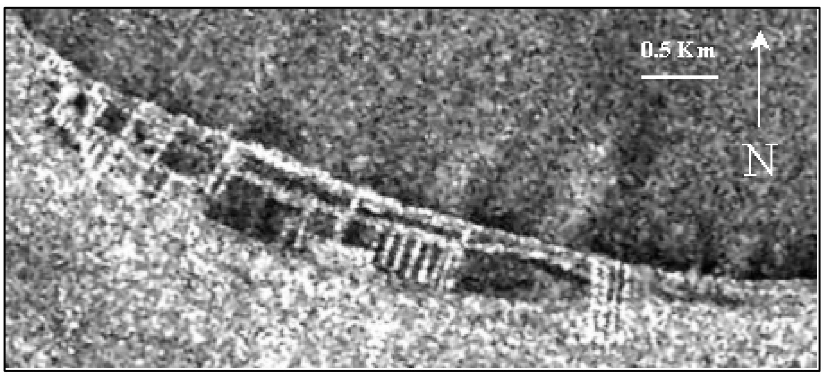
to the cross-track direction have typically high values; dykes parallel to the cross-track direction are not visible in the image, and dykes at intermediate angles have values similar to those of other surfaces.

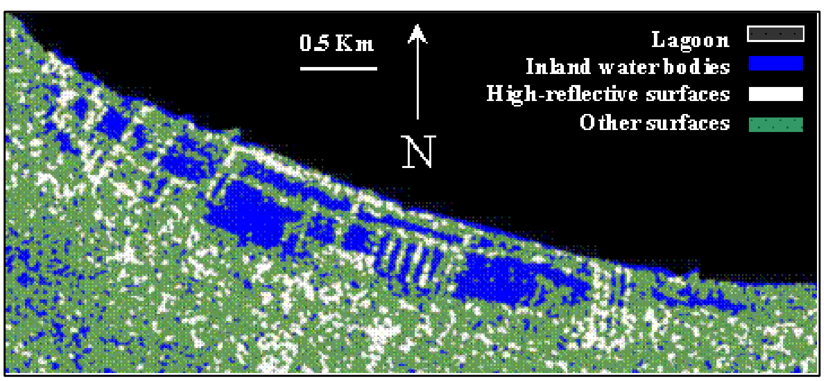
The analysis procedures are thus expected to identify water bodies and high-reflective surfaces, including some dykes. Other kinds of land cover are not of interest and the procedures assign all of them to another class.

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.

<u>Boundary detection</u>

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).

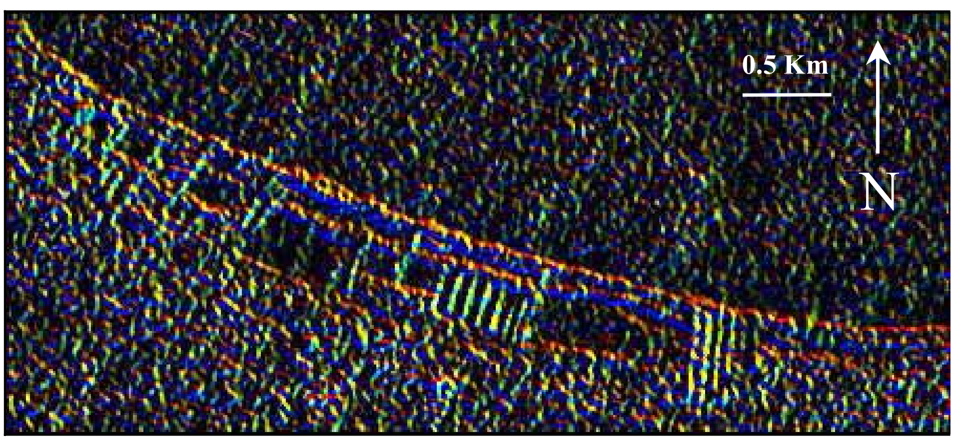



Figure 20 Uppadaluwa test site. Sobel filters applied to the 96/04/18 ERS SAR image. S-diagonal edges are displayed in red, vertical edges in green and horizontal edges in blue.

<u>Proximity analysis</u>

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.

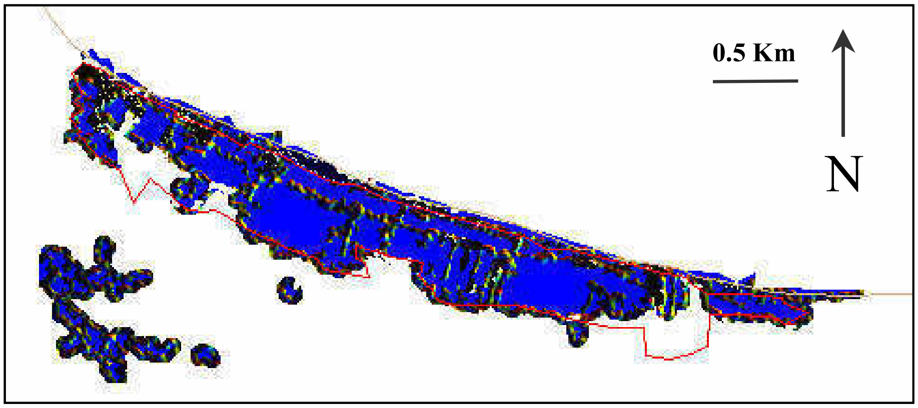



Figure 21 Uppadaluwa test site. Overlap of the two summary images and shrimp farms map obtained by visual interpretation (red line). The coastline is traced in brown

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 n. | Latitude deg | sec | d sec | Longitude deg | sec | d sec | epe[1] m | Image interpretation[2] 18/04/96,03/07/98,16/10/98,05/03/99 | Ground truth 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.

