CHAPTER 4

ESTIMATION OF SELECTED WATER QUALITY PARAMETERS

In this chapter the methods of chlorophyll-a measurement from water samples using the spectrophotometer and estimation of Chl-a from remote sensing data are explained. Existing models for water quality parameter estimation were used and their results are presented. The extraction of water quality parameters from satellite remote sensing data is explained. The spatial distribution of water quality parameters within a lake and across the lakes were studied and results presented. The performance of multispectral and hyperspectral data in extraction of water quality parameter are compared.

Selected water quality parameters like TSM, Chlorophyll-a, and Turbidity were estimated in three water bodies. The selected water bodies for the study are Krishnarajapuram lake which is referred as KR Puram Lake, Ulsoor Lake and Madiwala Lake. The study areas are located in Bangalore city and shown in the Figure 4.1 and 4.2 as seen by Landsat-8 OLI instrument on 16\textsuperscript{th} Jan 2016.

4.1 LAB MEASUREMENT

The selected quality parameters (TSM, Chlorophyll-a, and Turbidity) were measured in laboratory from the water samples collected at selected locations in lakes. These measured values were correlated with remote sensing based data model values to estimate the parameter.

4.1.1 Chlorophyll-a measurement

There are many methods to measure Chlorophyll-a concentration including spectrophotometry, fluorometry and High Performance Liquid Chromatography (HPLC). Spectrophotometer method is the classical method of chlorophyll measurement and is used in this study.
Figure 4.1 Study areas in Bangalore as seen by Landsat-8 OLI

The figure shows a portion of Bangalore city which covers selected study areas Ulsoor lake, Madiwala Lake and K.R. Purum lake. While the ulsoor lake is located at the center of the city, the K.R.Puram lake and Madiwala lakes are in eastern and southern Bangalore respectively. The bright areas are the buildings and Barren lands. While the areas shown in dark green are trees light green shows the grass and floating vegetation. The Airport runway is seen as gray strip. Views of these lakes are enlarged and shown in figure 4.2.
Water samples were collected in high density polyethylene bottles (HDPE) from the locations where spectral measurements were carried out. Samples of each one liter in volume were collected at a depth of 10 to 15 cm from the surface. The collected samples were kept in aluminum foil bags to avoid light entering into water sample which may cause photochemical break down of the chlorophyll. They were stored in icebox (-4°C) and taken to the laboratory for water quality parameter concentration measurement on same day.

Chlorophyll-a measurements were carried out with acetone extraction and spectral absorbance measurement. In this process, Chl-a was concentrated by filtering the water through a 47 mm filter (0.45 µm pore size) and left overnight[85]. If there is a delay in filtering the water, it was kept in the freezer at less than -20°C temperature as advised in method 446.0 guideline book of U.S Environmental Protection Agency. The pigments were extracted from the filter to acetone solution (90%). The chlorophyll-a concentration was determined by measuring the absorbance (optical density-OD) of the extract at wavelengths 664 nm, 647 nm and 630 nm using UV-2501 spectrophotometer. The Chl-a concentration in mg/m³ was calculated by Equation (4.1)[145]

\[
\text{Chl – a} = \frac{S+[11.85(a_{664})–1.54(a_{647})–0.08(a_{630})] \times L}{V} \tag{4.1}
\]

Where 

- \( S \) = volume of acetone used for the extraction (ml)
- \( V \) = volume of water filtered (in litre)
- \( a_{664} \), \( a_{647} \) and \( a_{630} \) are the absorbance values
- \( L \) = cell path length (cm)
4.1.2 Total Suspended Matters

TSM which can also be referred as Total suspended Solids (TSS) is the part of particulate matter that remains as suspension in water. TSM includes silt, industrial wastes, decaying plants and sewage[146]. This was measured in the laboratory using the gravity method. The glass fiber filters of 1.5 to 2 micron pore size were dried at 100 - 110°C, cooled and weighed using 0.01 mg resolution scale. 200 ml water from the collected samples were filtered through pre-weighed filters using vacuum filtration method and the filters were dried again at 100 to 110°C. The dried filters were weighed again and the TSM in mg/l was calculated using Equation (4.2) provided in the ESS Method 340.2.

