Title: INVENTORY AND MONITORING OF SHRIMP FARMS IN SRI LANKA BY ERS-SAR DATA

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ESA article: http://www.esa.int/export/esaCP/ESAAQWZ84UC_Protecting_0.html

Application Tool: Remote Sensing.

Main Issues Addressed: Suitability of the site and zoning.

The general problem, or aim of the study, and the contribution of GIS, remote sensing and/or mapping to the solving the problem: Inventory and monitoring of shrimp farms is essential for decision-making on aquaculture development, including regulatory laws, environmental protection and revenue collection from a government viewpoint. Inventory and monitoring also are important from the commercial viewpoint for a variety of management and development decisions including site selection and risk analysis.

In order to be timely and useful, identification and monitoring of shrimp farms demands an accurate, fast and mainly objective methodology. Synthetic aperture radar (SAR) data are uniquely useful not only for their inherent all-weather capabilities (very important as shrimp farms occur in usually cloudy areas) and frequent coverage, but mainly because the backscatter from surrounding dykes allows for recognition and separation of shrimp ponds from all other water-covered surfaces.

Main Environments: Brackishwater.

Culture Systems: Ponds.

Organism Divisions: Crustaceans.

Genera and Species: *Penaeus mondon*, tiger prawn.

Target Country: Sri Lanka.

Target Audience: Aquaculture planners in government agencies; shrimp farming trade organizations, shrimp farmers.

Duration of the Study and Year Begun: Four months; 1999 (see Table 10).

Personnel Involved:
Remote sensing specialist with a working knowledge of remote sensing applications in fisheries and aquaculture (FAO Remote Sensing Officer); assisted with the design of the study and analyses, and managed the project; full time.

Fisheries and aquaculture specialist with a working knowledge of GIS and remote sensing applications (FAO Senior Fishery Resources Officer); assisted with the design of the study, carried out the ground verification mission; part-time for the duration.

Digital image processing specialist (Consultant and Professor); modelling, image processing and analyses; full time.

Sri Lankan mariculture and GIS specialists (3) who played a key role in ground verification (see Acknowledgements); part time.

INVENTORY AND MONITORING OF SHRIMP FARMS IN SRI LANKA BY ERS-SAR DATA

Introduction

Perspective on shrimp farming

Global Importance of Shrimp Farming

Global farmed shrimp and prawn production amounted to 932 000 t in 1995 compared with some 170 000 t in 1984. Production has plateaued since 1991. Eighty-seven percent originated in Asia.

Constraints on the Further Development of Shrimp Farming

Despite the rapid growth of the industry, there have been setbacks due to diseases and due to the growing awareness of the environmental and social impacts of shrimp farming. Much of the debate has focused on the sustainability of shrimp farming. There is a trend for discussion on principles, the development of guidelines and the need for better management practices (FAO, 1998). It has been recognized that shrimp farming can be made more sustainable. Impacts can be reduced in a number of ways including through better regulatory and planning processes at State level. Key considerations are the siting of shrimp farms and monitoring their development.

State of shrimp farming in Sri Lanka (Northwestern coast)

Shrimp farming began in Sri Lanka in the early 1980s. Farming of the black tiger prawn, *Penaeus monodon*, was a successful and lucrative venture until major disease outbreaks occurred in the late 1980s (Wijepoonawardena and Siriwardena, 1995). Although the main cause for these outbreaks was thought to be the introduction of an exotic viral pathogen, uncontrolled proliferation of farm operations and related aquatic environmental implications appear to have made a direct contribution. Similarly, lack of planned development was identified as one of six constraints on shrimp farming and suitable locations in the NW were said to be almost saturated (Piyasena, 1996).

Currently, the shrimp culture sector in Sri Lanka is facing many of the problems previously encountered in other countries. The technical knowledge base of the majority of the shrimp farmers is very low and becoming increasingly so, as more small-scale farms are developed. Shrimp farming is still relatively small scale in Sri Lanka with a total area of approximately 2600 ha according to Funge-Smith (1998). These farms can be broken down by surface area as shown in Table 1.

The majority of the unregistered farms have encroached into reserved areas and are small farm operations – their size generally being below 2–3 ha. Farms over 4 ha are required to fulfil Initial Impact Investigation or Environmental Impact Assessment; small farms are exempted from this and this has contributed to the proliferation of small illegal operations.

Table 1 Size and relative occurrence of shrimp farms in Sri Lanka (Funge-Smith, 1998).

Area (ha)	**% of total area**
> 20	32
10 - 20	9
4.5 - 10	15
2 - 4.5	10
< 2	6
Unregistered farms	28

Small farms are usually owner operated and do not have a high level of technical input. There appears to be some form of technical service available whereby farmer groups are visited by local consultants. Large farms have well trained managers – often with overseas experience.

It is the lack of accurate information available to the farmers that results in inappropriate farming techniques, disease and production losses.

Plans are currently underway to develop shrimp farms in other parts of the country, utilizing seawater abstracted from the sea (full salinity) and not the brackishwater usually found in the Northwest Province lagoon systems. Culture in full strength seawater is possible providing a regular water exchange regime is practiced. Alternatively culture should only take place during the monsoon or rainy season, to prevent excessive salinity in the ponds. Before these developments proceed further, it is important to establish the principle factors underlying the disease problems in the Sri Lankan shrimp industry.

There is also the consideration that the Northwest Province may provide much of the country’s broodstock, and the development of shrimp farms in this area would certainly increase the risk of contamination of the broodstock supply.

Objective of the study

The main objective of this study has been to demonstrate, under operative conditions, and in support of TCP/SRL/6712 “Revitalization and Acceleration of Aquaculture Development” the usefulness of high resolution SAR data for the inventory and monitoring of shrimp farms, in view of developing and field testing adequate methodologies for future use in similar environments elsewhere.

To achieve this objective in the Sri Lanka case study, ERS SAR satellite data, acquired in 1996, 1998 and 1999, have been processed for shrimp farms inventory, and the resulting information has been compared to substantiate changes and trends in the development of shrimp farms.

Basically, the Sri Lanka Government requires up to date information on the spatial distribution of shrimp farms in order to enforce development regulations and in order to ensure a productive environment for shrimp farming with the least impact on other uses of land and water resources.

This study is timely because it coincides with two related activities, one of which is the zoning of aquaculture in Sri Lanka, and the other on disease prevention and health management in shrimp farming, both of which are FAO Technical Cooperation Programme projects.

Study area

The area under examination occurs along the western coast of Sri Lanka, north of Colombo (Figure 1 and Figure 2), approximately from 8° 23' to 6° 50' North Latitude (Table 2), covering a strip 30 km wide at its maximum and 172 km long. It is a coastal flatland, characterized by a series of inland lagoons and lakes (from North to South: Puttalam Lagoon, Mondal Lake and Chilaw Lake) connected by channels, meandering rivers and creeks.

The vegetation existing prior to the development of shrimp farms is reported in the 1984 topographic maps as being mainly composed of low forest, grassland and mangroves; the main agricultural crops were rice and coconuts.

Shrimp farms, which cover extensive portions of this area, can be subdivided into two major groups: industrial and artisanal.

Industrial shrimp farms (Figure 3) cover usually large areas with individual shrimp ponds arranged in an orderly way, rectangular in shape and all of the same size, with average dimensions of 30 x 50 metres. Industrial shrimp farms are usually surrounded by high walls or fences, in consideration of the considerable value of their product. Conversely, artisanal shrimp farms cover relatively small areas, the shrimp ponds are of various sizes and, often, of various shapes, and dykes surrounding individual ponds are less prominent than that occurring in industrial shrimp farms. Further, the shape of the complex is somewhat irregular as it exploits natural areas along creeks and canals.

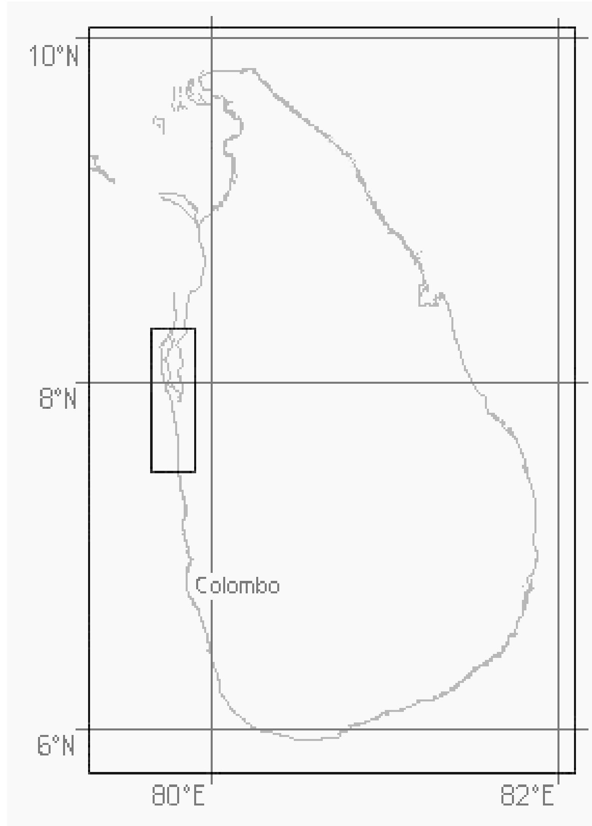


Figure 1 Study area (geographic reference grid).

