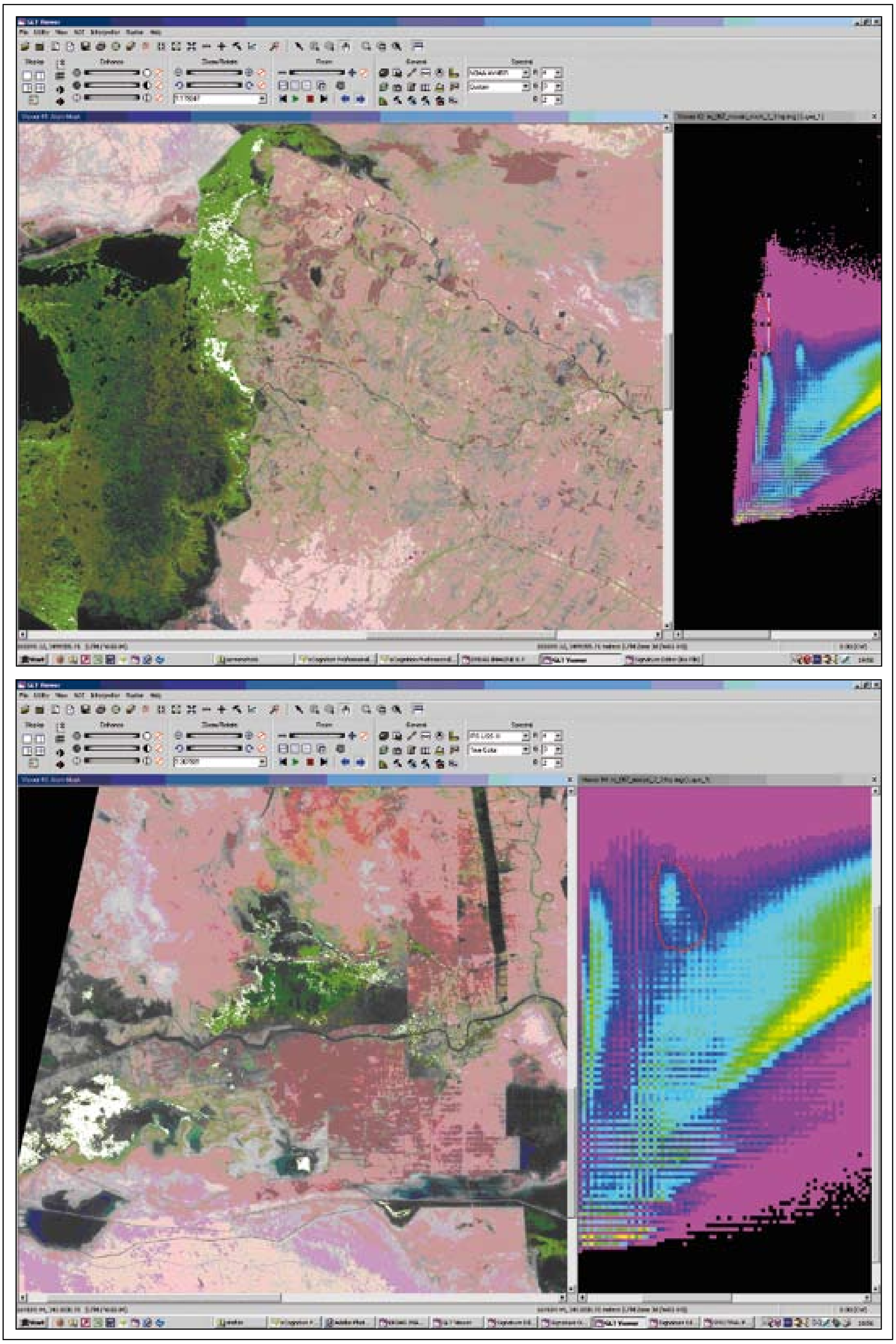


Figure 19: Red – NIR feature space plots of IRS images of 15.06.05 in Al-Hawizeh (top) and 22.08.05 in Al-Qurnah (bottom). Red ellipses indicate "High reflectance hydrophytes" (top) and "Hydrophytes with less water" (bottom)

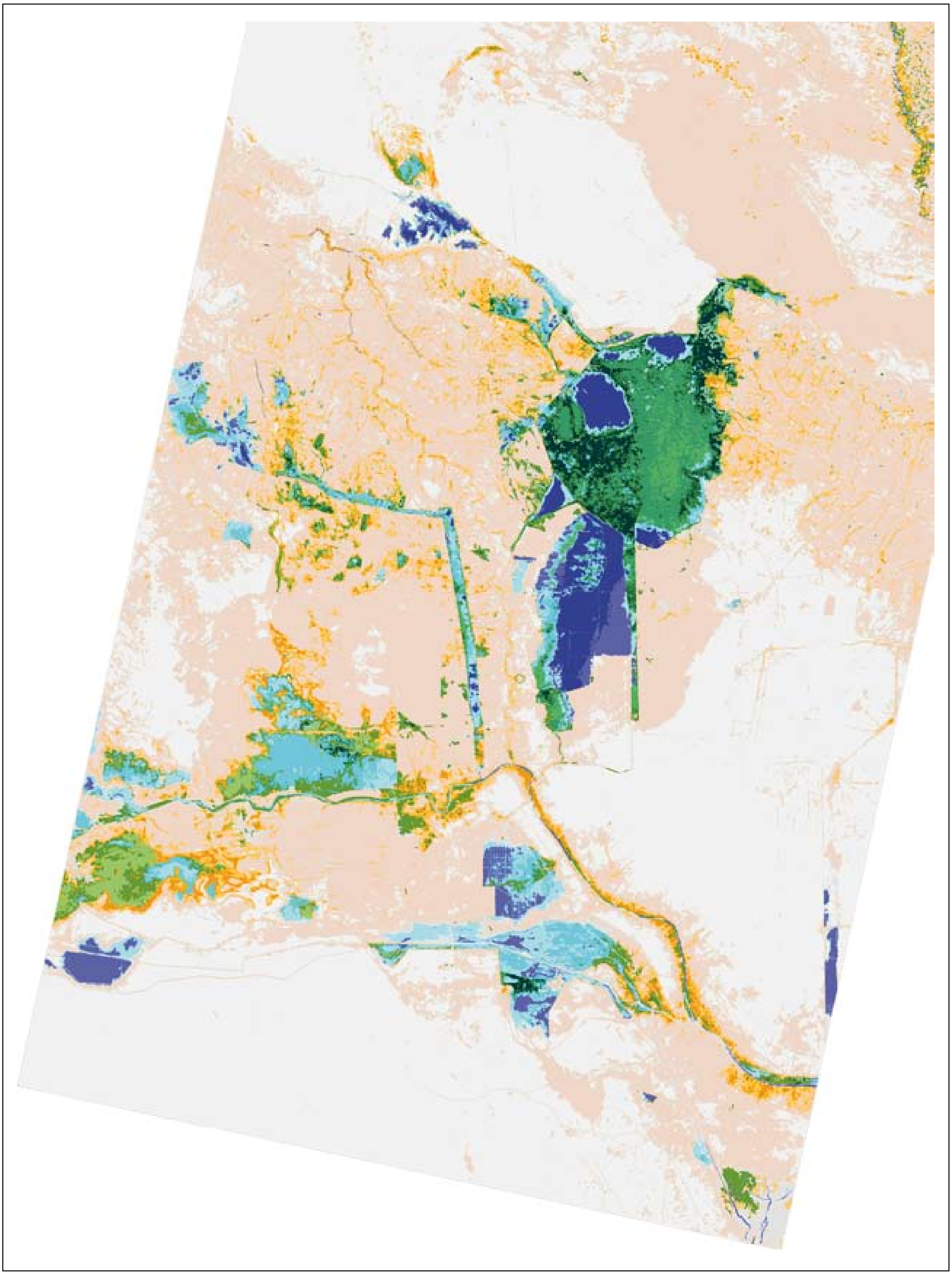


Figure 20: IRS-based SVC map. Eastern path: 15.06.2005. See Fig. 16 for legend

A general interpretation of the themes is given in Table 11. Since the objective of the IMOS was to map the extension of marshland vegetation and water, less emphasis was put on a detailed definition and separation of dryland vegetation. This would have been methodologically difficult to achieve. Indeed, separating agriculture from other types of terrestrial vegetation (particularly during the summer season when the IRS image was taken) is almost impossible, because their spectral signatures are undistinguishable. This lack of a distinct agricultural signature is probably owed to the fact that IRS images were taken when most fields had already been harvested. They were thus interpreted as bare soil or sparse vegetation. A shapefile delineating known agricultural areas would help improve the classification.

The distinction of dryland vegetation (xero-halophytes, halophytes) was further complicated by varying degrees of dryness: the spectral signatures of dry vegetation at different density stages and that of almost dry soil were also very difficult to distinguish. To produce a map with halophytes and xero-halophytes, the Pandam team (Inpex, 2005) had to carry out extensive field-work. Under these conditions, only a separation between "sparse" and "not sparse" terrestrial vegetation has been made.

6.2.2. IRS-based seasonal maps and statistics

Land cover maps for June, August, September and October of 2005 are shown in Figure 20-23. Discernible changes in marshland vegetation cover are visible, particularly in Al-Hammar. In June (Figure 20), there are large tracts of "hydrophytes with less water": this is vegetation with reduced water content (*i.e.*, drier) and/or growing on drier ground. A significant change can be observed in the September image (Figure 22), where the vegetation of the western Al-Hammar marshes is similar to the hydrophytic vegetation of Al-Hawizeh. Water supply in the western marshes varies considerably. During the period under observation, certain areas show a clear decrease in water surface, while others reveal the opposite. This is most likely due to significant regulation of water flows by human activities.

Theme	Sub-theme	Interpretation	Comments
Water			Generally trustworthy
	Vegetation in water - sparse		
	Vegetation in water – medium		
	Vegetation in water – dense		
	Deep water		
	Shallow water		
Hydrophytes		Difference either by amount of water penetrating the vegetation or by height of reeds?	
	- sparse		
	- medium		
	- dense		
	- high reflectance	Very luminant/light green colour especially at the eastern edges of Al-Hawizeh. Distinctly different from the rest.	High density reed beds in low standing water
	- on drier ground A	Different red values as the other Hydrophytes. Limited to Al-Qurnah.	Probably more Typha
	- on drier ground B	Different red values as the other Hydrophytes. Limited to Al-Qurnah.	Probably more Typha
Bare soil			
	Salty soil		
	Other soil		
Terrestrial vegetation		No way to distinguish dryland and agricultural vegetation.	
	- sparse	Very low density of vegetation. Halophytes, dried out other vegetation.	
	- not sparse	Denser, but not "dense" vegetation. Darker in colour.	
	Wet/algae ground	"Dry" riverbeds, small zones of ponds/pools	

Table 11: Landsat IRS imagery classification interpretation

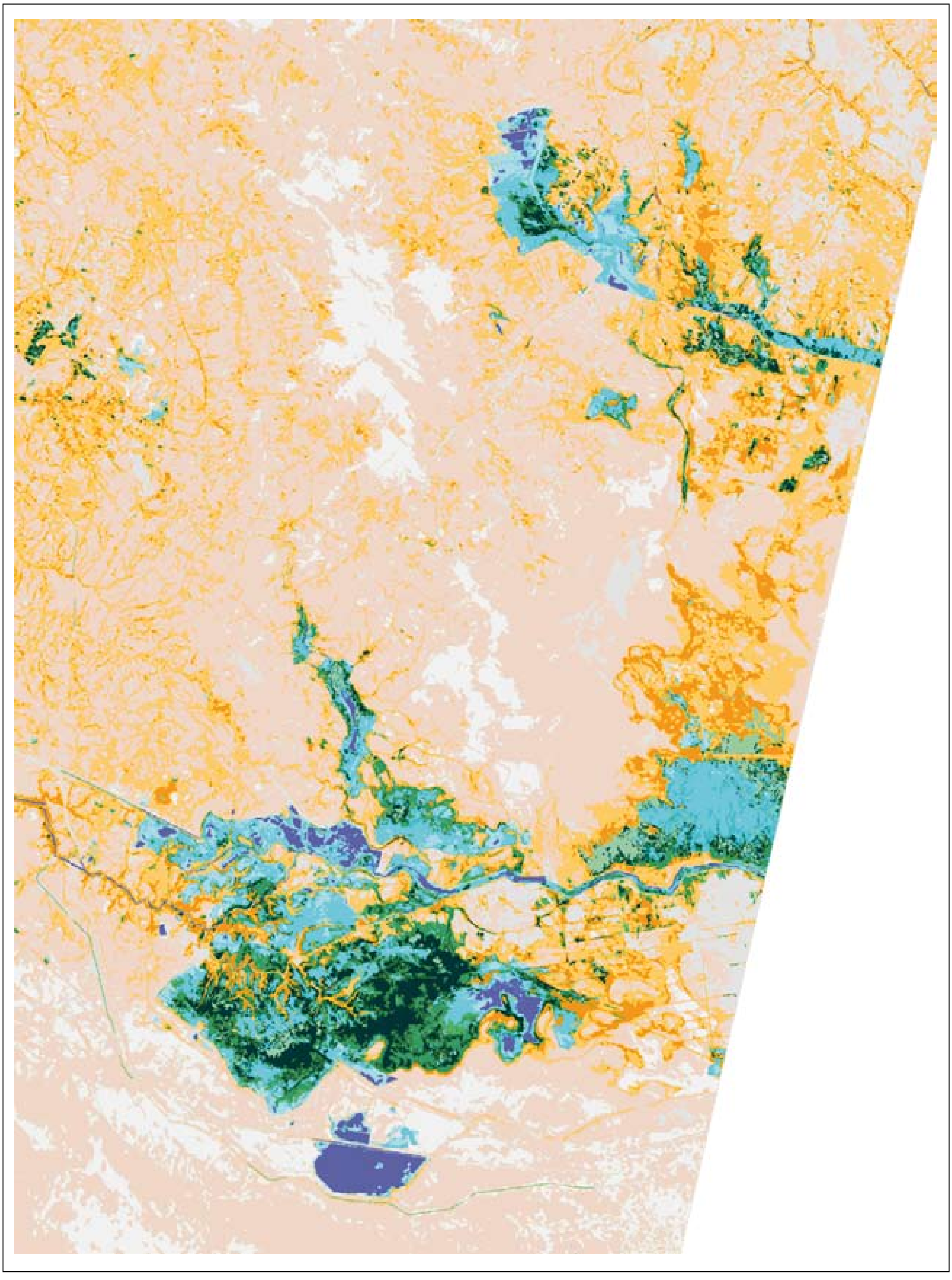


Figure 21: IRS-based SVC map. Western path: 22.08.05. See Figure 17 for legend. Zoom factor bigger than in Figure 20

