This is due the fact that the when the water level is low, the reservoirs contain more moist soil and vegetated area which eventually leads to misclassification of the peripheral pixels. Thus, the images that are almost entirely composed of water (FRL and near-FRL) are classified with higher accuracies, while the images with lower water level are classified with relatively lower accuracies. Such a trend indicates the occurrence of the mixed pixels in the peripheral areas of the reservoirs. Visit to the peripheral

![Figure 7.1](image)

**Figure 7.1** Overall accuracy of classification of images of (a) Nagarjunasagar, (b) Singoor and (c) Vaigai reservoirs, for various water levels
areas of Vaigai reservoir by the author of this thesis also reveals that there are more than one cover type (soil+water+vegetation) present in most of the 24 m x 24 m land parcels (corresponding to the IRS 1C pixel size).

Having compared the classification accuracies at different water levels of the reservoir, it is seen that though accurate mapping of the entire reservoir area is desirable, reasonable accuracy is achieved by the per-pixel approach for the central portion of the reservoir only.

The following explanation seems to be logical for the large inaccuracies encountered for the pixels representing the boundary of the reservoir.

- Presence of large, moist and vegetated area nears the periphery of the reservoir.
- Presence of rocks and hills which are partially submerged in water.

To conclude, it is observed that a reservoir does not contain homogeneous classes, but may contain many sub-classes which are mixed and heterogeneous. This is very well brought by the results of supervised classification of the various images used in the study. The implication of such an observation is that large inaccuracies encountered at the peripheral portions results is an error prone estimate of the reservoir water-spread area. Subsequently, estimation of reservoir the capacity is further error prone which makes the per-pixel approach an unacceptable one.

It is therefore opined that the image data with similar spectral resolution, but with improved spatial resolution (2 to 5 m) might result in accurate extraction of reservoir water-spread area information. However, the large cost and non-availability of high resolution images demands the use of
an alternative approach that can give accurate information about the reservoir water-spread area. Since the review of literature (Frazer and Wang 2011, Sentlinger 2008, Busetto 2008, Powell 2007, Liu and Wu 2005) and the earlier experience of this author suggest sub-pixel classification as an alternate approach, the same has been applied to have better estimates of reservoir water-spread area and capacity.

7.3 SUB-PIXEL APPROACH FOR RESERVOIR AREA AND CAPACITY ESTIMATION

For effective implementation of irrigation scheduling, industrial and domestic water supply, etc. accurate estimates of the reservoir area and capacity are important parameters to be considered. Many authors have emphasized the need for accurate estimation of water-spread area of the reservoir to precisely calculate the storage capacity of the reservoir (Abileah 2011, Peng 2010, Hui 2008, Rathore 2006, and Jain 2002). Though conventional classification algorithm applied to ‘coarse’ resolution multi-spectral data result in water-spread maps, they do not provide us with sub-pixel information such as the proportion of soil and vegetation in the peripheral pixels. Such information would help us in overcoming the limitations offered by the per-pixel approach. LMM may be a suitable technique to extract and provide sub-pixel information to accurately quantify the water-spread area of a reservoir.

Chapter-5 of this thesis has attempted to apply the LMM technique to unmix the pixels representing the peripheral regions of the three reservoirs in the image data and extract the proportion of water, vegetation and soil at the sub-pixel level. Realizing the significance of the end-members in LMM of the reservoirs, pure pixels of water, vegetation and soil were selected with standard techniques such as the scatter plot (red vs NIR) and the Pixel Purity Index approach. Selecting the end-members was easy since their spectra were
highly separable and they could be identified easily in the PPI image and in the various multi-spectral images used in this study.

As already mentioned in Chapter-5, the result of spectral unmixing is a set of monochrome images that represent the abundance of each of the end-members. The different gray levels in each of the image correspond to the different proportions of the respective end-member. The fraction images have certainly been of much use in deriving the exact area of water present in most of the pixels of the reservoir area. The sub-pixel information extracted from the image data agrees well with the site characteristics noted on the ground.