The study area is fully covered by two ERS SAR frames (Table 3). For monitoring purposes four different data sets were studied, acquired respectively by ERS 1 on 18 April 1996 and by ERS 2 on 3 July and 16 October 1998 and 5 March 1999.

The ERS SAR GEC (geocoded) data have a spatial resolution of 12.5 x 12.5 metres. Each scene covers an area of 100 x 100 km. Nominal frequency of data acquisition over a given area is of 35 days. The adopted projection is UTM (Zone Number 44N, spheroid and datum WGS84).

Table 2 Coordinates of the study area.

UTM 44N, WGS84	Upper left corner	Lower right corner
Northing (y)	928340	755690
Easting (x)	352219	382007

Table 3 Satellite data used in the study.

ERS SAR GEC	Orbit/Frame	Acquisition date
ERS 1	24885/3465 and 3447	18/04/1996
ERS 2	16735/3465 and 3447	07/03/1998
ERS 2	18238/3465 and 3447	16/10/1998
ERS 2	20242/3447	05/03/1999

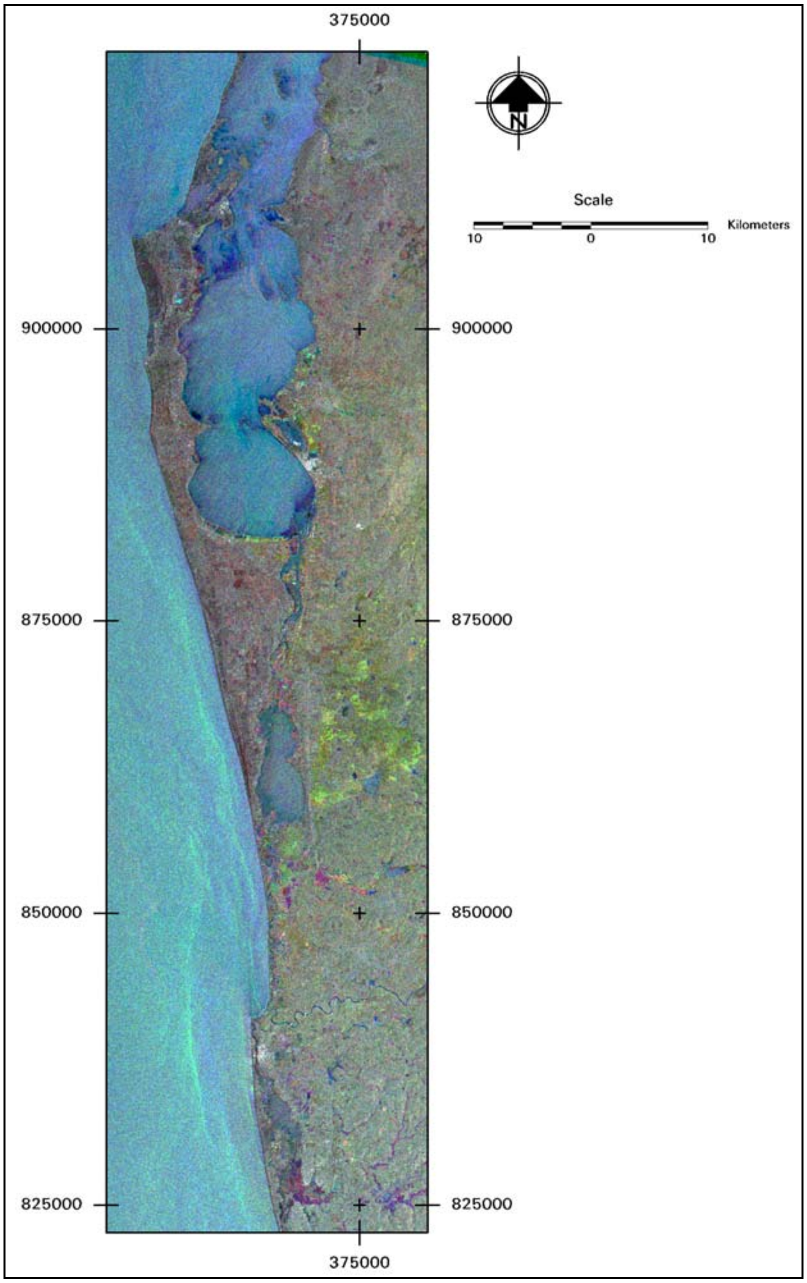


Figure 2 False colour composite of three ERS SAR images of the study area.
Red: 18/04/96, Green: 03/07/98, Blue: 18/10/98.

Materials and Methods

Shrimp farm mapping by imaging radar

The identification of shrimp farms (Figure 3) on SAR images is based on several elements: the signal received from the water surface of the ponds and from their surrounding dykes, the shape of the individual ponds, the pattern of groups of ponds and the relative direction of the dykes vis-à-vis the incoming radar beam. The location of shrimp farms is also typical, thus the analysis of their position and of the former land use of the area is necessary to verify the identification.

All these elements are discussed in the following sections.

Figure 3 Industrial shrimp farm (south of Chilaw Town).

SAR signal of ponds and dykes

Water-covered surfaces, such as shrimp ponds, are easily identifiable on SAR images due to their characteristically low response, resulting in a very dark grey level. The reason for the low response of water-covered surfaces, as well as of other very smooth surfaces, lies in the wavelength employed and in the peculiar acquisition geometry of SAR images.

The ERS SAR system operates in the C-band ($\lambda \cong 5.6$ cm), and the angle between the perpendicular to the imaged surface and the direction of the incident beam is approximately 23°. According to the Rayleigh criterion, a surface is considered smooth if the mean height of its structure is smaller than the incident wavelength. Small water bodies generally satisfy this condition, and according to Fresnel's Law, they reflect all the incoming radiation at an angle equal to the incidence angle, thus away from the satellite antenna (Figure 4). Consequently, the signal received from a small water body approaches zero, and the water body is visualized as a dark grey surface (Figure 5).

The identification of low-reflecting surfaces in an image is a simple task. Unfortunately, a low response is obtained by all calm water bodies, such as small lakes, reservoirs and flooded areas. The problem in identifying shrimp ponds on SAR images is then focused on separating the various kinds of low-reflecting surfaces by means of their peculiar characteristics of shape and pattern, and the characteristics of their neighborhood.

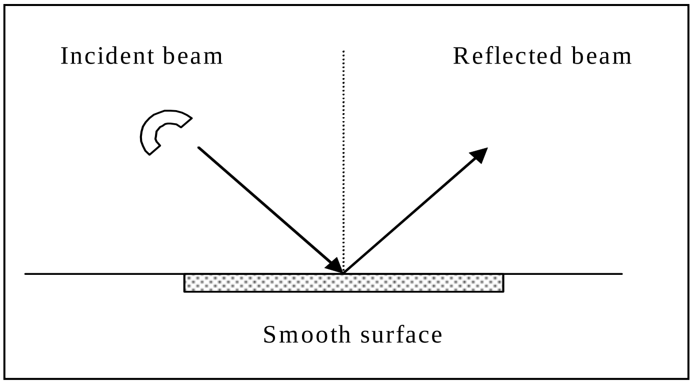


Figure 4 Interaction of a radar beam with a smooth surface.

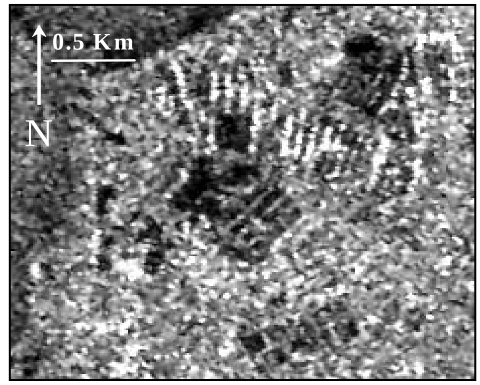


Figure 5 ERS SAR, 18/04/96: shrimp ponds at Vidatamunai, Puttalam Lagoon.

Shrimp ponds, unlike other water bodies, are surrounded by dykes. A dyke is an earthen wall whose thickness ranges approximately from half a metre to several metres, and whose elevation from the water surface is at the most a metre. The surface of a dyke can be considered smooth; the radar beams interaction with the dyke depends on their relative position.

If the long axis of a dyke is perpendicular to the cross-track direction, the resulting radar beam paths are shown in Figure 6. The radar beams that reach the upper part of the dyke are reflected in the direction opposite to the sensor, giving no return signal.

The beams which reach the vertical part of the dye are reflected towards the water surface of the pond first, then back to the sensor, generating a very strong return signal.

The same happens to the beams which hit the water surface near the dyke: they are first reflected towards it, then back to the sensor. If part of the dyke is inclined, the beams, which hit it, are reflected directly into the sensor, generating an even stronger return signal.

Another consequence of this peculiar imaging geometry is that the position of the dyke in the image appears to be shifted towards the sensor (layover effect: Figure 6).

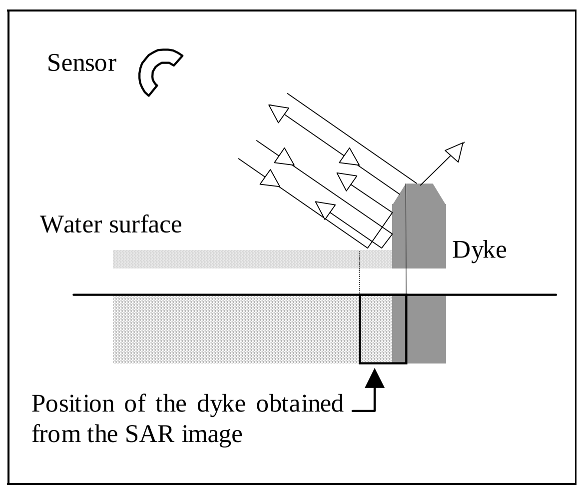


Figure 6 Interaction of radar beams with a dyke.