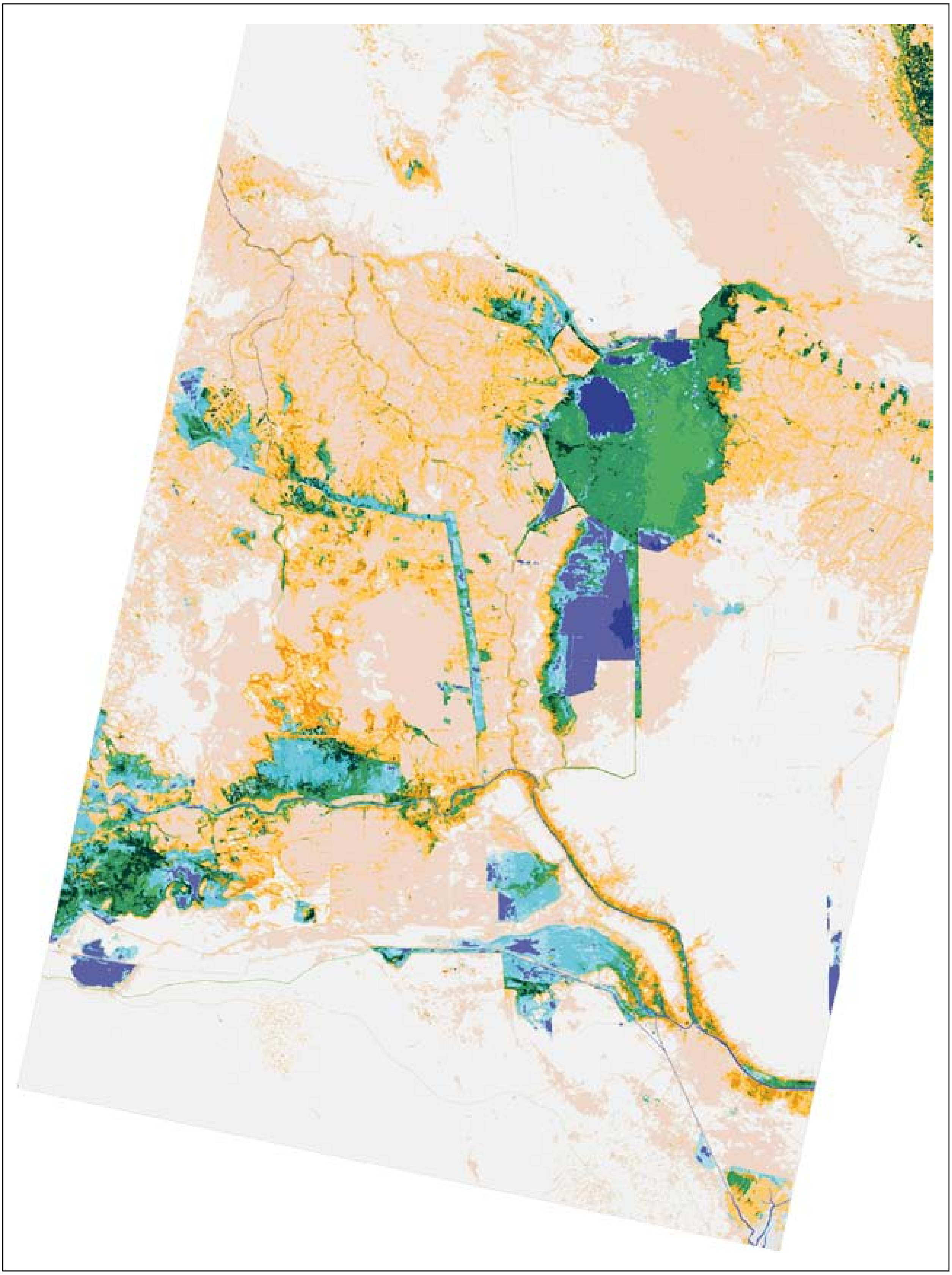


Figure 22: IRS-based SVC map. Eastern path: 20.09.2005. See Fig. 17 for legend

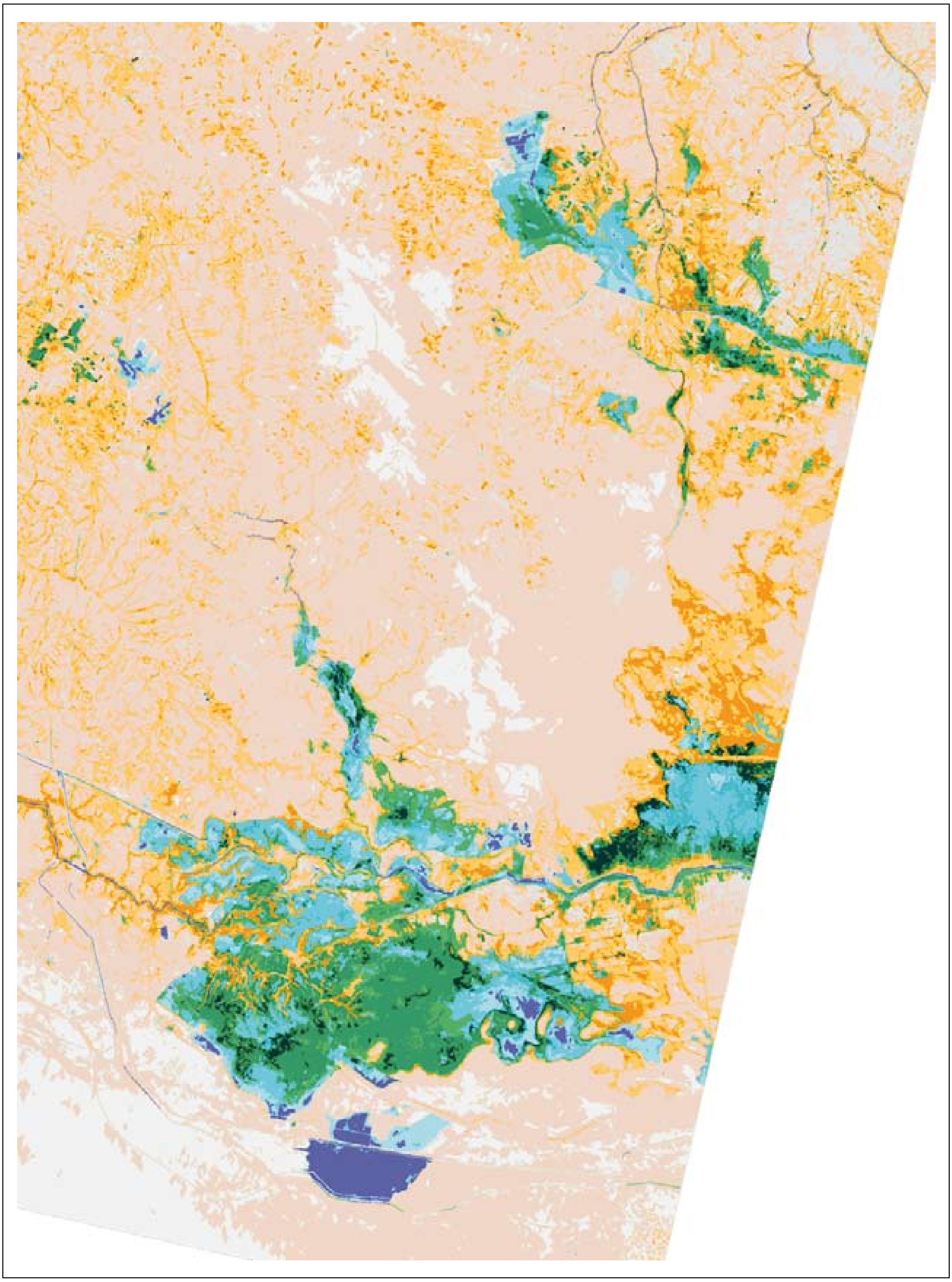


Figure 23: IRS-based SVC map. Western path: 09.10.2005. See Fig. 17 for legend. Zoom factor bigger than in Figure 20

Areal statistics evolution is summarized in Figure 24. Both the marsh and terrestrial vegetation surface areas increase between June and September. A comparison with MODIS estimates (Figure 25) reveals similar results for water. For hydrophytes, the larger surface area measured by MODIS can be explained by the inclusion of marginal objects at the edge of the reed beds.

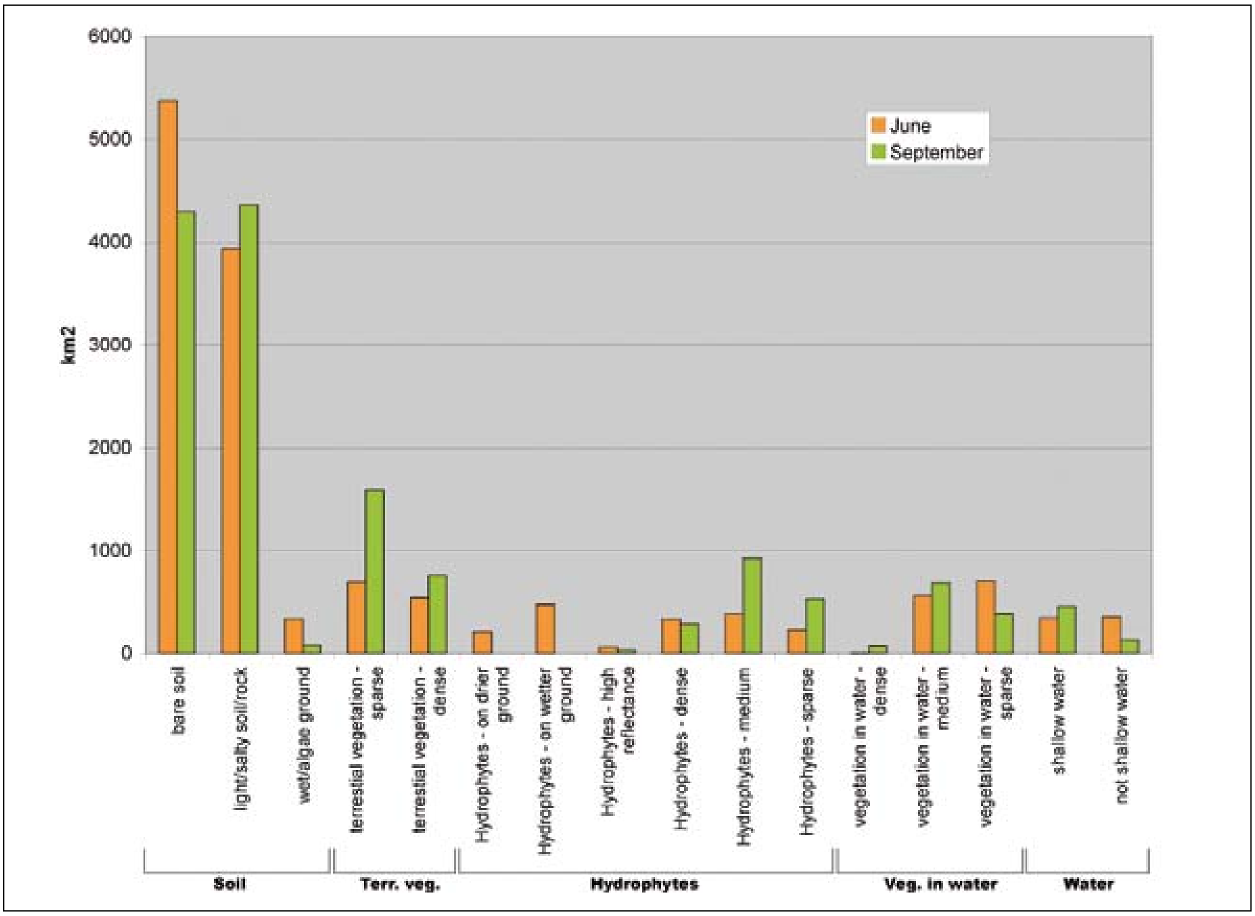


Figure 24: Evolution of the IRS-based land cover in the marshes between June and September 2005