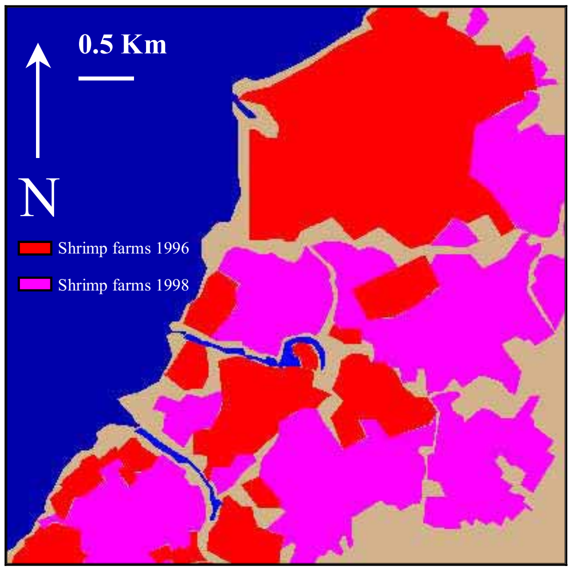



Figure 22 Shrimp farms map of the Seguwantiyu test site.

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.

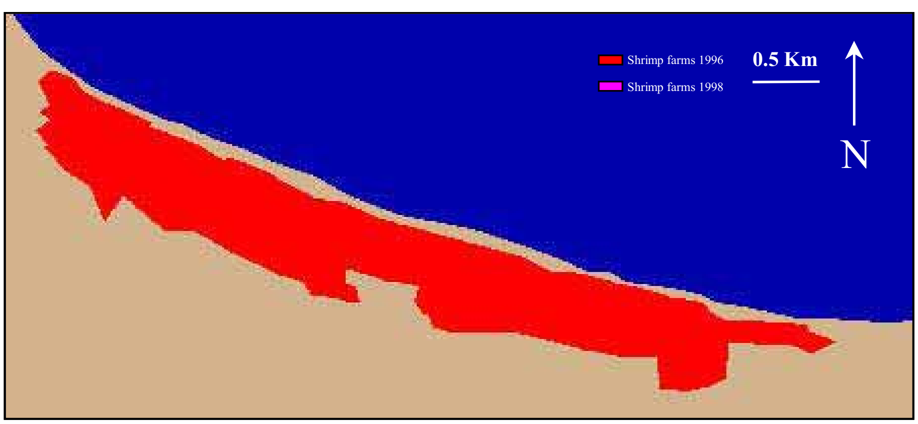



Figure 23 Shrimp farms map of the Uppadaluwa test site

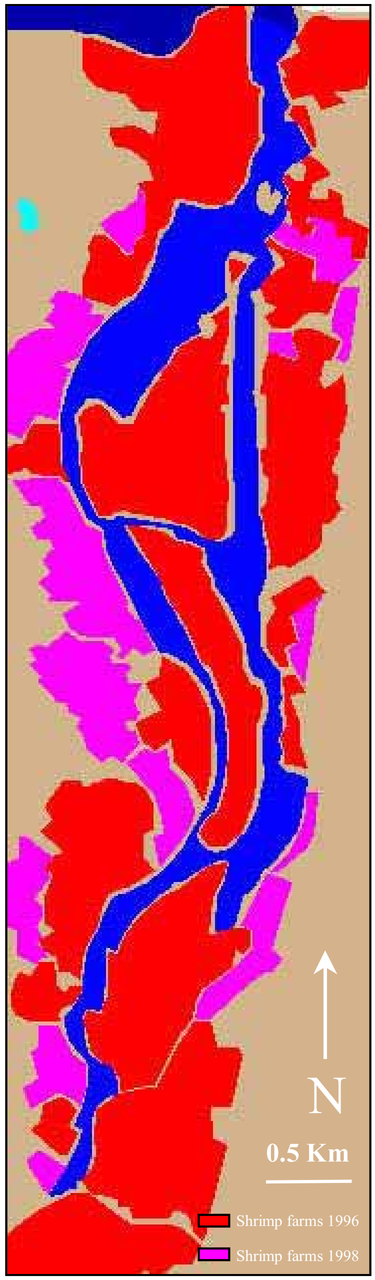


Figure 24 Shrimp farms map of the Dutch Canal test site

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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