The value associated with an ERS SAR image pixel (digital number, DN) is given by the average signal received from the corresponding surface on the ground. When a portion of the ground contains a small but highly reflective feature, the average signal is almost equal to the imaged feature, which appears then to be as big as the entire pixel. The object has "saturated" the pixel's value. This effect is caused by the dykes as well. The dykes are long but narrow structures, thus the DN value of a pixel is made up by the return signals from both a portion of the dyke and its surroundings. However, a dyke's return signal is so strong in comparison with the low signal of the water-covered ponds that the resulting value of the pixel is very high.

The multiple reflection effect spreads the high return signal to the surrounding pixels, increasing their values as well. Therefore the dyke, when perpendicular to the incoming radar beam, is easily identified in the SAR image as a white stripe (Figure 5) composed of several adjacent pixels, thus thicker than in reality.

Paddy fields are surrounded by smaller and lower dykes, which do not generate the same effect and consequently are not identifiable in SAR images.

The multiple reflection effect discussed above and its consequences take place on the portion of the dyke that directly faces the incoming radar beam. Consequently, the intensity of the return signal depends on the angle between the cross-track direction and the direction of the longer side of the dyke (Figure 7).

When a dyke is perpendicular to the cross-track direction, all the corresponding pixels have a very high return signal, as discussed previously.

When the angle between the longer side of the dyke and the cross-track direction decreases, the multiple reflection effect decreases as well. The resulting signal is weaker, and the dyke's pixels are displayed as darker grey in the SAR image.

Finally, when a dyke is parallel to the cross-track direction, it barely interacts with the radar beams, and is thus characterized by very dark grey tones in the image.

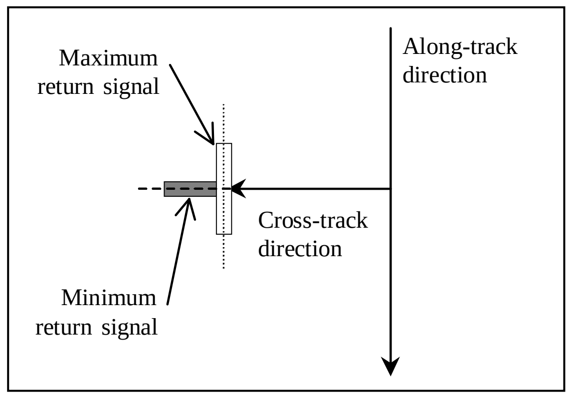


Figure 7 Return signal as a function of the angle between a dyke and the cross-track direction.

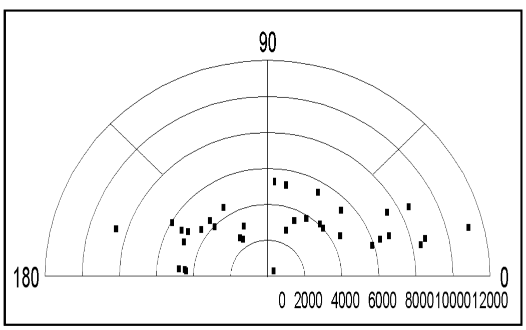


Figure 8 Dyke’s average values (DN) vs bearing (deg.)

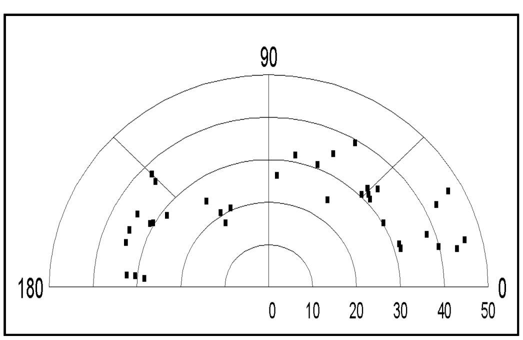


Figure 9 Dyke’s average thickness (m) vs bearing (deg.)

It has been observed previously that the dykes perpendicular to the cross-track direction appear to be thicker than they really are, due to the saturation effect. Dykes positioned at smaller angles from the cross-track direction have lower return signals; the saturation effect decreases and their apparent thickness decreases as well. When the angle between a dyke and the cross-track direction is zero, i.e. the dyke is parallel to the cross-track direction, it is barely visible in the image.

Both of these effects are evident in the ERS 1 SAR image of 18 April 1996 (Figure 5).

The average DN values and thickness of 35 dykes in this image have been plotted in Figure 8 and Figure 9. The two graphs show the effects explained above.

The along-track direction of the satellite during the acquisition was 192.5 deg. North.

Dykes parallel to the along-track direction (i.e. bearing 12.5 deg. North) look very bright and large in the image. At increasing angles between the dykes and the along-track direction, the dykes appear grayer and thinner. Finally, dykes perpendicular to the along-track direction (i.e. bearing 102.5 deg. North) are not visible in the image.

The most important consequence of the dykes' intensity and thickness variations with bearing is that they cannot be identified through automatic or semiautomatic image processing procedures, because both these procedures identify surfaces only if their characteristics are constant in the entire image.

From the above discussion it follows that automatic or semiautomatic SAR image analysis allows identification of all water-covered surfaces, including shrimp ponds, and high reflective surfaces, including the dykes positioned perpendicularly to the sensor's cross-track direction. It is then necessary to use visual interpretation techniques to recognize the shrimp ponds among these surfaces. These techniques, applied by an operator, take into account the dykes' variations in intensity and thickness with bearing, plus shape and pattern of ponds and dykes. The latter elements are discussed below.

Size, shape and pattern of ponds and other water-covered surfaces

The characteristics of all kinds of water-covered surfaces in the study area must be analyzed to infer the peculiarities in the appearance of ponds and groups of ponds in SAR imagery, and define both the identification criteria and the minimum identifiable pond size.

As indicated, two kinds of shrimp farms are present in the study area (Figure 10): industrial and artisanal shrimp pond systems.

- *Industrial shrimp farms* are generally large, rectangular in shape and associated in a pattern of regularly alternating dykes and similarly sized ponds.
- *Artisanal shrimp farms* are generally smaller in size, less regular in shape and form groups without a regular pattern; also, their surrounding dykes are less evident.

Both kinds of shrimp farms are located along rivers, canals and creeks.

Other water-covered features present in the study area are reservoirs, lakes, rice paddies and flooded surfaces of various kinds.

Lakes and reservoirs (Figure 11) cannot be misidentified as shrimp ponds because they are large, isolated features with irregular shape. Moreover, part of their surface may be roughened by wind, or covered by vegetation; in these cases they appear noticeably less dark than ponds or paddies.

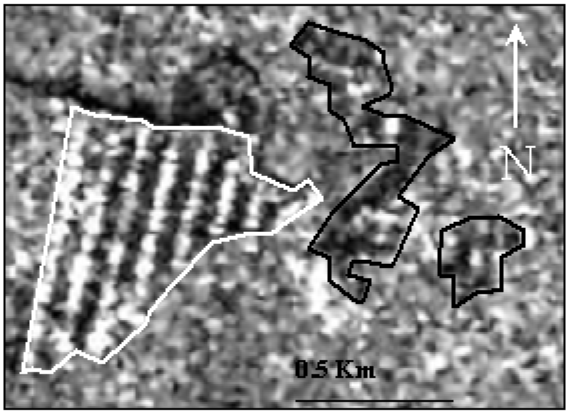


Figure 10 Industrial and artisanal shrimp farms.
ERS 1 SAR, 18/04/96

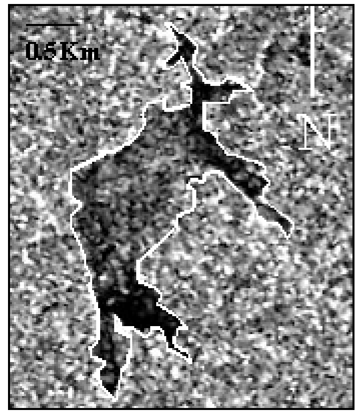


Figure 11 A reservoir.
ERS 1 SAR, 18/04/96

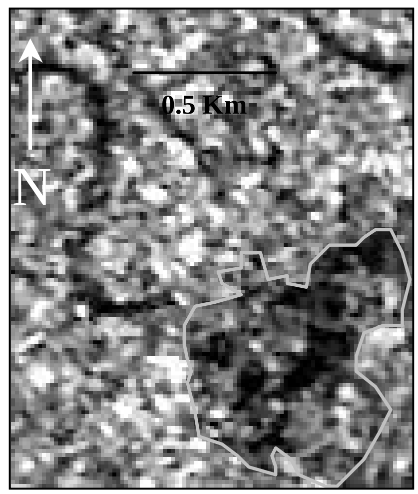


Figure 12 Rice paddies and their appearance on 18/04/96 ERS 1 SAR image (grey-outlined area)

a) Flooded fields

b) Flooded bare soils

c) Flooded grassland along a river bank

Figure 13 Flooded surfaces in the study area

Rice paddies (Figure 12), when flooded in the early stage of rice cropping, are surrounded by very small dykes, and are characterized by varying size, almost rectangular shape and lack of regular pattern. Therefore adjacent paddies, when flooded, may be easily confused with groups of artisanal shrimp ponds.