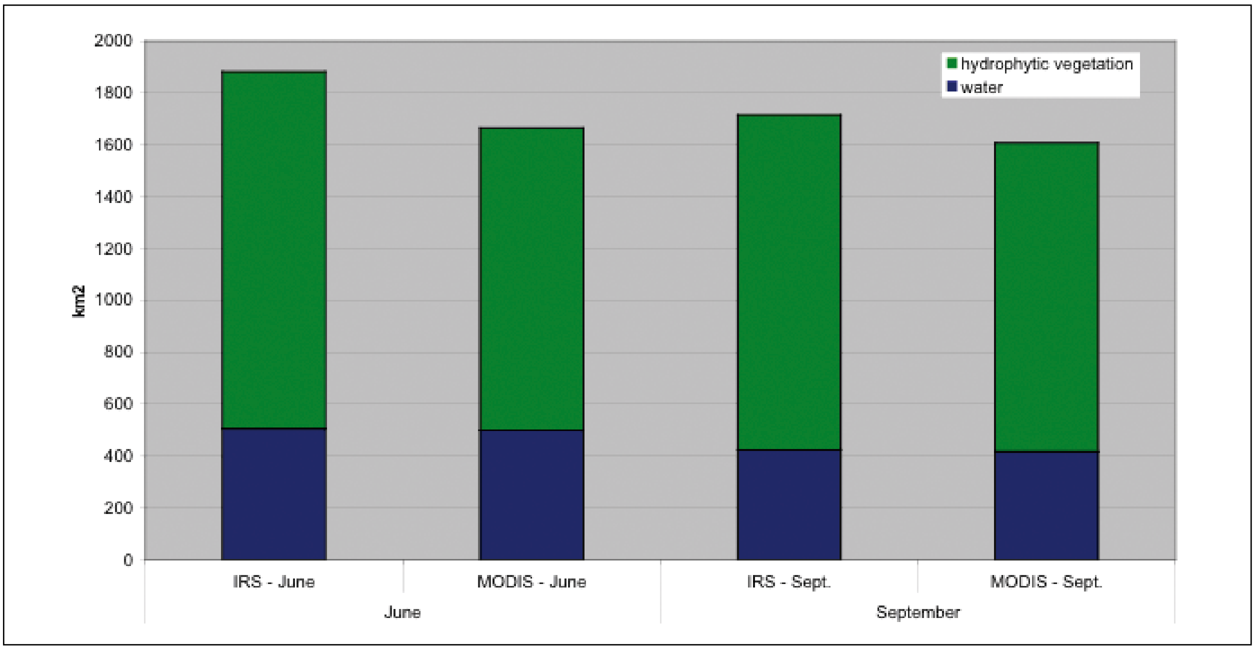


Figure 25: Comparison of MODIS and IRS-based area estimates for marsh vegetation and water surfaces (June and September 2005)

6.3. Landsat ETM+ Seasonal Vegetation Maps

One medium resolution land cover map was produced by the classification of a mosaic of two Landsat ETM+ scenes (166/038 and 39) taken on 6 May 2003, prior to the SLC breakdown. This date coincides with the actual onset of the re-flooding, as dykes and embankments were breached and flood gates opened.

6.3.1. Land cover themes definition

The class hierarchy derived from eCognition classification is shown in Figure 26; the criteria and thresholds are provided in Table 5. The first dichotomy separates water from land using the MIR1 band (ETM+ 5), as was done for IRS imagery (Figure 16 and Figure 17). At this point, the two hierarchy trees diverge: for ETM+ the next distinction is based on "marsh" or "not marsh", whereas for IRS it is based on "hydrophytes" or "not hydrophytes". One of the consequences of this divergence is that in the ETM+ classification marsh soils are distinguished from terrestrial ones.

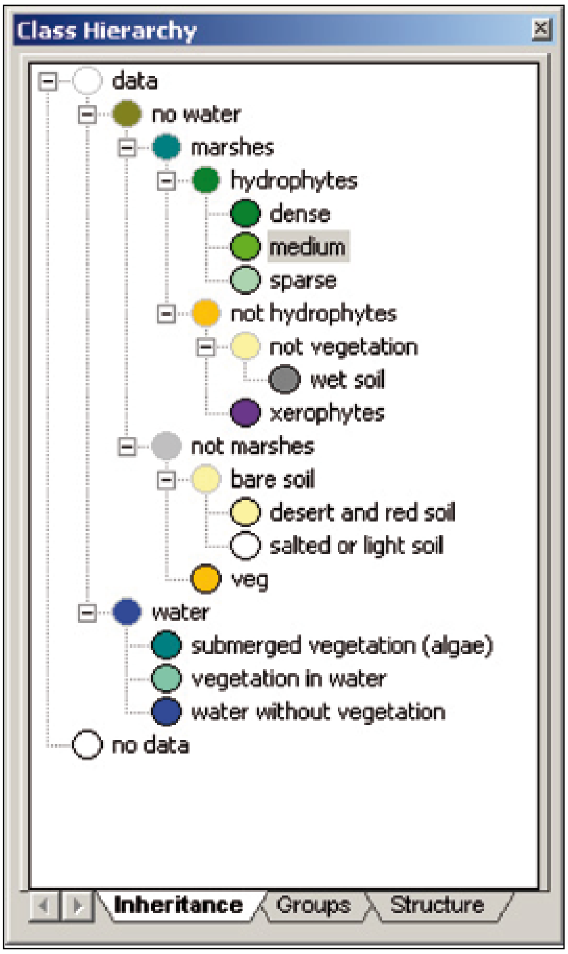


Figure 26: ***eCognition*****; Class hierarchy of Landsat ETM classification**

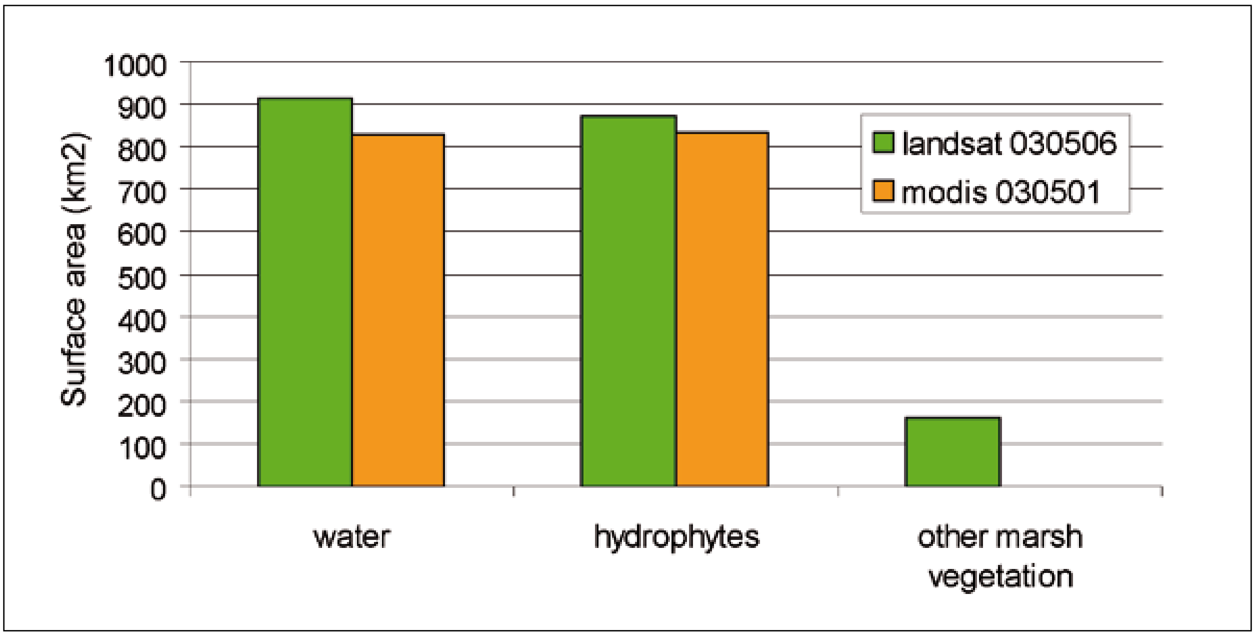


Figure 27: Comparison of areal statistics for marshlands computed from MODIS and Landsat ETM imagery (May 2003)

[9] The surface of Al-Hammar is slightly truncated to the West.

6.3.2. Landsat ETM+ seasonal maps and statistics

The land cover map for 6 May 2003 is shown on Figure 28. The marshland vegetation is practically entirely confined to the intact core of the Hawizeh marshes, but there is extensive flooding in the "Glory River" and Hawr Al-Audah in the Central marsh, the Suq al-Shuykuh fan (Kirmashiyah) and the Mashab-Salal area north of Basrah in the Hammar, and Hawr Al-Sanaf which has established connectivity with Hawr Al-Hawizeh.

Areal statistics for "water" and "hydrophytes" categories have been computed [9], and compared to their MODIS SLCIM equivalent of 1 May 2003, an image taken five days before (Figure 27). The differences in marshland cover are less than 10%. "Other marsh vegetation" comprises non-hydrophyte categories mapped with Landsat ETM+ but which were not discernible using MODIS.

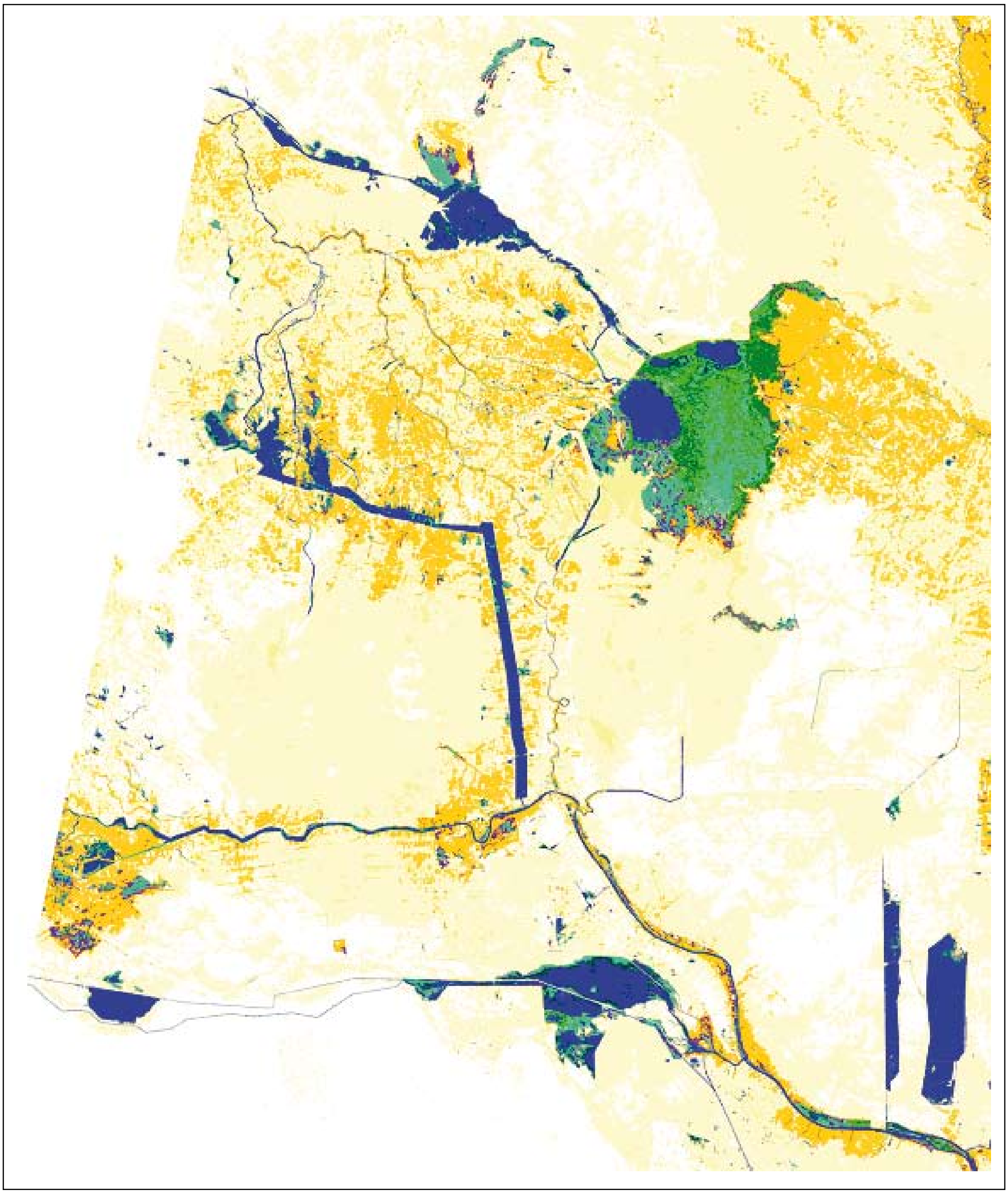


Figure 28: Landsat ETM-based SVC map: 06.05.2003. See Figure 21 for legend

6.4. Landsat SLC-off Seasonal Vegetation Maps

Four land cover maps based on Landsat ETM+/SLC-off imagery are presented in Figure 32 (autumn 2003), Figure 33 (spring 2004), Figure 34 (autumn 2004) and Figure 35 (spring 2005). Because the original images from which these interpreted maps were derived are, in fact, a combination of several dates, their chronological status and reliability are different from that of other IMOS products.