### 7.3.1 Validation of the results of sub-pixel classification

To make the unmixing model operational, we have to be convinced that the sub-pixel information, about the peripheral pixels extracted from the image data, are accurate and this is a factual information about the prevalent ground conditions. One of the ways to be convinced is to carryout the validation exercise which compares the output of the spectral unmixing model and independent estimates such as field data or classified maps from other finer resolution remotely sensed images data.

Several investigators (Haerttel et al. 2004, Foody 2007) have shown that the recovery of sub-pixel information from medium resolution data is feasible and this information can be directly compared to that obtained at higher scales. In line with these studies, it was decided to validate the result of the sub-pixel classification approach (which was carried out using the 24m resolution image data) using high resolution image data which have a spatial resolution of 5m (resampled IRS 1C-PAN).
Table 7.1 Validation of the results the per-pixel and the sub-pixel approaches.

<table>
<thead>
<tr>
<th>Satellite/Sensor</th>
<th>IRS-P6 / LISS-III (24 m)</th>
<th>IRS-1C/PAN (5m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of Satellite Pass</td>
<td>Water-spread area Sub-Pixel (Mm$^2$)</td>
<td>Water-spread area Per-pixel (Mm$^2$)</td>
</tr>
<tr>
<td>03 Feb 2006 (Validation-1)</td>
<td>118.69</td>
<td>119.82</td>
</tr>
<tr>
<td>23 Mar 2006 (Validation-2)</td>
<td>106.73</td>
<td>107.49</td>
</tr>
<tr>
<td>15 Jan 2005 (Validation-3)</td>
<td>39.68</td>
<td>40.32</td>
</tr>
</tbody>
</table>

The validation shows that the application of the sub-pixel approach produced very less error (1.00% of water-spread area is over-estimated) than the per-pixel (3.14% of water-spread area is overestimated) based approach, where a large error is reported. Relatively lesser error shown by the sub-pixel approach presents its potential use for estimation of area of other reservoirs with acceptable accuracy.

The above said validation exercise could not be carried out for Nagarjuansagar and Vaigai reservoirs due to the non-availability of contemporaneous high resolution (2.5 to 5 m) data.

During the field visits, it was observed that there were many instances of trees being surrounded by water in the peripheral region of the reservoirs, giving an impression of a water logged forest area. This scenario, when translated in to an image pixel, would mean that the pixel is a mixture of both vegetation and water. However, it is of interest to note that classification of certain pixels located in the peripheral portions of the reservoir seem to show inaccurate proportions of water. This can be attributed to the proportions in which water, vegetation and soil are mixed. However, the presence of water under the canopy results in overall reduction in the DN values of vegetation in the NIR bands. This, in turn results in over-estimation
of the abundance of water fraction in that particular pixel. This phenomena does not apply to the pixels which have a mixture of soil and water.

Thus, despite the limitations of LMM approach, the fraction images provide acceptable information about the water, vegetation and soil cover proportions in the peripheral pixels, which may be used to estimate the area of water-spread more accurately.

In order to make the unmixing technique more reliable and operational, it is imperative that the role of proportion of each of the component in contributing to the DN value of the image pixel has to be better understood. For this, several studies on the spectra of mixtures containing water, vegetation and soil were carried out, which are described in the next section.

7.4 MODELING THE EFFECT OF LAND COMPONENTS ON THE SPECTRAL PARAMETERS OF THE RESERVOIR

As already mentioned in sections 7.2 and 7.3, the image based studies for estimation of the area occupied by water in reservoirs using the per-pixel and sub-pixel approaches were carried out. During the analysis of the results, it was realized that certain pixels, especially in the peripheral region of the reservoir, tend to be misclassified (in the per-pixel approach) or fractions of the components in the pixels are incorrectly estimated (using the sub-pixel approach). To explore the reasons for such errors, laboratory based spectral studies of the components of the pixels of the peripheral region of the reservoirs and their mixtures (in varying proportions) were attempted.