Three potentially flooded surfaces occur in the study area: agricultural fields, bare soil and grassland along rivers and creeks (see Figure 13).

Flooded agricultural fields (Figure 13a) have regular shape; their appearance on SAR images is indistinguishable from shrimp ponds or rice paddies.

Bare flooded soils (Figure 13b) are characterized by irregular shape and low response intensity, and are located along rivers and creeks. This position may cause them to be confused with shrimp ponds whenever their extension is small and their irregular shape cannot be appreciated.

Flooded grassland along rivers and creeks (Figure 13c) is easily misinterpreted as artisanal shrimp farms or small rice paddies, while dense flooded vegetation may only be confused with rice paddies.

The analysis of size, shape and pattern of water-covered surfaces allows an easy identification of large water bodies and water body associations, such as reservoirs and industrial shrimp farms. Difficulties arise in recognizing artisanal shrimp farms, due to their limited size. Small flooded surfaces may also lead to misidentification errors.

Theoretically, a water body is detectable in an image even if its surface is smaller than a pixel's, because of the saturation effect. When a portion of the ground corresponding to a pixel (12.5 x 12.5 m) contains a small and very low-reflective feature, the pixel's value is low as well, and can easily be identified as a water-covered surface. Unfortunately its shape and pattern are not defined, so it is impossible to infer its nature.

Thus, even if it is possible to identify water bodies up to 10 x 10 m in size, a shrimp pond must be at least a few pixels wide to be recognized as such. Even so, the identification is uncertain.
The artisanal shrimp ponds are generally small, and the surrounding dykes are not always evident. Often these shrimp ponds are also irregularly grouped, and consequently they may be confused with paddies or small flooded surfaces.

Thus, to confirm the identification of artisanal shrimp farms, the operator must analyze their location and previous land use, as explained in the following sections.

Location of shrimp farms

Shrimp farms require brackish or salt water. Consequently, shrimp ponds must be located along rivers and creeks, in proximity to lagoons. A system of channels carries water from the river through the connected ponds, and then back to the river.

The topographic maps of the study area, produced in 1984, show that the majority of shrimp ponds have been built over uncultivated land, such as mangroves and swamps. In some cases the ponds are located over former forest and coconut plantations; only rarely has there been a conversion of land use from rice paddies to shrimp ponds.

Thus the former land use may help in distinguishing between shrimp ponds and other water-covered surfaces.

Water coverage throughout the year

Another characteristic that differentiates shrimp ponds, paddies and flooded surfaces is the water coverage throughout the year. Shrimp ponds usually are covered by water, while paddies are flooded only during the early stage of rice growth.

Sri Lanka has a tropical climate, and therefore the stages of rice cultivation may not be related to the seasons. Thus all phenological stages of rice can be present at the same period of the year. Consequently, it is not possible to distinguish between paddies and shrimp ponds by a temporal criterion only: whenever a SAR image is acquired, both flooded and dry rice fields may simultaneously occur on it.

The presence of flooded surfaces is instead related to the occurrence of rainfall, which is in turn seasonal. By acquiring SAR images in a dry period of the year it is possible at least to minimize the occurrence of flooded surfaces, thus improving the identification of shrimp ponds.

The rainfall over the study area in 1998 is shown in Fig. 14. From the graph it is evident that the SAR image acquired in April 1996 corresponds to a rainy period, while the two ERS SAR images acquired in 1998 (Table 2) correspond to a dry (July) and a wet (October) period, respectively. By comparing the water-covered surfaces identified in the two 1998 images, it is thus possible to improve the discrimination between shrimp ponds and flooded surfaces.

<u>Image analysis procedure</u>

The inherent characteristics of shrimp ponds and of other kinds of water-covered surfaces in SAR images, as indicated in the previous paragraph, allow an image analysis methodology to be designed in order to identify and map shrimp farms.

All water-covered surfaces have a peculiar appearance in SAR images. They may be easily identified and mapped using automatic classification techniques. It is then necessary to recognize shrimp ponds among the different kinds of water bodies.

Unlike other water bodies, shrimp ponds are delimited by dykes. The dykes are identified in the image using automatic boundary detection and classification techniques. Therefore to identify shrimp ponds it is necessary to search the images resulting from classification of water bodies for evidence of dykes in the strip of terrain surrounding the water-covered surfaces. This is done by means of proximity analysis techniques.

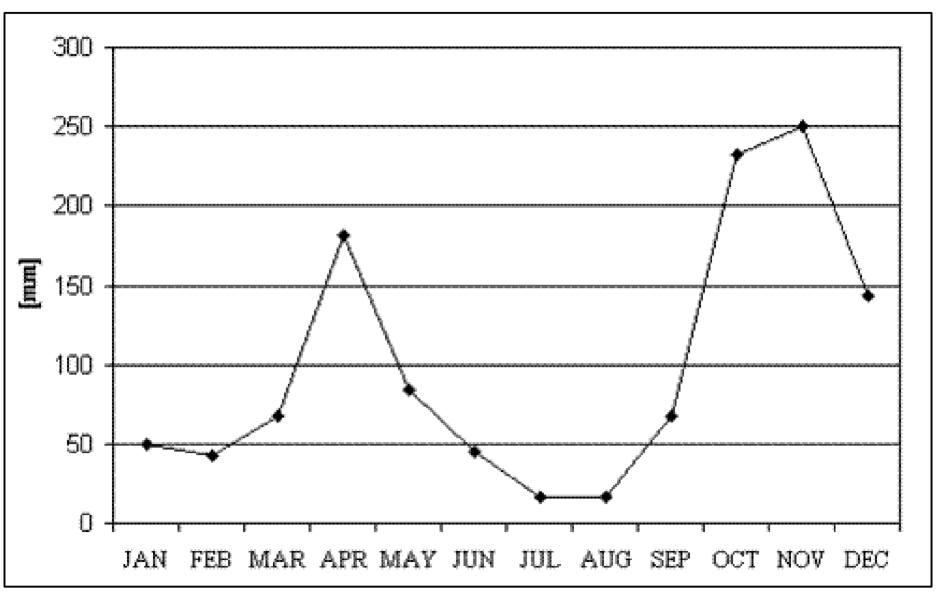


Figure 14 Monthly rainfall at Puttalam (Sri Lanka), 1998

This approach produces images containing water-covered surfaces and the terrain surrounding them, showing strong-reflecting and weakly-reflecting boundaries. These images are the result of automatic procedures, and summarize the information on shrimp farms that can be obtained from a SAR image. They are thus named "summary images".

The summary images must then be visually analyzed by an operator, who identifies shrimp farms among the other water-covered surfaces by means of visual interpretation techniques. These include the evaluation of shape and pattern of water bodies and of the presence of well-defined boundaries surrounding them.

Finally, a confirmation of the identifications is made by examining the location and previous land use of the selected areas, obtained from topographic maps.

The analysis procedure is summarized in Figure 15. The steps are discussed in the following paragraphs.

Pre-processing

The first step of the procedure aims at preparing the data for the analysis proper.

The study area is covered by pairs of frames that must be mosaiced, i.e. attached together to form a unique image, from which the study area is selected and extracted. The images of the study area must then be filtered to minimize the typical noise of SAR images, called *speckle*.

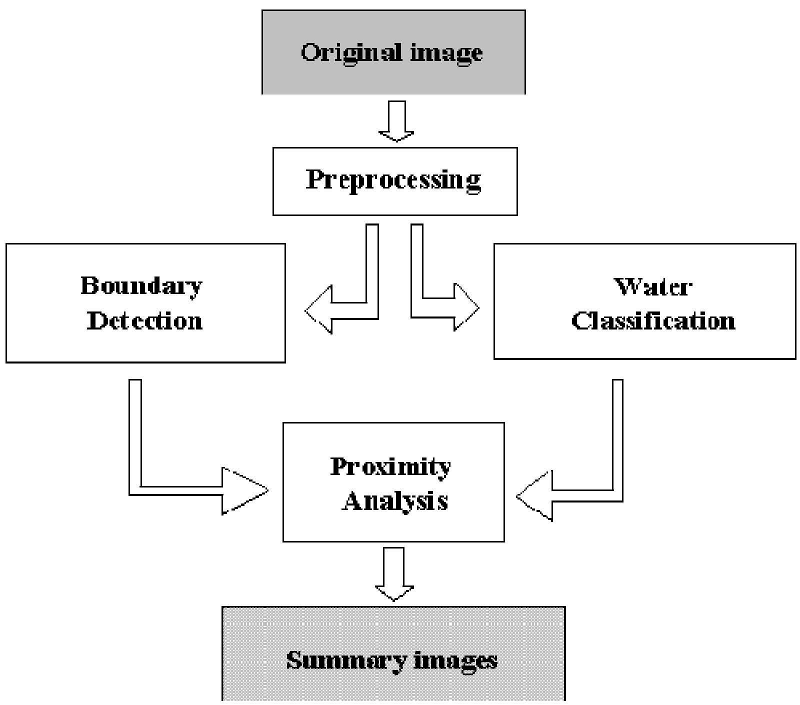


Figure 15 SAR image analysis procedure

Image mosaicing

The three georeferenced ERS SAR frames that cover the study area (Table 3) partially overlap. They have been attached overlapping the northern frame (3447) over the southern (3465).