6.4.1. Land cover themes definition

The class hierarchy derived from *eCognition* classification is given in Figure 29; the criteria and thresholds are provided in Table 7. The hierarchy structure is different from that used for the MODIS, IRS and Landsat ETM+ (SLC-on). A trichotomous separation of "emergent marsh", "marginal marsh" and "soil" is made (primary classes 1, 2 and 3 in Figure 29). Delineating these three categories was difficult, as there was no detectable linear distinction in the feature space of Figure 30. This fuzziness was addressed by classifying overlapping sub-groups. For example, in Figure 29, soil_water (2.1) includes land cover classes from primary classes 1 and 3. Certain similarities with the classification procedure for Landsat ETM+ SLC-on and IRS exist, however (Figure 16, Figure 17 and Figure 26).

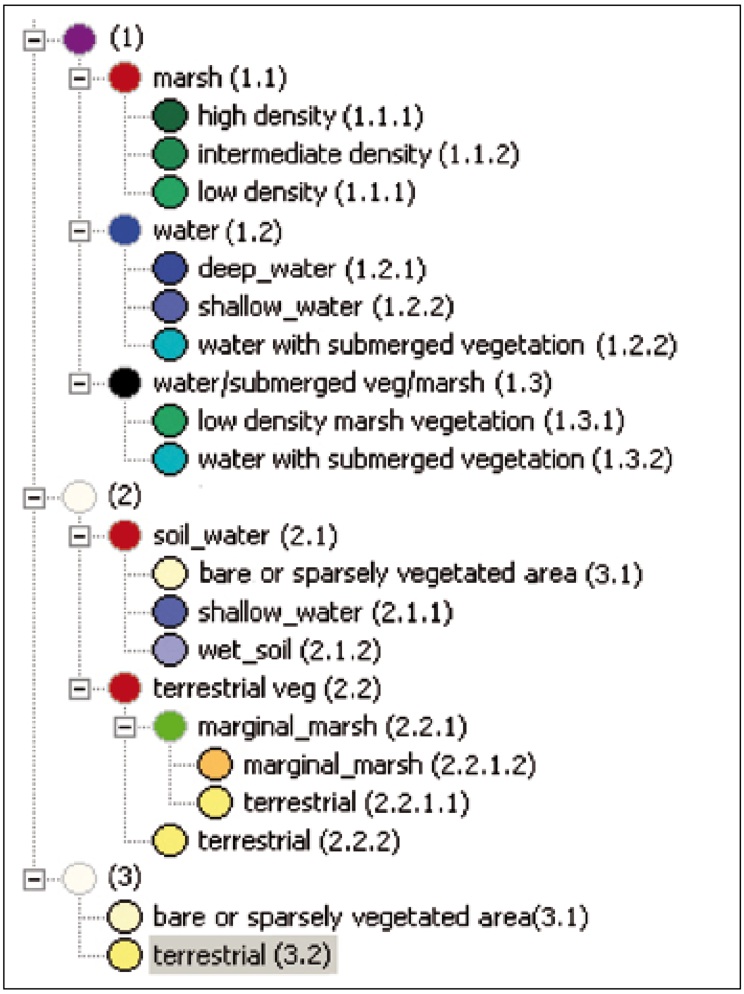


Figure 29: eCognition; Class hierarchy of Landsat ETM/SLC-off classification

In Figure 30, the primary class "emergent marsh and water" (3) includes not only emergent wetland vegetation (hydrophytes) but also areas with deep and shallow water bodies, and those with submerged vegetation (Figure 32). "Marginal marsh vegetation and other terrestrial vegetation" (2) is a primary class separating marginal wetland vegetation from other vegetation such as agriculture. As distinguishing agriculture from other vegetation is difficult, masking these areas would be appropriate. "Soil" (1) is categorized spectrally as a class with high values in the NIR and Red bands. Some smaller areas with sparse vegetation might be found in this category.

The use of imagery from different seasons in the classification process is necessary as it leads to an improved temporal understanding of the ecosystem. The classification hierarchy of Figure 29 was used to interpret all four seasons: autumn 2003, spring 2004, autumn 2004 and spring 2005. The thresholds specified in Table 7 were generated based on the spectral characteristics of the different classes. The only alteration in thresholds comprised minor adjustments to the spring 2005 classification (Table 7). Table 12 provides the logical framework for the Landsat SLC-off imagery interpretation, which was found suitable for all four seasons.

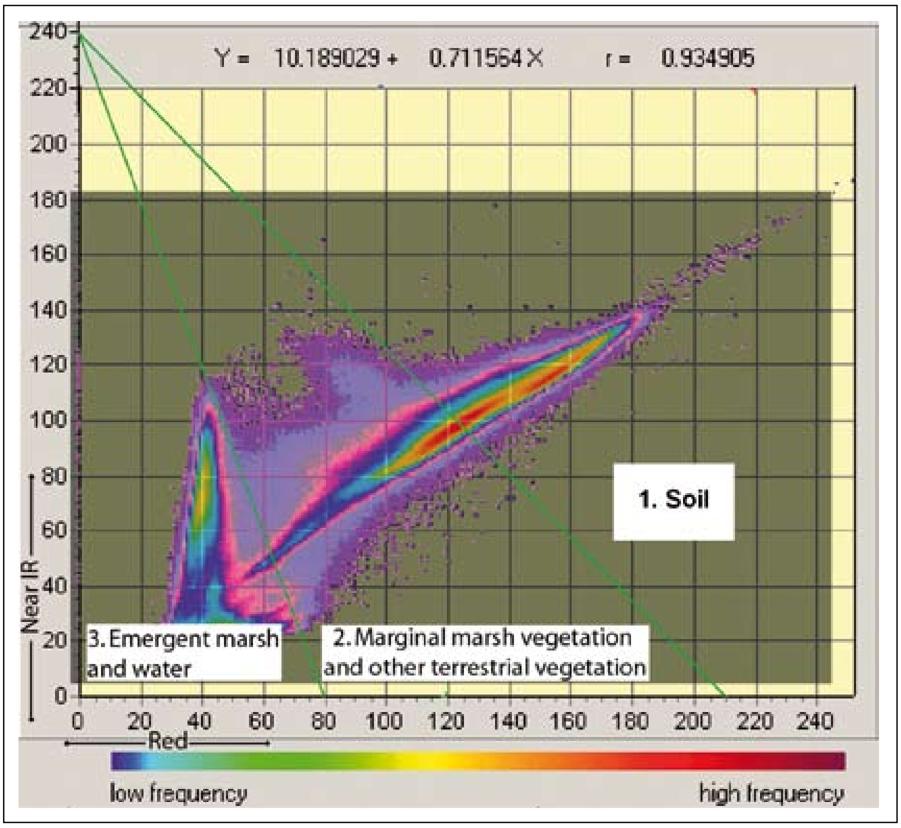


Figure 30: Top class separation of Landsat ETM+/SLC-off images in R/NIR feature space

Theme	Sub-theme	Interpretation	Comments
(1) Emergent marsh vegetation and water	Marsh, Hydrophytes (high, intermediate and low density)	Differences largely distinguished based on volume of water flooding the vegetation. Other parameters of importance are density, maturity or height of reeds	Clear distinction between this vegetation type and other flora due to high reed bed density. Consequently high NDVI values
	Water (deep_water, shallow_water)	Water bodies that are permanent or identifiable over the two seasons (spring and autumn)	
	Water with submerged vegetation	Water bodies with high NDVI values, that are not covered by reeds throughout the year	
(2) Marginal marsh vegetation and other terrestrial vegetation	Other terrestrial vegetation (A)	Including agricultural land that has noticeable variations throughout the year. This class also includes vegetation that is not identifiable as wet marsh vegetation i.e. in some cases this category is valid for dry marsh vegetation	Identifiable category using Landsat band 7 (MIR) in combination with band 3 (Red)
	Marginal marsh	Vegetation along riverbeds and on the edges of surrounding water bodies, ponds and lakes	Probably Xero-halophytes
(3) Soil	Soil	Dry conditions defined by Landsat band 3 and 7	
	Other terrestrial vegetation (B)	Smaller vegetated areas whose development varies due to precipitation	

Table 12: ETM/SLC-off imagery classification interpretation

6.4.2. Landsat SLC-off seasonal maps and statistics

Despite the aforementioned limitations of the Landsat SLC-off data, the classification shows results that are overall homogenous for all four seasons, with only minor distortions. The results are illustrated in the maps (Figure 32- Figure 35) and summary statistics provided in Figure 31. The seasonal analysis effectively documents the key phases of marshland re-flooding. Particularly remarkable is the difference between the widespread re-flooding in spring 2004 (Figure 33) – when large tracts of the marshlands were under water but only limited wetland vegetation growth was apparent – and the situation only one season later, in autumn 2004 (Figure 34), when wetland vegetation had rapidly colonized the re-flooded areas, its density continually increasing, as illustrated in Figure 35 for spring 2005. Thus, the overall trend is one of initial water expansion followed by rapid wetland vegetation development, with a corresponding restriction in open surface water cover.

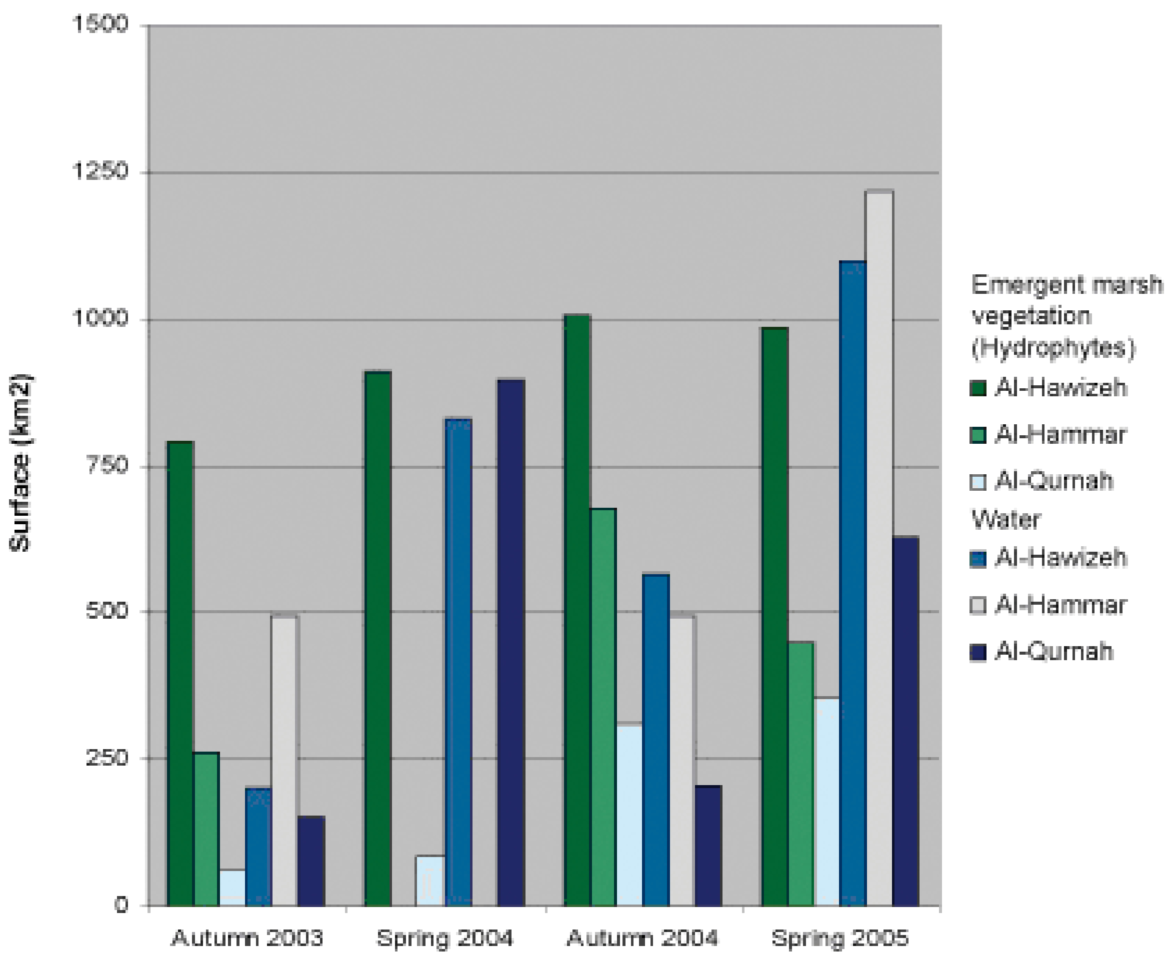


Figure 31: Evolution of land cover in the individual marsh units between autumn 2003 and spring 2005, based on ETM/SLC-off