Based on the attempt to relate the spectral characteristics of various mixtures and their effect on the accuracy of per-pixel and sub-pixel classification approaches the following aspects are deliberated.
For a set of mixtures, when water fraction is more than 60% in any of the mixtures, then the spectral separability is minimal or nil in the visible region, whatever be the fraction of soil present in the mixture. It is also to be noted here, that there is appreciably higher spectral separability in the NIR region for mixtures with low amounts of water (10 to 40%), than for mixtures with high amount of water (> 60%). These observations makes us infer that estimation of water fraction in peripheral pixels of reservoir with low abundance of vegetation will be more accurate while performing sub-pixel estimation rather than for pixels of the reservoir which have high abundance of vegetation.

The implications of the above listed observations are that the estimation of water/vegetation/soil fractions by sub-pixel classification will be accurate for pixels which have upto 40% vegetation in them.

The decrease in spectral separability for high-vegetation and low-water mixtures could result in erroneous estimates of vegetation and water fraction while performing sub-pixel classification of images of reservoirs that are bound by dense vegetation.

Estimating vegetation fraction using the slope of the spectra in the 700 to 730 nm region as a parameter may be error prone. For higher abundance of vegetation, the spectral curves i.e 50%, 60%, 70% and 80% have an overlap in the 700 to 730 nm region, which primarily accounts for this poor relationship.

It may be inferred that vegetation fraction above 40% can be estimated with greater accuracy using slope in the 765 to 950 nm region as a parameter.
This study has lead to the inference that sub-pixel classification of images of reservoirs with low abundance of vegetation in the periphery will be more accurate than for images of reservoirs which have high abundance of vegetation in the periphery. Specifically, it can be mentioned that estimation of water/vegetation/soil fractions by sub-pixel classification will be accurate for pixels which have upto 40% vegetation in them.

7.5 CONCLUSIONS

While information on water-spread area and capacity of reservoirs are important parameters that cannot be overlooked for reservoir management, we should take in to account the fact that estimating these parameters by manual and ground-based methods or by remote sensing method may not give satisfactory results.

To understand the issues related to accurate estimation of these two parameters, this study using remote sensing has highlighted: (i) unacceptable and unsatisfactory results by remote sensing approach may result if inappropriate image processing techniques are adopted (ii) the dominant landcover component present in the periphery of the reservoirs also controls the accuracy of the information extracted from the satellite images.

Per-pixel classification, the popular image classification technique when applied to the multi-spectral satellite images of three large reservoirs of south India has shown that there is a tendency for over estimation of the reservoir water-spread area and capacity. This over estimation is some times very alarming and can lead to unacceptable reservoir volume estimation.

To overcome such a limitation offered by the per-pixel approach, the sub-pixel classification approach has been adopted and applied to all the twenty six images of the three reservoirs. After, selecting appropriate end-
members, the sub-pixel classification resulted in fraction images which contain sub-pixel level information about the reservoir and its peripheral region. Information derived from the water fraction image, when translated into water-spread area, results in near accurate estimation of reservoir water-spread area (at all water level considered here) and capacity for all the reservoirs. Such estimates are certainly closer to the actual values shown in table 6.7 and 6.8. These tables reveal that the sub-pixel approach produced very less error (1.00% of water-spread area is overestimated) than the per-pixel approach (3.14% of water-spread area is overestimated). Thus, the sub-pixel based approach can be applied to estimate the capacity of the reservoirs with higher accuracy than the per-pixel approach.

Despite the superiority of the sub-pixel approach, a closer examination of the fraction images of reservoirs during all the water levels considered, shows that the fractions of the landcover component in certain pixels of the periphery of the reservoir are incorrectly estimated. The laboratory based spectral studies of these landcover components indicates that inaccurate computation of the abundance of water in certain pixels occurs only when the pixels contain more than or equal to 40% vegetation. In periphery pixels of the reservoir containing less than 40%, vegetation computations of abundance of water by sub-pixel approach is more accurate. However, when soil, instead of vegetation, is present in a peripheral pixel along with water, then the sub-pixel approach performs well and computation of water abundance is more accurate.

Thus, the wholesome approach of image based studies and spectroradiometric studies of the reservoir components has indicated that sub-pixel classification approach applied to medium resolution images and for reservoirs whose peripheries are vegetation deficient, will result in accurate estimate of water-spread area and reservoir capacity, which is a boon to the reservoir managers.