From each of the three mosaics a strip containing the study area has been selected and extracted (Figure 1 and Table 2). These three strips have been used as reference images for further analysis, after geometric correction to ensure that they would perfectly overlay.

Inside the study area, three sites characterized by different kinds of shrimp farms have been selected to test the image processing procedures:

1. The area from Vidatamunai to Seguwantiyu, Manativu Division; it contains several groups of medium-sized shrimp farms and many smaller ones.

2. The Uppadaluwa area, in the Satapolai Division; it contains a group of large, industrial shrimp farms.

3. The northern part of the Dutch Canal. Large groups of small-sized shrimp farms cover all the islands in the Canal and its neighboring terrain.

The location of the test sites is shown in Fig. 16, and their coordinates are listed in Table 4.

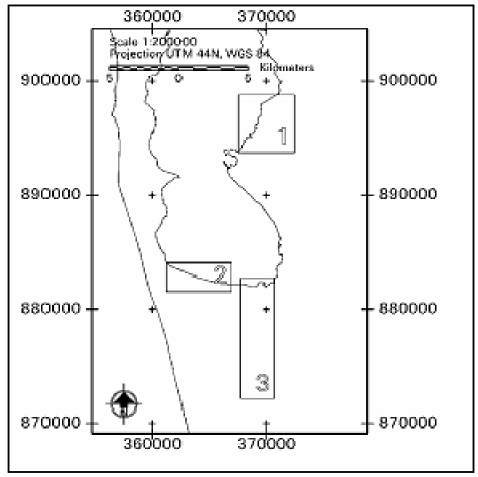


Figure 16 Location of the test sites

Table 4 Coordinates of the three test sites.

Test sites	**Upper left corner**		**Lower right corner**	
UTM 44N, WGS 84	**Northing (y)**	**Easting (x)**	**Northing (y)**	**Easting (x)**
Manativu Division	898743.75	367506.25	893756.25	372493.75
Uppadaluwa	884043.75	361256.25	881556.25	366868.75
Dutch Canal	895618.75	381881.25	889993.75	387506.25

Speckle removal

SAR images are affected by a kind of noise called speckle. The speckle causes randomly scattered pixels to have particularly high or low values, thus increasing the error in classifying low-reflecting surfaces as water-covered surfaces.

The speckle is minimized by applying speckle suppression filters to the image. A filter is a matrix of values (also called template, box, window or kernel), whose dimensions are chosen by the operator. The filter matrix is moved over the image row by row and column by column. The pixel values covered by the matrix at a particular position are then used to define a new value for the pixel corresponding to the central element of the matrix (Richards, 1993). The noise reduction is generally accompanied by a loss of details; therefore the choice of the filter depends both on the characteristics of the image and on the kind of subsequent analysis.

The aim of the present study is to identify shrimp ponds, which may be small in extension, thus the loss of detail must be kept to a minimum. Also, the presence of noise may be partially tolerated as part of the analysis is performed visually by an operator. Finally, the entire image processing procedure must be as simple as possible, including the noise reduction technique, to allow for its use by people not highly trained in SAR image analysis and interpretation.

In order to choose the speckle removal procedure that satisfies those requirements, the following speckle suppression filters provided by ERDAS IMAGINE (version 8.3) have been tested:

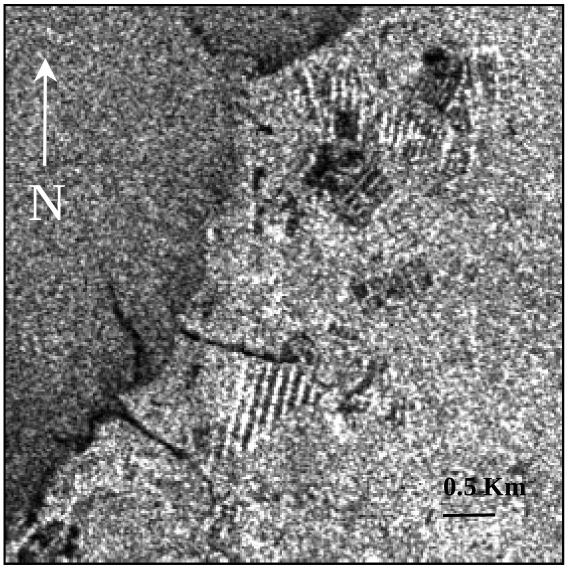
- *Lee-Sigma filter:* replaces the pixel of interest with the average of all DN values within the moving matrix that fall within the selected range of standard deviation.
- *Local Region filter:* divides the moving matrix into eight regions based on their angular position respect to the pixel corresponding to the central element of the matrix (North, South, East, West, NW, NE, SW, and SE). Then selects the region in which the pixels have the lowest variance, and average their values to obtain the new value of the central pixel.
- *Lee filter:* is based on the assumption that the mean and variance of the pixel of interest is equal to the local mean and variance of all pixels within the user-selected moving matrix.
- *Frost filter:* is a minimum mean square error algorithm which adapts to the local statistics of the image to preserve edges and small features.

These filters are generally applied iteratively until the desired effect is reached. Three combinations of filters have been applied to the three test sites and their results have been visually analyzed to choose the one which satisfies the balance between noise reduction and identification of the smallest shrimp ponds:

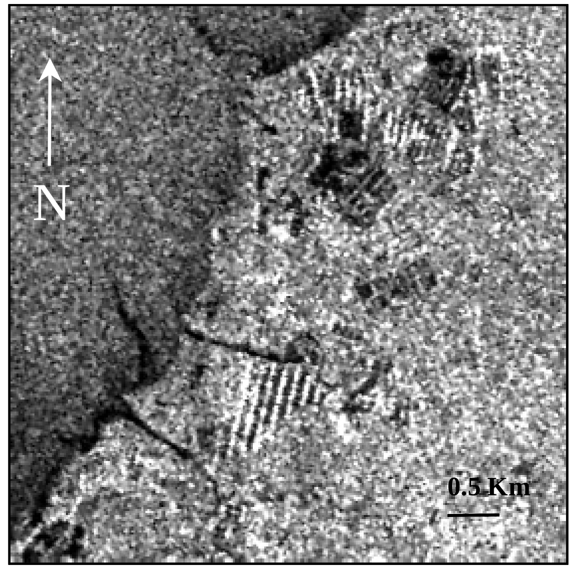
1. Three applications of Lee-Sigma filter, increasing the window size (3 x 3, 5 x 5, 7 x 7) and increasing the coefficient of variation multiplier (0.5, 1, 2);
2. Application of Lee and then Local Region filters at constant window size (5 x 5);
3. Three applications of Frost filter, at increasing window sizes (3 x 3, 5 x 5, 7 x 7).

Analysing each passage of the three filtering sequences on the test sites it has been noted that the smallest shrimp ponds are still visible only after a single application of the Frost filter, using a 3 x 3 moving matrix. Therefore the three images of the study area have been subjected to this filter to conclude the preprocessing procedure.

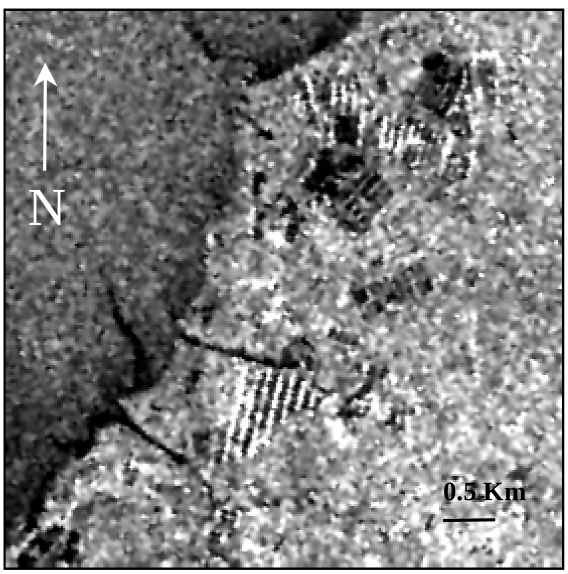
The images obtained from the sequential application of the Frost filter to the Seguwantiyu test site are shown as example in Figure 17.