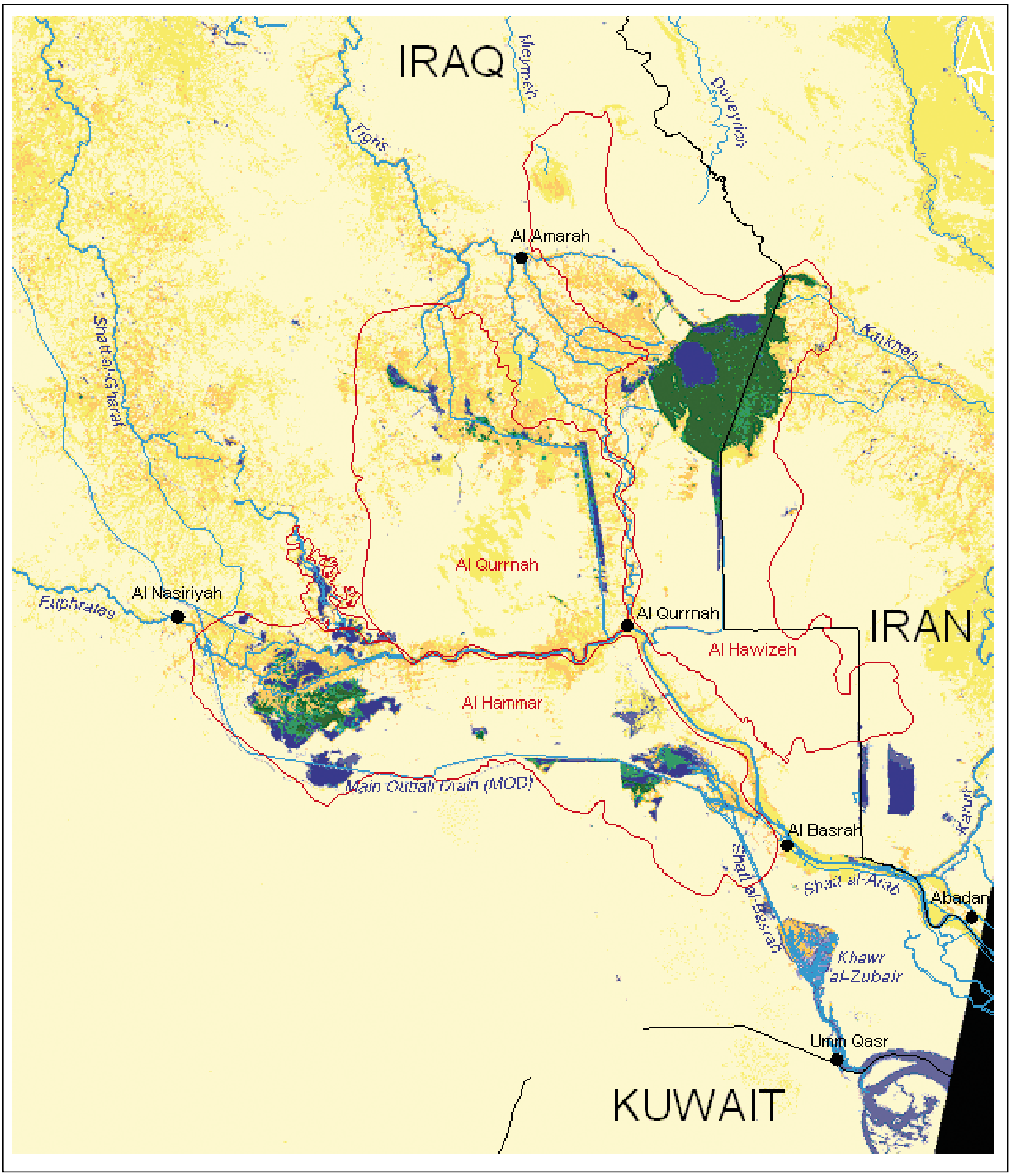


Figure 32: ETM/SLC-off-based SVC map: autumn 2003. See Figure 29 for legend

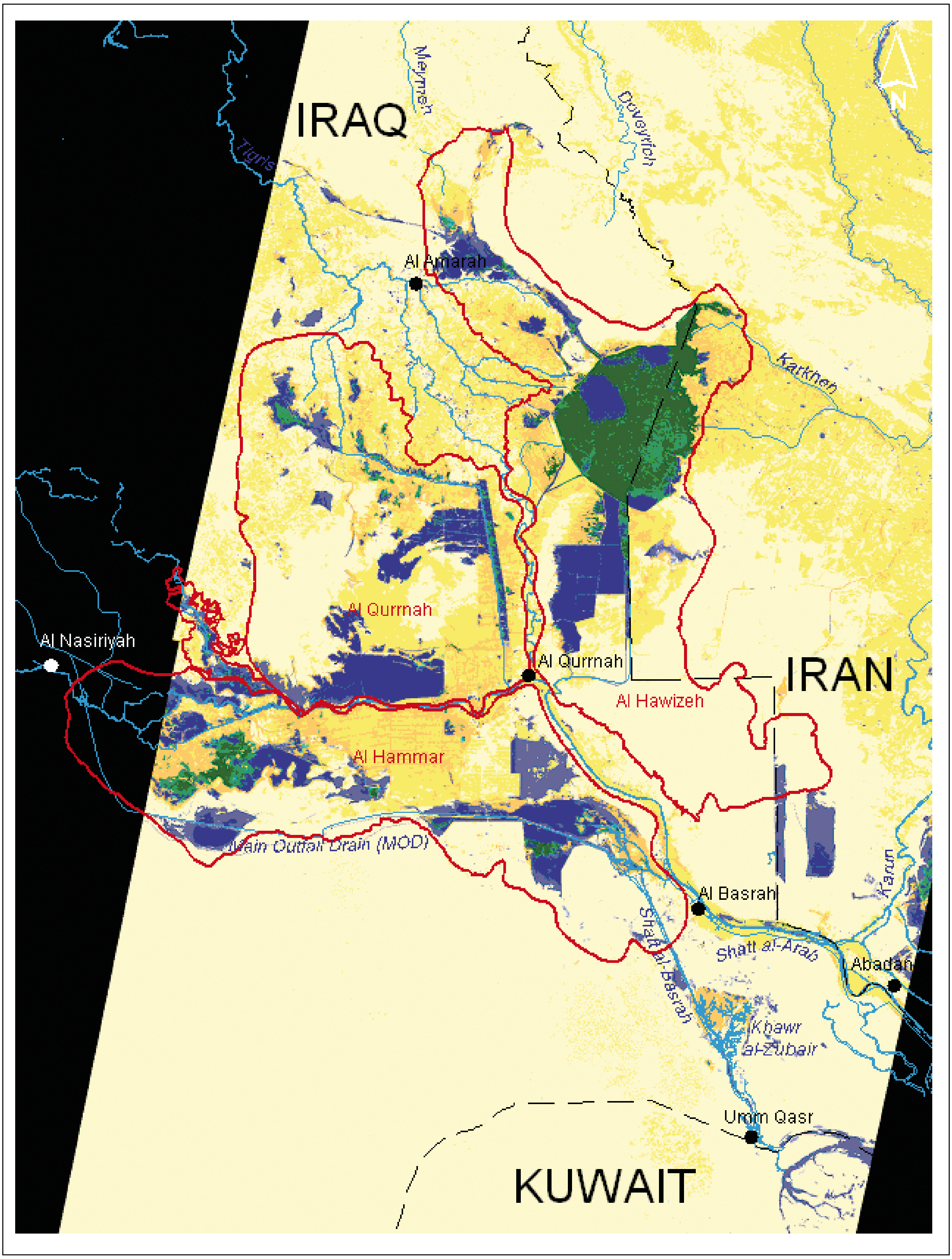


Figure 33: ETM/SLC-off-based SVC map: spring 2004. See Figure 29 for legend

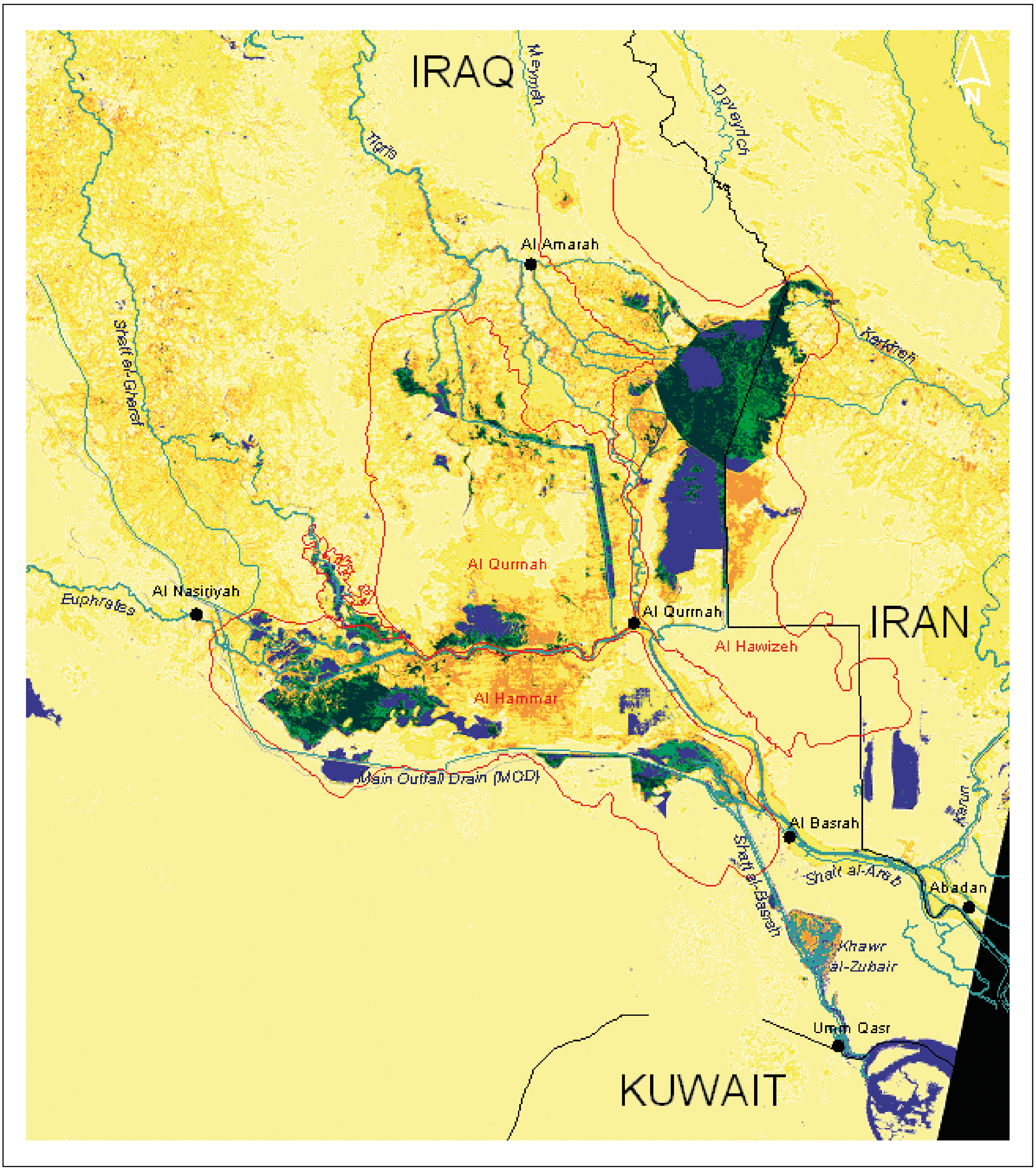


Figure 34: ETM/SLC-off-based SVC map: autumn 2004. See Figure 29 for legend

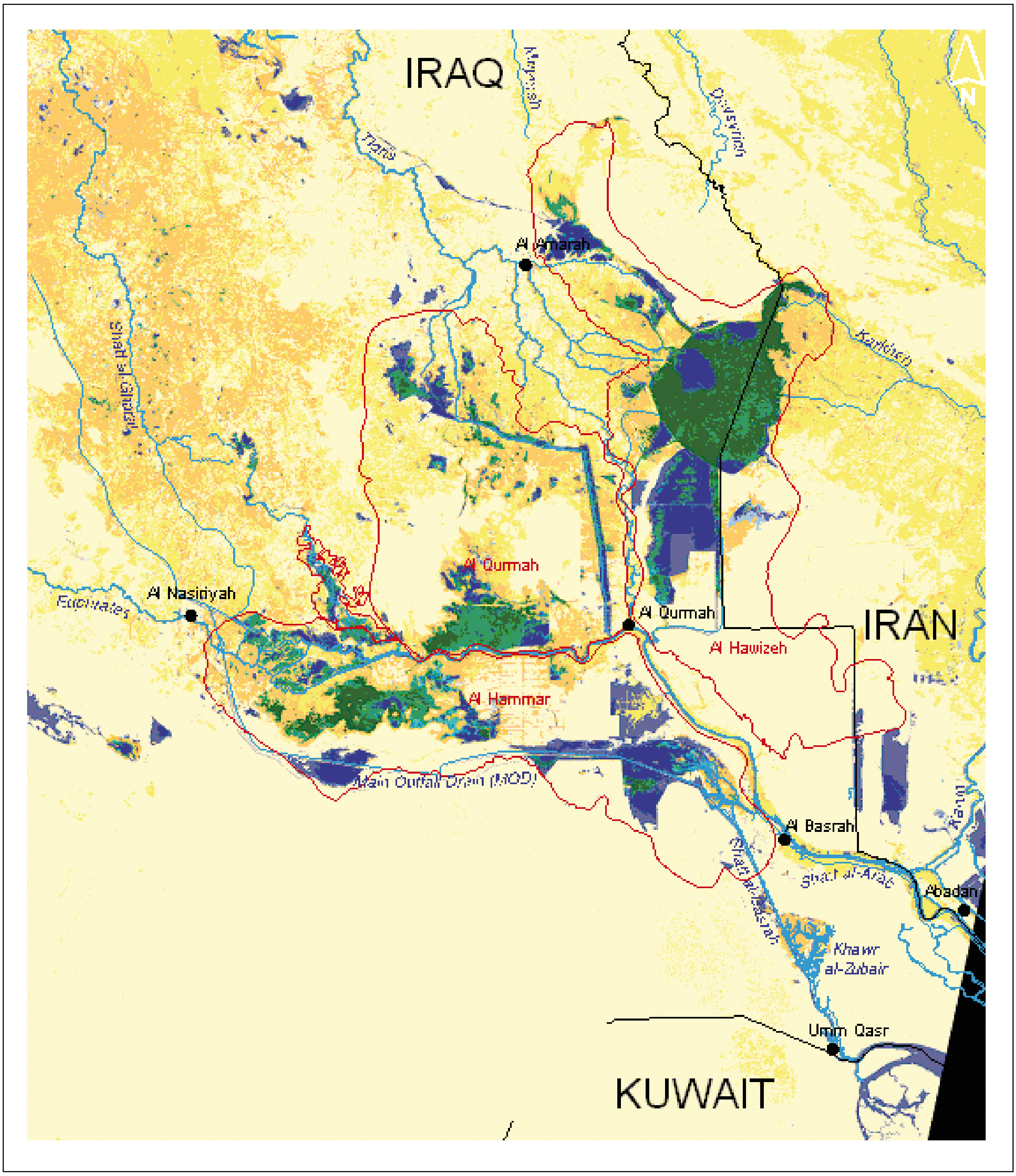


Figure 35: ETM/SLC-off-based SVC map: spring 2005. See Figure 29 for legend

6.4.3. Comparison of land cover surface estimates

MODIS and Landsat SLC-off estimates of water and marsh vegetation surfaces are compared in Figure 36. In autumn 2003 and 2004, estimated surfaces are similar. In spring 2005, the water surface computed from Landsat data is much higher than that of MODIS, whereas vegetation is lower. This last discrepancy is difficult to explain; it is perhaps due to artifacts in SLC-off imagery.

Figure 36: Comparison of land cover change analysis based on MODIS and Landsat SLC-off

7. Discussion

7.1. Methodological issues

Multi-platform, multi-scale imagery sources

Satellite imagery is at the core of the Iraqi Marshlands Information System. Ideally, such a system has the versatile qualities of long-term availability, high temporal frequency, adequate spatial and spectral resolution, and cost-effectiveness. To achieve this, the following components have been combined in decreasing order of importance:

- MODIS Reflectance (250 m): daily frequency, acceptable resolution, comprehensive geographic coverage of the marshes, low cost and easy accessibility. This is the main source of data for IMOS and the best suited for the overall surveillance of the marshlands restoration.

- IRS P6 LISS-III: good spatial resolution compensates for the low temporal frequency and somewhat complicated ordering process (acquisition has to be programmed). It is not possible to map the whole extension of the marshes at the same date, because the four scenes needed fall on two paths with a time offset of several weeks. The restricting factor of cloud cover also needs to be taken in consideration. Overall, this type of imagery offers the possibility to "snapshot map" the marsh vegetation in more classes than MODIS, at best at a seasonal frequency, and for a relatively high cost.

- Landsat ETM+ (prior to May 2003): this type of imagery offers an excellent combination of spatial and spectral resolution, at low cost and without having to program acquisition. It can be used (as was done for the marshlands in 2003) to generate baseline archive maps of land cover.

- Landsat ETM+ SLC-off: the use of this type of imagery is problematic due to the merging of images from several dates and the artefacts present on a relatively large proportion of the scenes.

Exploratory statistics

At low and medium imagery resolution, the most relevant information is spectral: land cover themes are distinguished by their colour *sensu lato* (that is, visible, NIR and MIR domains). For this reason, an important phase of pre-treatment was included in IMOS methodology, consisting of exploratory statistics by means of 2D or 3D feature plots. The simultaneous, interactive location of pixels in both spatial and spectral domains is a good way to decipher the spectral expression of the various land cover themes, so that the spectral thresholds can be defined and applied during the subsequent classification phase.

Object-oriented information extraction

After considerable trial testing during the first phase of the project, it was decided to abandon the traditional pixel-based classification method due to its restriction to spectral information. Instead, an "object-oriented" approach was pursued, such as made possible by the eCognition software. Although "object-oriented" analysis is normally associated with very high resolution imagery, its application to MODIS as well as IRS and ETM+ imagery was deemed justifiable given the possibility of multi-scale segmentation.