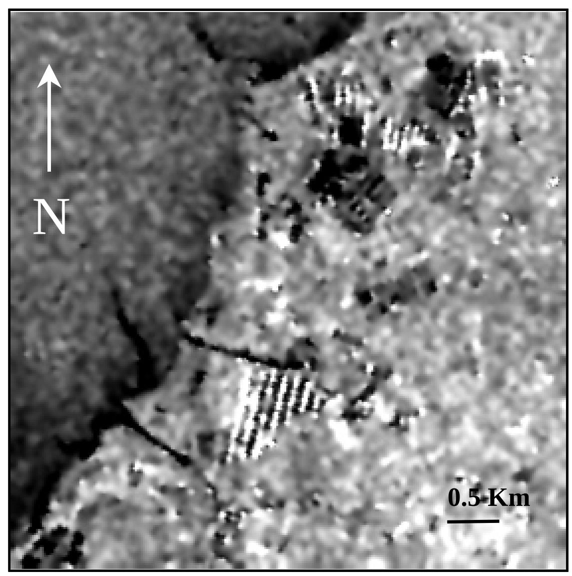
a) Original image



b) First application of Frost filter, 3 x 3



c) Second application of Frost filter, 5 x 5



d) Third application of Frost filter, 7 x 7

Figure 17 Sequential application of Frost filter to the image of Seguwantiyu test site

Classification

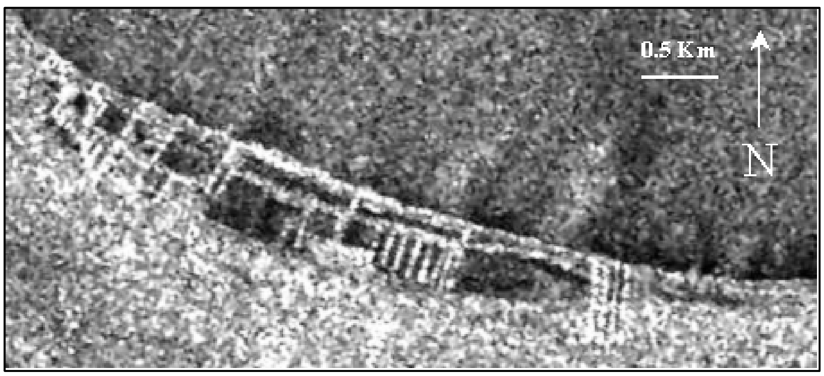
The purpose of this part of the analysis procedure is to identify water bodies, and possibly dykes, in the ERS SAR images. The identification of other types of land cover is not required. Thus, the images can be analyzed only by means of unsupervised classification procedures or by histogram thresholding.

As described in the preceding paragraph, water bodies are characterized by typically low values in SAR images. Conversely, the values of dykes surrounding shrimp ponds vary in SAR images according to their position relative to the satellite cross-track direction. Thus, dykes perpendicular to the cross-track direction have typically high values; dykes parallel to the cross-track direction are not visible in the image, and dykes at intermediate angles have values similar to those of other surfaces.

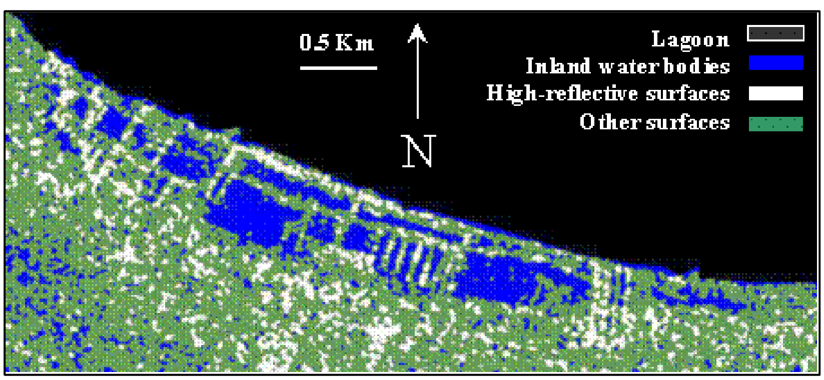
The analysis procedures are thus expected to identify water bodies and high-reflective surfaces, including some dykes. Other kinds of land cover are not of interest and the procedures assign all of them to another class.

The images acquired on 18 April 1996 on the three test sites and filtered with one passage of 3 x 3 Frost filter have been first classified using the ISODATA unsupervised classification procedure (Lillesand and Kiefer, 1987). The operator is required to specify the number of classes to identify (three in this case) and input the coastline that defines the area where the procedure is applied. After, the operator must visualize the results and identify the surface covers corresponding to the classes obtained from the procedure.

The procedure is thus almost completely automatic. The classifications obtained for the three test sites have been compared with the available ground truth. The unsupervised classification performs satisfactorily; for example, see the Uppadaluwa classified image in Figure 18.



a) ERS SAR image 96/04/18, filtered with a 3 × 3 Frost filter



b) Unsupervised classification of image a)

Figure 18 Mapping of water bodies, Uppadaluwa test site

The second analysis procedure that may be applied to SAR images to identify water bodies and high-reflective surfaces is named histogram thresholding. It is a supervised procedure: the operator must analyse the image histogram to identify the peaks corresponding to water, high-reflective surfaces and other surfaces, and define the threshold digital values that separate them. All the image values are thus assigned to one of the three classes comparing their values with the threshold values. The operator is thus able to guide the assignment until a satisfactory result is obtained. The thresholding procedure has been applied to the same images of the three test sites. The results are almost identical to those obtained from the unsupervised classification. As thresholding requires a greater amount of operator's time, it is suggested to use the unsupervised classification instead.

Boundary detection

The dykes surrounding shrimp farms may also be identified applying edge detection filters on ERS SAR images. These filters have the purpose of identifying the boundaries between homogeneous areas; the other information is lost in the output image. The Sobel filter (Richards, 1993) has been chosen for this study.

This filter is a non-directional operator that simultaneously calculates the horizontal and vertical gradient in the portion of the image covered by the filter kernel.

The result is equivalent to the simultaneous application of two directional kernels (Fig. 19 a and b).

1	2	1
0	0	0
-1	-2	-1

a) horizontal

-1	0	1
-2	0	2
-1	0	1

b) vertical

-2	-1	0
-1	0	1
0	1	2

c) Z-diagonal

0	1	2
-1	0	1
-2	-1	0

d) S-diagonal

Figure 19 Directional Sobel filters.

The application of each filter produces an output image that contains only the edges, defined by lines two pixels wide. A color combination of the filtered images allows an enhanced visualization of the boundaries in the study area (Figure 20).

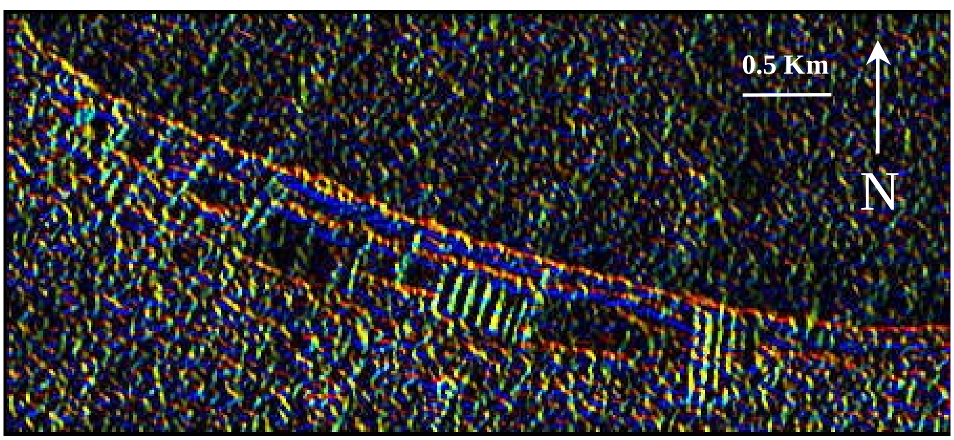


Figure 20 Uppadaluwa test site. Sobel filters applied to the 96/04/18 ERS SAR image. S-diagonal edges are displayed in red, vertical edges in green and horizontal edges in blue.

Proximity analysis

The occurrence of highly reflective surfaces around water surfaces is an indication of the presence of shrimp farms. The proximity analysis examines the boundaries of water bodies obtained from the unsupervised classification, up to a user-specified distance, to locate both highly reflective surfaces in the classified image and edges in the Sobel filtered images. The proximity analysis produces two "summary images" that synthesize the shrimp ponds-related information contained in an ERS SAR image.

The summary images allow the operator to locate the areas where there is a greater evidence of the occurrence of shrimp farms, and help in tracing the farms' boundaries.

Figure 21 shows the overlap of the two summary images for the Uppadaluwa test site.

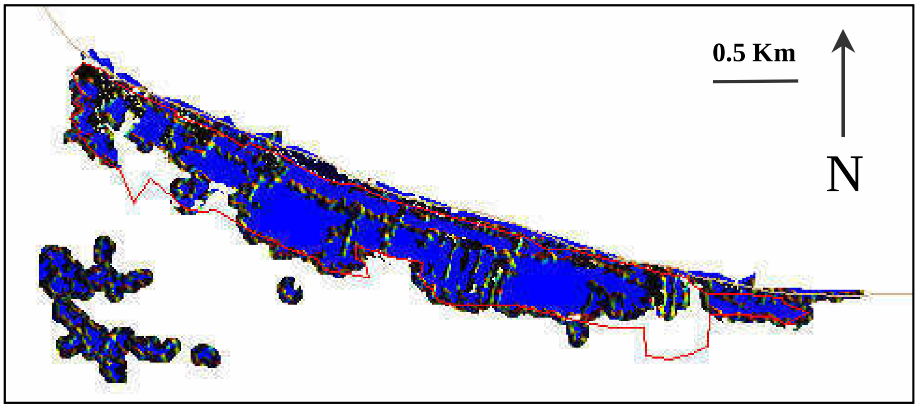


Figure 21 Uppadaluwa test site. Overlap of the two summary images and shrimp farms map obtained by visual interpretation (red line). The coastline is traced in brown

Highly reflective surfaces and sharp boundaries are displayed in black tones, water bodies are blue.

This figure shows also how the areas displayed in the summary images have been further analyzed using the criteria outlined in the first paragraphs of this chapter. The cluster of small water bodies located in the lower right corner of the image has been identified as rice paddies. The identification of the larger group of water bodies as shrimp farms has been confirmed and its contour traced on the SAR image using the summary image as reference, and completing it visually with the addition of a few areas of smaller ponds which had not been enhanced by the automatic procedure.