Due to time constraints, it was not possible to explore and apply all the classification criteria offered by *eCognition*. Only spectral criteria were applied. Nevertheless, there are significant advantages to the "object-oriented" approach, such as:

- A common methodology for all images;

- The definition of a logical and hierarchical legend for land cover themes;

- The production of "simpler" and hence more readable land cover maps than the pixel-based approach (which produces a "salt and pepper" effect).

7.2. Reliability of maps and statistics

Normally, supervised image classification is dependent on the existence of training sites of known nature, followed by field verification through formal survey procedures. Because of the security situation in Iraq, it was not possible to plan and conduct field campaigns to collect a sufficient number of well-placed training and test sites specifically identified for image classification purposes. As a result, during the one year course of IMOS implementation, only a relatively limited amount of field data collected by Iraqi partners was made available. In addition, the field data was mainly obtained along roads, as large tracts of land remained inaccessible (due to minefields, oilfields, and proximity to international borders, for example).

In a strict sense, the IMOS procedure is not a supervised one. Rather, it is an iterative process of thematic imagery interpretation, based on a priori knowledge of the Iraqi and other marshlands, supplemented by field information (photographs and field descriptions) as available. The key role of the analyst in this procedure could be considered a disadvantage, leading to relatively arbitrary results. However, the sequence of operations followed in eCognition is fully documented and saved, thus guaranteeing that it is perfectly replicable.

MODIS-based Simplified Land Cover and Inundation Maps (SLCIM)

To maximize the reliability of interpreted maps and the statistics derived from the analysis, the following set of rules were adhered to:

- A relatively small number of classes (9), as a compromise between thematic representativity and the low image resolution[10];
- A class hierarchy starting with the fundamental dichotomy vegetation/non-vegetation, based on the robust criterion of NDVI. As a ratio, NDVI is less sensitive to the spurious influence of atmospheric and geometric factors, and hence provides better repeatability through time. It is further used to define density sub-categories. In this case, density represents not only the number and "greenness" of stems per unit area, but also of the possible presence of water between the vegetation stands;
- Again for reasons of robustness and replicability, the essential distinction between marsh and terrestrial vegetation was simplified by considering the former to consist only of hydrophytes. The criteria used are complex (Table 3), as they are derived from a combination of spectral bands and a vector layer delineating potential marshland extent.

A measure of NDVI ability to monitor vegetation status through time is given by the graphs illustrated in Figure 37. The quasi-invariance of NDVI for a desert target[11] indicates that it is little affected by atmospheric variations. It can also provide a good criterion for the discrimination of various types of agriculture based on plant phenology (one or two crops per year) (Lu et al., 2001; Geerken et al., 2005).

The mapping of water surfaces proved more difficult than anticipated. Several criteria were tested, including NDVI, and a decision was finally made to use MIR with a variable threshold, generally <1000 for water (see Annex I for a complete list). The validity of this procedure is supported by the complete lack of correlation between threshold value and water surface area estimate. In areas unobstructed by hydraulic works such as dykes, the very flat topography blurs the limit between land and water *sensu stricto*. An intermediate category of "wet soils or very shallow water" was accordingly introduced.

[10] This induces a large proportion of mixels.

[11] The spectral properties and albedo of a desert are considered constant in time.