Field verification

Field verification was carried out by a four-person team, including the second author, in December 1998. The basic strategy was to verify the four classes produced by interpretation of ERS SAR data, reported on maps at a scale of 1:50 000: shrimp farms existing up to 18 April 1996, shrimp farms constructed between the former date and 16 October 1998, areas tentatively identified as shrimp farms and inland water bodies. In order to cover as much of the area of interest as possible, verification sites were selected that were adjacent to main roads. In order to discriminate between shrimp farms constructed before and after 18 April 1996, it was necessary to interview knowledgeable people.

At each verification site, a location (in both latitude/longitude and UTM coordinates) and estimated position error ("epe", in metres) were obtained using a GPS receiver. Verifications were carried out from the southern limit of the area of interest to the NE extreme and nearly to the NW extreme. In all, 32 waypoints were acquired. At some points where there was certainty of location, observations without GPS coordinates served as supplemental verification sites. The location of the sites field-checked, the estimated positioning error and the results of the verification are reported in Table 5.

The ground truthing indicated an 86 percent accuracy of the interpretation. The field observations permitted the interpretation keys to be refined and in this way some potential misinterpretation of the SAR data were eliminated. The accuracy of shrimp farms mapping, revised after the field verification, is, thus, estimated to be more than 90 percent.

Table 5 Location of waypoints and results of the verification.

WP	Latitude			Longitude			epe[1]	Image interpretation[2]	Ground truth
n.	deg	sec	d sec	deg	sec	d sec	m	18/04/96,03/07/98,16/10/98,05/03/99	December 1998
1	7	27	37	79	49	63	26	Reservoir.	Reservoir (Matha Weva).
2	7	28	39	79	49	71	52	No shrimp farms identified.	Rice paddies, forest.
3	7	28	61	79	49	81	32	Reservoir.	Reservoir (Tinabitiya Tank).
4	7	30	6	79	49	64	24	No shrimp farms identified.	Plantations.
5	7	29	80	79	49	45	44	Shrimp farms (1999).	Shrimp farms in construction.
6	7	29	89	79	49	0	27	East: Shrimp farms (1999). West: Shrimp farms (1996).	East*:* shrimp farms in construction West*:* shrimp farms, built in 1995.
7	7	33	56	79	47	49	73	Shrimp farms (1996).	Shrimp farms, built before 1996.
8	7	32	67	79	47	71	40	Shrimp farms (1996).	Industrial shrimp farms.
9	7	30	92	79	47	98	33	Shrimp farms (1996).	Shrimp farms.
10	7	36	17	79	48	73	47	**Shrimp farms (1998).**	**Trees and sandy terrain.**
11	7	37	18	79	48	83	74	Shrimp farms (1996).	Shrimp farms, built before 1996.
12	7	38	31	79	48	58	41	No shrimp farms identified.	Rice paddies.
13	7	47	98	79	48	55	37	Shrimp farms (1996).	Shrimp farms, built before 1996.
14	7	39	58	79	48	11	38	Shrimp farms (1996 and 1998).	Shrimp farms.
15	8	13	52	79	45	21	23	**Shrimp farms (1998).**	**Partially flooded vegetation, marshland, flooded fields.**
16	8	11	11	79	44	49	26	Shrimp farms (1996).	Shrimp farms
17	8	10	56	79	44	52	23	Shrimp farms, uncertain assignment.	Abandoned shrimp farms, shrimp farms, bare and flooded areas
18	8	9	52	79	44	25	26	Shrimp farms (1996)	Shrimp farms, built in 1996
19	8	5	80	79	43	93	29	No shrimp farms identified.	Coconuts, mangroves, lagoon.
20	8	5	5	79	43	84	33	Shrimp farms (1996).	Shrimp farms
21	7	59	48	79	44	71	31	Shrimp farms (1996).	Shrimp farms.
22	7	59	19	79	44	94	53	Shrimp farms (1996).	Shrimp farms.
23	7	58	50	79	48	73	41	Shrimp farms (1996).	Shrimp farms.
24	7	58	20	79	48	70	30	Shrimp farms (1996 and 1998).	Shrimp farms.
25	7	58	79	79	49	35	28	Shrimp farms (1996), salt pans.	Shrimp farms, salt pans.
26	8	4	48	79	49	26	41	Shrimp farms (1996 and 1998).	Shrimp farms.
27	8	6	27	79	50	67	24	**Shrimp farms (1998)**	**Semi-inundated area and farmland**
28	8	6	88	79	50	26	37	Shrimp farms (1998).	Shrimp farms
29	8	6	53	79	50	15	51	Shrimp farms (1998).	Shrimp farms.
30	8	6	18	79	49	91	23	Shrimp farms (1998).	Shrimp farms.
31	7	52	82	79	48	93	25	**Right side of the road: shrimp farms (1996).** Left side: shrimp farms (1996).	**Right side of the road: vegetation.** Left side: shrimp farms.
32	7	47	93	79	49	24	41	**Shrimp farms (1996).**	**Lagoon, coconut and rice paddies**

[1] epe = estimated positioning error.
[2] Bold characters indicate interpretation errors.

Results

The methodology described in the previous chapter, with interpretation keys refined after the field verification of the preliminary results, was applied to the ERS SAR data of the study area acquired in 1996, 1998 and 1999. As inventory and monitoring of shrimp farms were the objectives of the study, the maps produced show only four classes, namely: 1) water bodies (lagoons, canals, creeks); 2) shrimp farms occurring up to 18 April 1996; 3) expansion of shrimp farms up to 16 October 1998; and 4) expansion of shrimp farms up to 5 March 1999.

To facilitate field use, seven maps at 1: 50 000 scale with UTM grid have been prepared. A union sheet at 1: 250 000 scale shows the entire study area and the relative position of the seven larger scale maps.

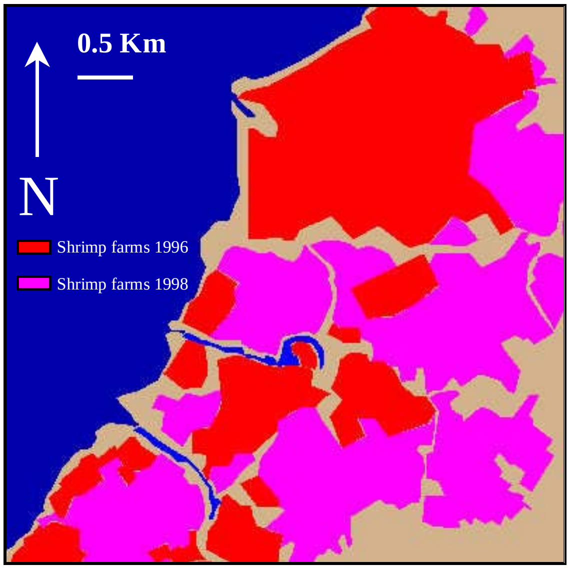


Figure 22 Shrimp farms map of the Seguwantiyu test site.

Figures 22, 23 and 24 show the inventory and monitoring of the expansion of shrimp farms at the three test sites. Tables 6, 7 and 8 quantify the results for each test site. Finally, Table 9 shows the comprehensive results of the mapping of the shrimp farms in the three test sites and in other portions of the study area.

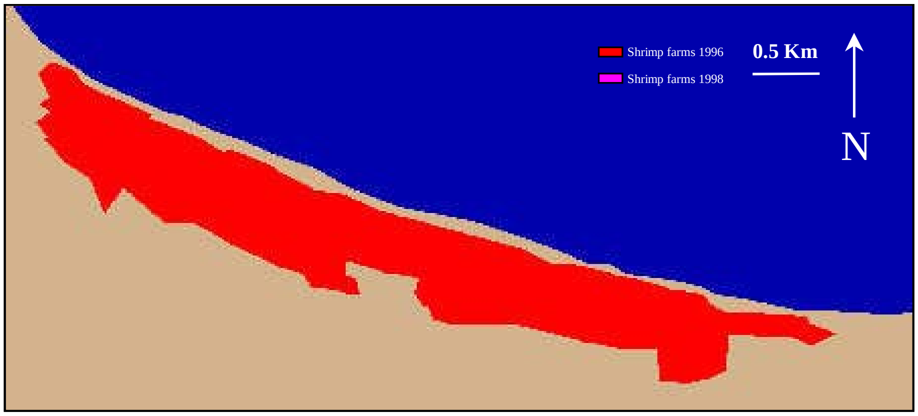


Figure 23 Shrimp farms map of the Uppadaluwa test site

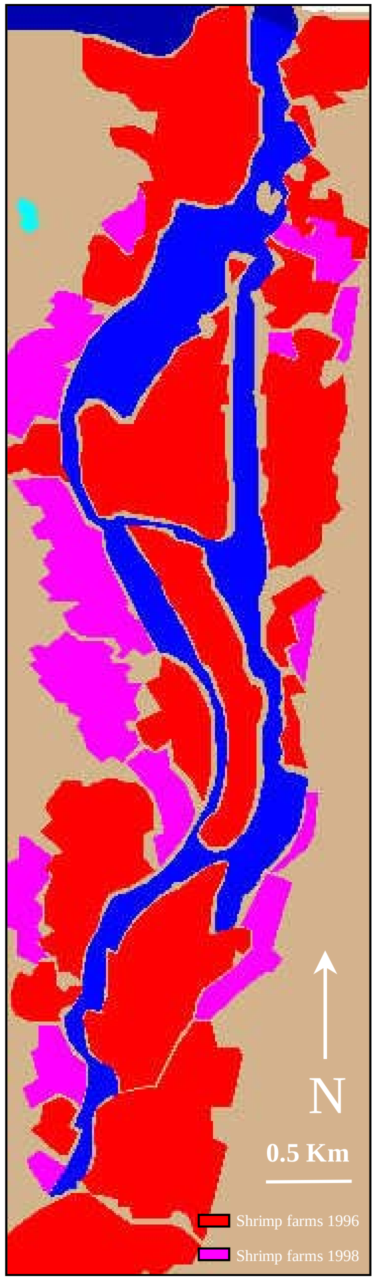


Figure 24 Shrimp farms map of the Dutch Canal test site

For the immediate use of the results by the FAO project TCP/SRL/6712, maps have been converted to IDRISI files and additional information such as roads, railroads and other reference points has been added.

Figures 22 and 24 clearly define the enormous expansion of shrimp farms in the Seguwantiyu and Dutch Canal test sites. Conversely, Figure 23 shows a static situation in the Uppadaluwa test site, probably because opportunities for the expansion of shrimp farms were few because of their already high density in this area on or before April 1996.

Table 6 Area coverage of shrimp farms at Seguwantiyu test site.

Class	Area (hectares)
Shrimp farms 1996	643.53
Shrimp farms 1998	1328.70
Shrimp farms 1999	1328.70
Difference 1999–1996	685.17

Table 7 Area coverage of shrimp farms at Uppadaluwa test site.

Class	Area (hectares)
Shrimp farms 1996	247.72
Shrimp farms 1998	247.72
Shrimp farms 1999	247.72
Difference 1999–1996	0

Table 8 Area coverage of shrimp farms at Dutch Canal test site.

Class	Area (hectares)
Shrimp farms 1996	1118.57
Shrimp farms 1998	1489.63
Shrimp farms 1999	1489.63
Difference 1999–1996	371.06

Table 9 Total surface covered by shrimp farms in Northwestern Sri Lanka.

Class	Area (hectares)
Shrimp farms 1996	6139.78
Shrimp farms 1998	8652.89
Shrimp farms 1999	8846.05
Difference 1999–1996	2706.27
Uncertain	213.39

The cumulative results in Table 9 indicate the rapid expansion of the shrimp farm industry in North-western Sri Lanka, which has increased its area coverage by 44.08 percent in less than three years.

Discussion

The methodology developed in support of TCP/SRL/6712 and field tested in the study area in Sri Lanka has proven to be reliable and very accurate. As far as we know, this is the first time that SAR imagery has been employed in this way. As indicated in the previous chapter, the field verification of location and occurrence of shrimp farms at 32 sites identified through ERS SAR images showed an 86 percent positive identifications. The calibration of the interpretation keys resulting from this field verification definitely increased the accuracy of the approach, as it has been possible to eliminate some potential misinterpretations of SAR data. It is thus estimated that the final accuracy of the methodology described in this report is more than 90 percent. Thus, the most recent estimate (1999) of shrimp pond surface area in North-western Sri Lanka is 8846.05 ha $\pm$ 885 ha.

Inventory and monitoring of shrimp farms are essential tools for decision-making on aquaculture development, including regulatory laws, environmental protection and revenue collection.

There are two main advantages to employing SAR for shrimp farms inventory and monitoring. The first is timeliness. Our results indicate that shrimp farming is growing at a very rapid rate in north-western Sri Lanka and that the surface is much more extensive than reported by Funge-Smith (1998). The second, an important advantage over traditional surveys, is that the resulting digital radar maps can be incorporated into an existing GIS. Once incorporated into the GIS, the shrimp pond locations can be evaluated in terms of a number of characteristics of site suitability and also with regard to prior uses of the land. In this way the development of shrimp farming can be planned and regulated in a more rational way than is possible without such information. In this regard, it is important to note that such information is of use not only to government, but valuable also to associations of commercial shrimp farmers whose underlying purpose is to maintain a dependable supply of good quality products at competitive prices.

The need for shrimp farm mapping is both qualitative and quantitative. In this regard, the results of this pilot study, reviewed in the preceding chapter, show that the location of commercial shrimp farms can be accurately obtained, and their collective size estimated with satisfactory results. It is sometimes difficult to estimate the area coverage of individual, small sized shrimp farms, but it is generally possible to estimate with good approximation the area coverage of a cluster of shrimp farms.

Once the potential of ERS SAR data for shrimp farms mapping has been tested and verified, it is necessary to perform a cost/benefit analysis of the entire procedure to assess its practical applicability. In this particular case, Table 10 indicates costs and time associated with SAR mapping of shrimp farms, obtained from this study.

Table 10 Cost and time for SAR mapping of shrimp farms.

	Costs (US$/Km^2)	**Time (months)**
Acquisition of satellite data	0.15	1.0
Image processing and interpretation	2.00	2.0
Ground survey	0.10	0.2
Map preparation	0.10	0.2
Total	2.35	3.4

As indicated, a ERS SAR scene covers 100 x 100 km; its cost is of Euro 1 400 (approx. US$ 1 530). This cost is independent of the size of the study area, as no subscenes can be acquired.

Once the first SAR inventory of shrimp farms in a given area is completed, its update on a routine basis (i.e. once a year) is an easy task. SAR provides both timeliness and flexibility because of its independence from weather conditions on the ground. Thus, in theory, an update can be obtained by ordering the acquisition of an image on a month's notice.

In fact, the most time- and money-consuming task, i.e. the calibration and validation of the methodology, is performed once and for all in the inventory phase. Thus, ground checking can be reduced to a bare minimum, and only changes in land use should be assessed and quantified. Table 11 shows costs and time needed for monitoring the expansion of shrimp farms.

Table 11 Cost and time for SAR monitoring of shrimp farms.

	Cost (US$/Km^2)	**Time (months)**
Acquisition of satellite data	0.15	1.0
Image processing and interpretation	0.50	0.5
Ground survey	0.05	0.1
Map preparation	0.10	0.2
Total	0.80	1.8

The image processing and interpretation times described in Table 10 and 11 have been obtained by a trained remote sensing professional with experience in radar image analysis.

Although hardware (PC-based digital imagery analysis systems) and software (ERDAS 8.3 or equivalent) are now usually available in remote sensing agencies and laboratories, the methodology used in this study implies a good background in imaging radar theory and a considerable practice in handling and processing SAR data; both requirements are not common knowledge at present. However, the report provides detailed examples of SAR imagery interpretation and a clear sequence of actions, thus it can be considered as a case of technology transfer as well.

Possible improvements and present constraints

All ERS SAR data used in the present study were acquired in descending orbit, thus the SAR cross-track direction always had the same relative direction vis-à-vis the longer axis of dykes bordering shrimp ponds. Thus, the 1996, 1998 and 1999 images always show in particular evidence the same group of dykes.

Conversely, using two sets of SAR data, one from a descending and one from an ascending orbit, the shrimp farms would be "illuminated" from two different directions: each image would show a different set of dykes, complementing each other's information. Applying the same methodology to such a data set would certainly greatly increase the dyke's discernibility and consequently improve mapping of shrimp ponds.

Unfortunately, at least over Sri Lanka, the number of SAR acquisitions during ascending orbits is very limited, as other ERS sensors are generally active during these orbits; it was thus impossible to study our area with data from both ascending and descending orbits.

Further, as data acquisition from non-ESA receiving stations is based on various types of agreements, we discovered that the recording of a particular SAR scene, indicated as possible in the ESA listing, does not necessarily take place. Long processing time, usually a month or more, from data acquisition to delivery to user in georeferenced format (GEC) and the impossibility to have an indication of data quality if not after the processing of a particular scene has been requested (a Russian roulette scenario), are the main constraints of working with ERS SAR data.

On the other hand, we believe that SAR data are unique for mapping shrimp farms, not only for their inherent all-weather capabilities, but mainly because the backscatter from surrounding dykes allows for recognition and separation of shrimp ponds from all other water-covered surfaces. Sensors working in the visible and near-to-mid infrared portions of the electromagnetic spectrum, such as Landsat TM, SPOT, IRS, permit clear identification of industrial shrimp farms only.

Artisanal shrimp farms, with their small size and irregular shape, may be easily confused with other water covered surfaces such as flooded rice paddies, etc. In addition, the main limitation of these sensors is that the study area is clearly visible only in cloud-free days; a serious problem, as shrimp farms are located in tropical and sub-tropical areas.

In the context of government aquaculture development policy, much attention needs to be focused on the identification and monitoring of the expansion of shrimp farms. Thus, the availability of an accurate, fast and, mainly, objective methodology that also allows the observation of remote areas, assumes a great value. The methodology is also economically viable, as the value of shrimps more than justifies an accurate inventory and monitoring of the development of the farms.

As indicated, some constraints occur at present, such as the scarcity of SAR data over some areas. However, this difficulty could be overcome by utilising SAR data acquired from other satellite systems (JERS, RADARSAT).

Finally, a sound technology transfer programme on SAR data handling is recommended to acquaint potential users in Fisheries Departments and Remote Sensing Agencies of concerned countries on the routine use of the methodology and its associated tools, such as Geographic Information Systems (GIS) and Global Positioning Systems (GPS).

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