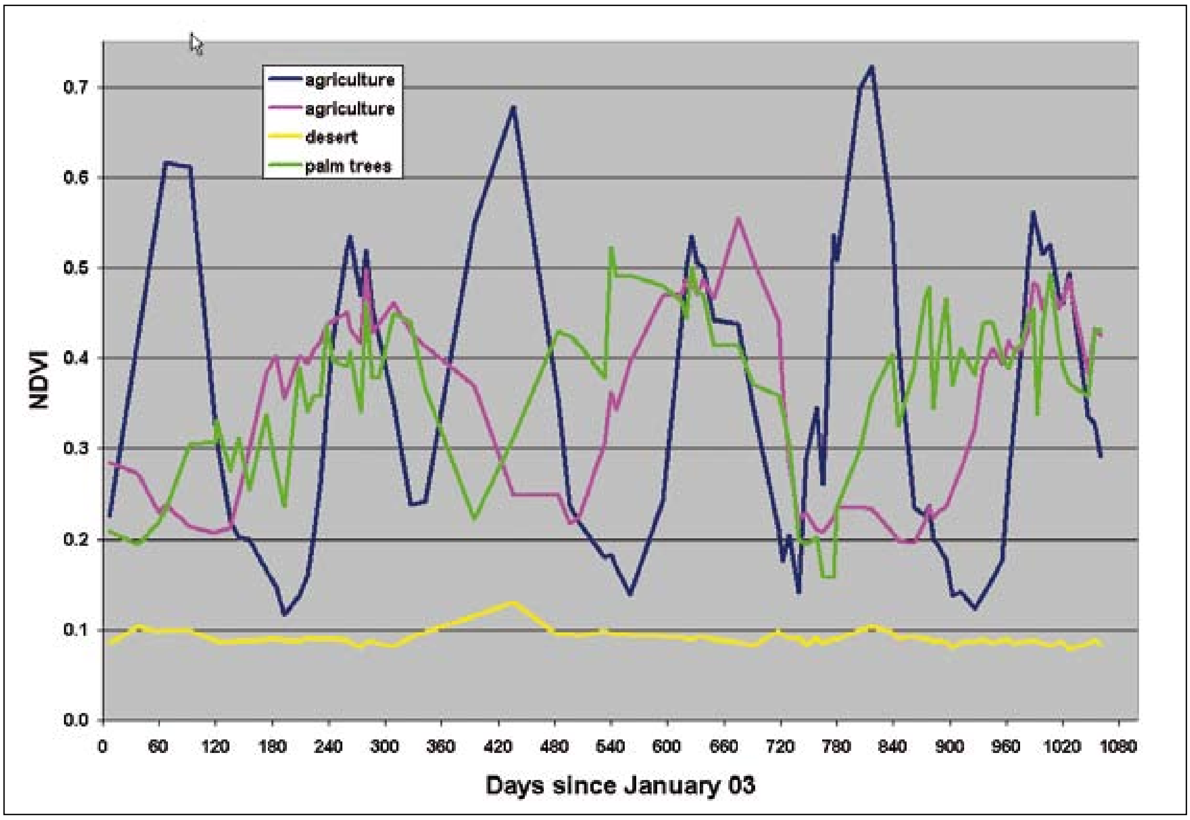


Figure 37: NDVI evolution of characteristic land covers between 2003 and 2005

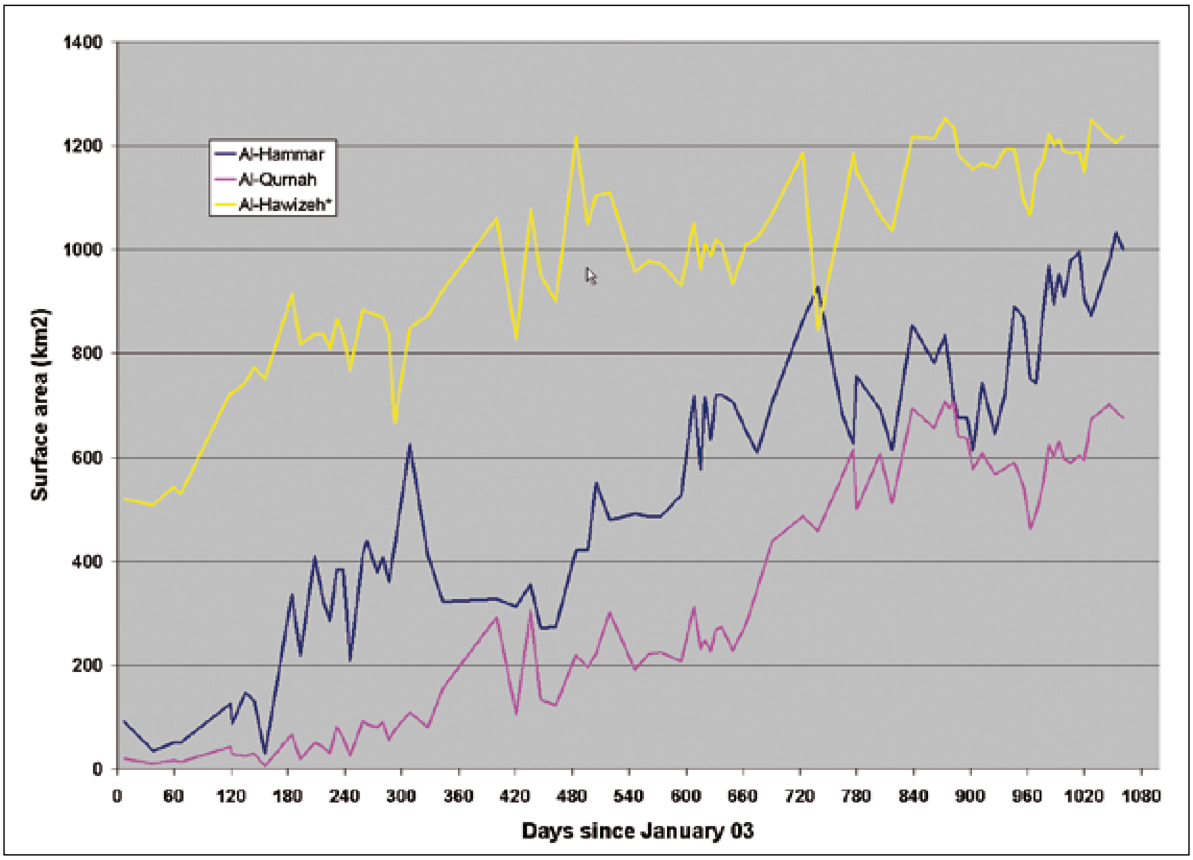


Figure 38: Temporal evolution of marshlands surface area between 2003 - 2005

MODIS-based statistics

Despite efforts to ensure good replicability from one weekly MODIS map to the next, temporal graphs showing the evolution of marsh vegetation and water surface areas are "noisy" (Figure 15). This is also apparent for the individual marshland units (Figure 38). Whereas the upward trend in wetland vegetation is unquestionable, the presence of peaks requires further elaboration. Although in Al-Hawizeh and Al-Qurnah there are indications of a low-frequency "seasonal" variation, it is not as clear in Al-Hammar, most likely because of the more regulated flows of the Euphrates as compared to that of the Tigris.

According to the signal analysis reported in Annex K, high-frequency variations in the total marsh vegetation graph are "noise" stemming from imprecisions in the classification: the variability of the trend is ± 300 km^2, or approximately 15 per cent of the mean surface area[12]. This is quite comparable with, or even below, the variability found in the time series of daily NDVI values (van Dijk et al., 1987; Viovy et al., 1992)

The seemingly seasonal variations in individual marshes raise a more fundamental question: what is meant by "surface area of marsh vegetation"? It is known that hydrophytes, particularly *Phragmites* and *Typha* reeds which are the dominant vegetation of the marshlands, undergo an annual phenological cycle. Specifically, they become dormant and mostly dry in the winter season. As a result, they are difficult to map using the same criteria as during other periods of the year[13]. Hence, the smaller surface area seen on the graphs in winter does not mean a reversal in the marshes' recovery, but rather the presence of dry biomass (Figure 38; Al-Hawizeh around day 680).

It is legitimate, then, to use a least-square adjusted trend line[14] to gauge the overall evolution of the marsh vegetation (Figure 15).

The analysis of open water surface evolution reveals a different dynamic than that of marshland vegetation. As illustrated in Figure 15, water bodies exhibit clear seasonal oscillations, with an expected minimum in summer. The behaviour of this times-series can be modelled by the convolution of three elementary sinusoids (Figure 39)[15]. In addition to a pluri-annual trend (increase, then stabilization, then possible decrease), a clear yearly periodicity and a weaker seasonal one exist: Figure 41 shows an expanding trend in the water surface area of the three units from the onset of the re-flooding in spring 2003 until spring 2004. After that, seasonal cyclicity predominates. Furthermore, it is probable that from spring 2004 onwards, the growth of hydrophytes occurs at the expense of a reduction in open water surfaces.

7.3. Re-flooding succession and events

There is an obvious functional relationship between water availability and marsh vegetation development. The large damming and drainage efforts that took place during the 1980s and 1990s resulted in a severe shrinkage of marshland extent by 2000 (Partow, 2001, map 8), when only the north-eastern part of Al-Hawizeh remained. The decline continued at a rapid rate until early 2003 (UNEP Press Release, 2003; Figure 13, top).

In terms of both speed and scale, the recovery of the marshlands has been equally remarkable. At the beginning of 2003 (Figure 40 and Figure 41), water surface area was only between 100 and 200 km2 in Al-Hawizeh and Al-Hammar, and close to zero in Al-Qurnah. One year later, in February 2004 (Figure 40), extensive inundation had taken place in the three principal marshland domains.

Wetland vegetation re-growth, however, was only beginning to take hold in the western Al-Hammar. By December 2005, 41 per cent of the original marshland extent had "recovered" (Figure 9).

[12] Taken half-way between January 2003 and January 2006 on Figure 15.

[13] To help deal with this problem the green band is used in the winter season (Table 3).

[14] The correlation coefficient for the trend line has the very high value of 0.96.

[15] Operations in Annex K were performed using AutoSignal; see: http://www.clecom.co.uk/science/autosignal/details.html

Significantly, wetland vegetation made an exceptional comeback, increasing almost five-fold from 630 km^2 in January 2003 to 2,893 km^2 in December 2005.

Rehabilitation trends are generally similar in the three marshland units. However, the central and northern parts of the Al-Qurnah marsh have received less water input (Figure 41), and marsh vegetation has consequently not returned there to any large extent. In addition to the lack of water, it is possible that saline soils and lack of marsh-riverine connectivity have limited reed growth.

The hydrological data available to IMOS is scanty and lacunal (Cattarossi, 2005). A compilation done under HEC of water flows into the three marshland units is shown in Figure 41. There is an evident correlation between the recorded discharge in the Tigris watershed (the Kahlah River feeding into Al-Hawizeh) and the water surface area peaks in the winter and spring of 2005. On the other hand, the Euphrates high water levels at Nasiriyah also coincide with maxima in water surfaces. The Kahlah River hydrograph is very irregular, with sudden peak flows. This is a likely indication of a complex mixture of natural flow events and man-made releases on the hydrological cycle. Differentiating planned water flows from natural ones will require further investigation, in consultation with the water engineers managing Iraq's extensive irrigation network.

7.4. Rapid assessment of wetland restoration

Marshland re-flooding has been proceeding under the overall stewardship of the Centre for the Restoration of the Iraqi Marshlands (CRIM), established by the Ministry of Water Resources in 2003. The breakdown of authority following the collapse of the former regime provided opportunities for local initiatives, and local communities or individuals used the initial governance void to manipulate, modify or destroy hydraulic and drainage infrastructure. These types of actions have had a significant impact on the marshes' hydrological regime, which has brought about a substantial re-growth in the reed beds. This is evident from the survey statistics provided in Figure 13 and Figure 15 (see Annex F for details).

The total marshland extent (water plus vegetation) expanded from 10 per cent of its 1970s extent in January 2003 to 41 per cent by December 2005, which represents an increase of 400 per cent. Both Al-Hammar and Al-Hawizeh presently cover over 50 per cent of their original area. The former's recovery is particularly exceptional, increasing from a low of six per cent to 51 per cent of its original surface. Within this specific context, marshland restoration may certainly be considered a "success", but to make a more accurate evaluation of "restoration" success, the recorded

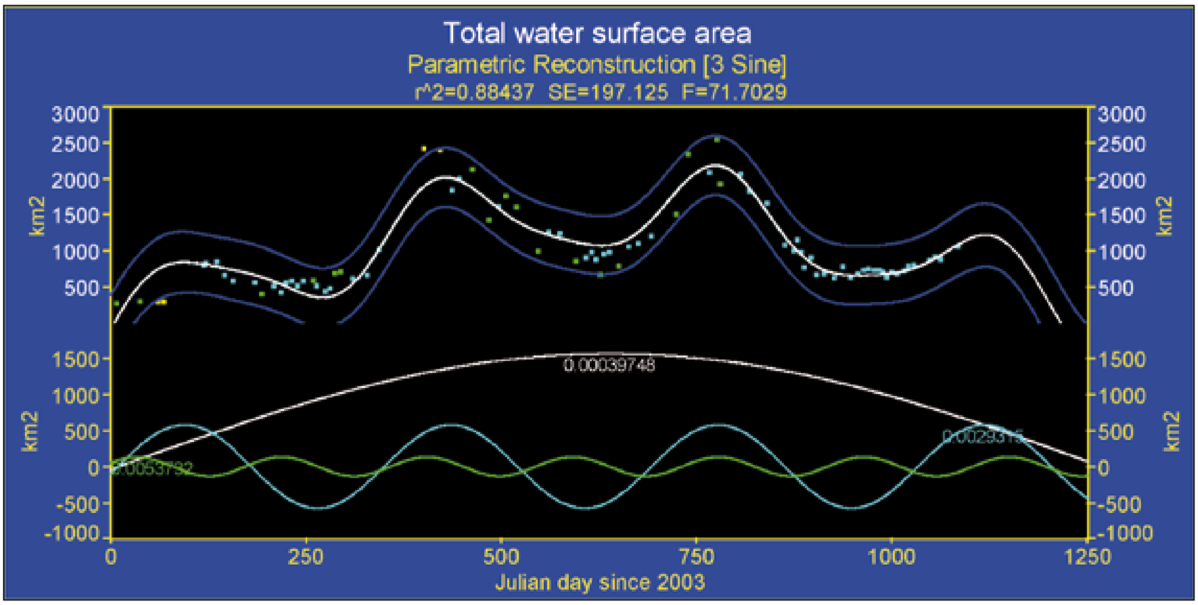


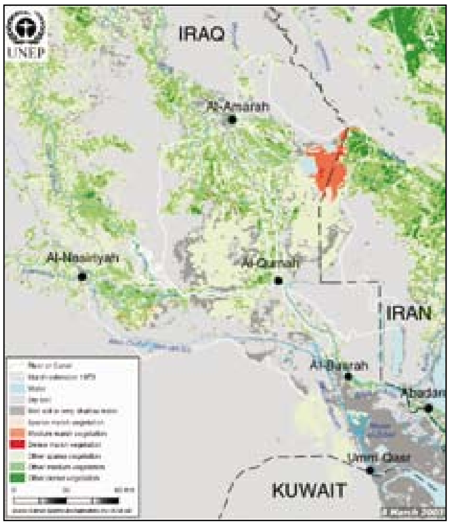
Figure 39: Parametric reconstruction of Total water surface area time-series, showing pluri-annual trend (white), yearly (blue) and seasonal (green) periodicities

changes should be measured against established quantitative targets. However, the CRIM's vision "to [restore] the marshlands to the maximum extent possible" and its objective "to achieve effective restoration of the Iraqi marshlands" are both qualitative statements open to interpretation. It is therefore not possible to accurately rate the relative effectiveness of wetland restoration without more information on applied targets. At the same time, caution should be exercised not to equate wetland re-inundation with actual restoration. As noted by Professor Edward Maltby: "just because it looks like a wetland, does not mean it is functioning like a wetland."[16] Additional field data on wetland structure and functioning (i.e. water quality, biomass, biodiversity indicators, socio-economic goods and services) are therefore needed to assess the actual quality of the restored wetlands, as opposed to their surface area only.

Since January 2003, the surface of the marshes has been steadily growing at a rate of approximately 900 km^2 per year. At the end of 2005, the remote sensing survey showed that the marsh surface reached 3,000 km^2, corresponding to a surface of water bodies varying between 700 km^2 (summer) and 2000 km^2 (winter-spring). These oscillations are due both to seasonal climatology and to the spread of hydrophytes in areas of open water surfaces. Links between the hydrological regime and the growth of hydrophytes are well documented in the literature. The marked seasonal oscillations of water surfaces illustrated in Figure 41, is an indication that the marshes system has entered a state of dynamic equilibrium.

At the risk of making a gross extrapolation, based on the current rate of re-flooding, it would take five to six years for the marshes to be restored to their full 1970s extent. Such a scenario clearly depends on the amount of water available in the Tigris-Euphrates river system, as well as competing water demands from other economic sectors. The restoration should also be guided by more specific restoration targets defined by the Iraqi authorities, and by directing engineering activities to attain the set objectives.

[16] Discussions with Edward Maltby, Geneva, 12 October 2005.

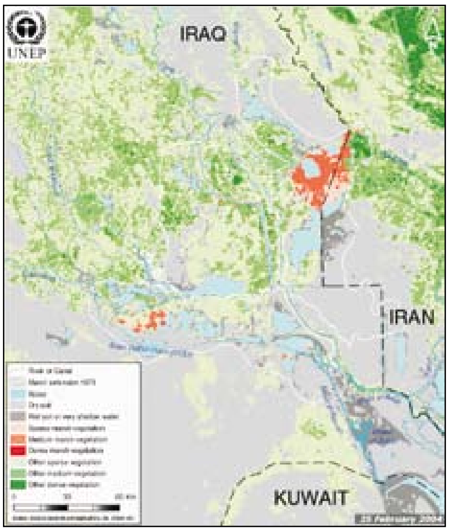


8 March 2003

Only part of the Hawr Al-Hawizeh marsh remains.

Central (Qurnah) and Al-Hammar marshes are virtually totally desiccated.

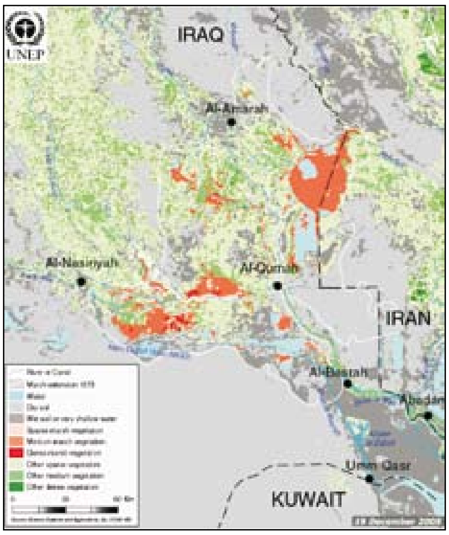
292 (water) + 593 (marsh. veg.) = 885 km2
10% of 1973-76 baseline (8,926 km2)



25 February 2004

Al-Hawizeh starts recovering.
Marsh vegetation reappears in western Al-Hammar.
Extensive flooding but overall limited wetland vegetation re-growth.

2,417 (water) + 1,180 (marsh. veg.) = 3,597 km2
40% of 1973-76 baseline (8,926 km2)



19 December 2005

Marsh recovery continues in Al-Hawizeh and Al-Hammar. Extensive wetland vegetation recovery. Marsh vegetation reappears in the Central marshes along the northern bank of the Euphrates and at the riverine fan of Al-Muminah/Butaira.

1,067 (water) + 2,707 (marsh. veg.) = 3,774 km2
42% of 1973-76 baseline (8,926 km2)

Figure 40: Snapshots of marshlands recovery (SLCI maps)

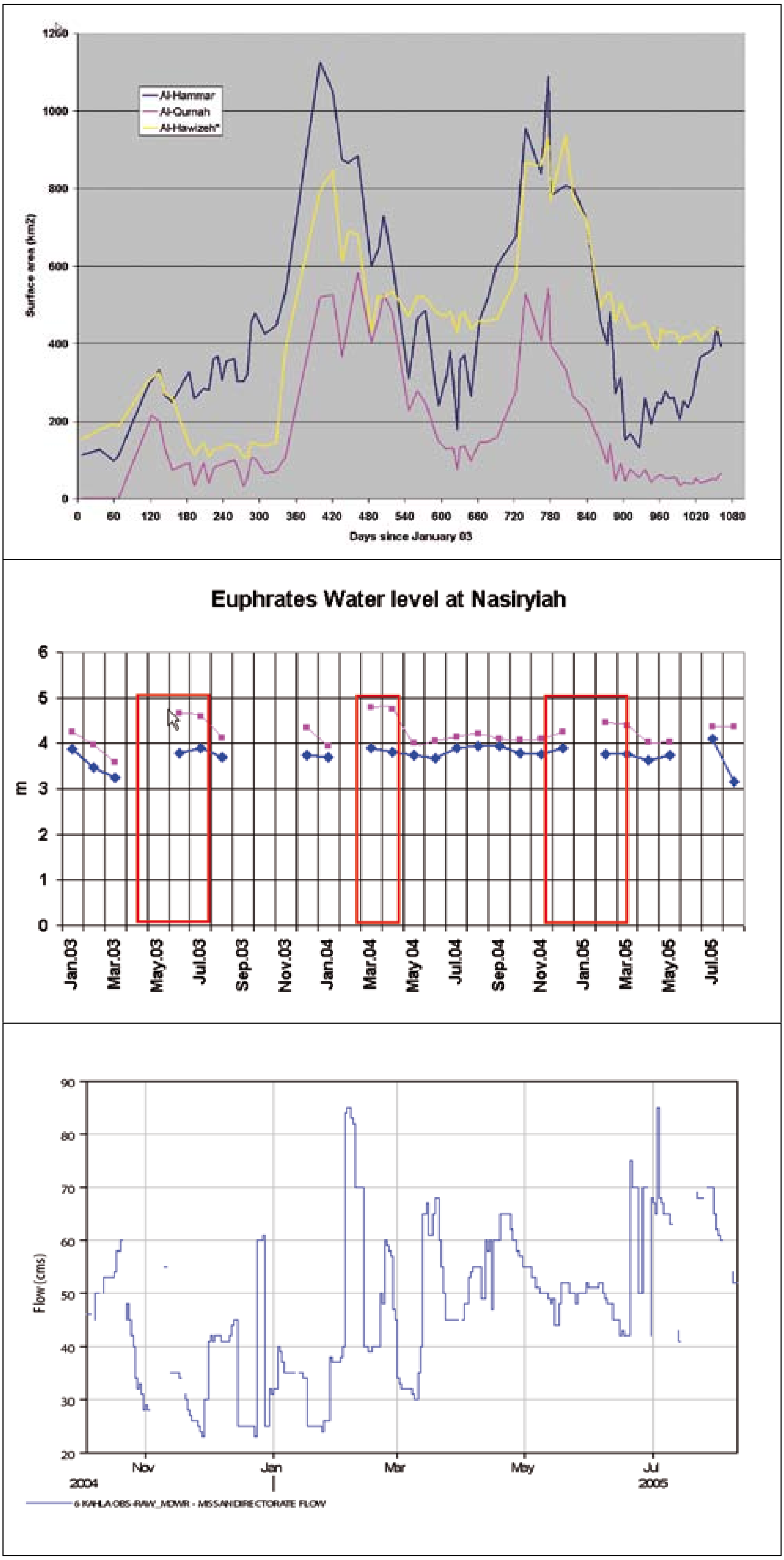


Figure 41:

Comparison between:

(a) water surface evolution within the marshlands (top),

(b) the Euphrates water level at Nasiriyah (centre; red boxes indicate floods), and

(c) discharge of Kahla River into Al-Hawizeh (bottom).

From Cattarossi (2005)

8. Conclusions

Three objectives were set for the IMOS. The first two were fully met; the third was only partially attained and remains to be reached:

- The *development and implementation of IMOS* met the first objective to systematically acquire, analyse and exchange data and information on the rapid changes taking place in the marshland environment. The IMOS comprises an articulated ensemble of concepts, data, methodology, software and products, most of which are accessible through its website. Given the vast size of the Iraqi marshlands and the prevailing security conditions, remote sensing was the only practical approach to observe their evolution. Daily MODIS imagery was the main source of data, supplemented by IRS and Landsat imagery obtained at seasonal frequency. Thematic information was extracted from all the imagery by a unified, object-based approach, followed by a fuzzy, multi-criteria classification. Due to the scantiness of field data, the role of the analyst's expertise was essential to the interpretation process. The possibility to log and store the algorithms used assures, however, that the results are fully replicable;

- Key outputs meeting the second objective of this project – to provide *information products and services* – include MODIS-based SLCI maps and statistics that were incorporated into weekly reports. More detailed seasonal vegetation maps were also developed based on the higher-resolution imagery of IRS and Landsat. Posters summarizing the findings of the IMOS were also prepared. All images, maps and reports are displayed and accessible via the IMOS website, which includes an Internet Map Server for easy display and downloading of satellite imagery;

- The evaluation of the *magnitude* and *character* of wetland restoration, and more specifically of its "success", was the third somewhat ambiguous objective. While the IMOS was able to survey the *progress* of wetland restoration (vegetation + water) and therefore to quantify the physical "magnitude" of rehabilitation, the qualification of the "character" of wetland restoration requires more detailed information on the structure and functioning of the wetland system. A more accurate assessment of the level of "success" would require measuring the area rehabilitated with quantitative targets fixed beforehand by the CRIM.

Beyond the formal objectives set by the IMOS, the following conclusions can be drawn:

- In its present form, the core of the IMOS (the production of the MODIS-based SLCI maps) can be operated by one full-time geomatician/analyst;

- The disproportion between the size of the IRS scenes and the whole marshland extension does not allow for a comprehensive image capture at any given date. It is therefore impossible to map the whole marshland extent on a single date, as the four scenes needed fall on two paths with a time offset of several weeks. This explains that the acquisition and purchase of this type of imagery should be done with a view to examining the individual marshland units or portions thereof in more detail;

- The abovementioned problem does not exist for Landsat ETM+ scenes. However, only SLC-off imagery – which is made of a superimposition of several scenes taken at different dates and whose quality degrades towards the image edge – is currently available. The overall quality of these images is poor and their *temporal* status unclear.

9. Recommendations

Recommendations on follow-up activities include:

- Capacity building and technology transfer: given that the IMOS is relatively complex, it is imperative that it not be handed over to Iraqi partners/users in the form of a solitary report. However detailed the documentation, it will not be sufficient to transmit the IMOS methodology. A well-planned process of knowledge and technology transfer should be developed. This implies sessions of hands-on training of selected Iraqi technicians/analysts, who are already trained in the basics of remote sensing and image interpretation. These could be individuals who participated in the introductory wetland remote sensing training course conducted in February 2005 under the IMOS.

- Pending the transmission of the IMOS to Iraqi partners, UNEP should continue to host and maintain the IMOS website.

- Enhance image classification methodology:

  - For MODIS-based SLCIM, the criteria for the separation of water and wet soils, of marsh and terrestrial vegetation, and of hydrophytes and other marsh vegetation should be refined.

  - For IRS- and Landsat-based SVM, the context and textural criteria to map xerophytes and xero-halophytes should be used. Whenever possible, parallel-piped criteria should be replaced by distribution-oriented ones.

- Terra-ASTER and Ikonos or QuickBird imagery should also be used to supplement mapping of marsh vegetation. The methodology could be improved through:

  - More accurate SLCIM mapping conducted by refining criteria for separating water from wet soils, and marsh vegetation from terrestrial vegetation;

  - The use of more textural and contextual criteria for classification, exploiting the *eCognition* software to a fuller potential;

  - Better quality mapping of xerophytes and xero-halophytes.

- Field data such as photos and vegetation cover descriptions should be integrated more fully into the classification process. This will require greater collaboration with Iraqi partners conducting field campaigns and a wider choice of sites, covering all parts of the marshes.

- A more complete hydrological database and model are needed to test the accuracy of the water surface area time series, and to examine the role of water budgets and fluctuations on the growth of marsh vegetation.

- Consultations with the Ministry of Water Resources/CRIM officials on official restoration targets as well as hydraulic manipulations implemented in the field should be initiated.

- Based on the two previous recommendations, a full narrative delineating the process and key phases of marshland restoration with a view to identifying and prioritizing areas for restoration should be developed.

- A functional wetland typology of re-flooded landscapes should be developed in collaboration with wetland scientists, and mapping of these units using remote sensing and GIS techniques should be attempted. An assessment of the functional aspects of re-flooded marshes will depend on the results of the remote sensing survey but equally on water, soil and biodiversity data, as well as socio-economic information.

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Annexes

A. Simplified Land Cover and Inundation Mapping Methodology

B. IRS-based Seasonal Vegetation Mapping Methodology

C. Landsat ETM-based Seasonal Vegetation Mapping Methodology

D. Landsat SLC-off-based Seasonal Vegetation Mapping Methodology

E. Website methodology

F. SLCI reports with maps

G. Atlas of field photographs

H. List of MODIS images (2003-2005)

I. MODIS images classification thresholds

J. ArcView project for Field Database

K. Signal analysis of NDVI and surface area time series

L. DVDs

Further information

Further technical information may be obtained from the UNEP IMOS website at: http://imos.grid.unep.ch/

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