\[ TSM = \frac{(A-B) \times 1000}{C} \]  

Where: A is weight of filter with residue in mg  
B = weight of filter in mg and  
C = volume of water filtered in ml

4.1.3 Turbidity

Turbidity is an important water quality parameter, a measure of cloudiness of the water and indicates the concentration of foreign particles and coloured material in water. Turbidity is measured in four different units called Nephelometric Turbidity Unit (NTU), Formazin Nephelometric Units (FNU), Formazin Attenuation Units (FAU) and Jackson Turbidity Unit (JTU).

These units are almost equal but vary in measurement methods and instruments. NTU and FNU are measured based on the amount of scattered light measured in 90° from the incident light. While FNU is used with ISO 7027 (European) turbidity measurement method, the NTU is used with USEPA Method 180.1. FAU is measured at an angle of 180°. JTU unit is used with Jackson Candle Turbidity meter.

In this study, turbidity was measured using [EPA method 180.1] Nephelometer which measures the scattered light in 90° away from light incident direction. The scattered light intensity depends on particle concentration (mg/l), particle size (microns) and particle composition.
4.2 CORRELATION STUDY

4.2.1 Regression

In this study, statistical correlation study was carried out with values of Hyperspectral reflection indices and the measured values of water quality parameters to find the relation between them. The regression analyses were carried out with the Pearson regression test using the statistical least square method by best fitting the data obtained from the spectra and the measured values. If there are ‘n’ measurements, there will be n index values and n number of laboratory measured values. If they are mentioned as $x_i$, $y_i$ where i= 1, 2, 3, ... n then the coefficient can be estimated using following correlation equation[147] correlation coefficient is computed using the Equation (4.3).

$$
R_{xy} = \frac{n \sum x_i y_i - (\sum x_i)(\sum y_i)}{\sqrt{n \sum x_i^2 - (\sum x_i)^2} \sqrt{n \sum y_i^2 - (\sum y_i)^2}}
$$

(4.3)

The determination coefficient $R^2$ is calculated using the Equation (4.4).

$$
R_{xy}^2 = 1 - \frac{s_{yx}^2}{s_y^2}
$$

(4.4)

where $s_{yx}^2$ is the square of the error of a linear regression of $x_i$ and $y_i$ as given in Equation (4.5)

$$
s_{yx}^2 = \frac{1}{(n-1) \sum_{i=1}^{n} (y_i - a - bx_i)^2}
$$

(4.5)

and $s_y^2$ is the variance of $y$ is calculated using the Equation (4.6).

$$
s_y^2 = \frac{1}{n-1} \sum_{i=1}^{n} (y_i - \bar{y})^2
$$

(4.6)

In this study the values of $x_i$ and $y_i$ correspond to the results of the remote sensing reflectance indices and water quality parameters of different sampling stations.
4.2.2 Root Mean Square Error (RMSE)

The Root Mean Square (RMS) is used to assess the accuracy. The RMS error is calculated by using Equation (4.7).

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left( \frac{x_{est,i} - x_{meas,i}}{x_{meas,i}} \right)^2}{n}} \quad (4.7)
\]

Where \( x_{est} \) is estimated and \( x_{meas} \) is measured values.

It can be expressed as percentage and the percentage calculation is as given in the Equation (4.8).

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left( \frac{x_{est,i} - x_{meas,i}}{x_{meas,i}} \right)^2}{n}} \times 100 \quad (4.8)
\]

4.3 COMPARISON OF MULTISPECTRAL AND HYPERSONTRAL DATA IN CHLOROPHYLL-a ESTIMATION

4.3.1 Chlorophyll-a Estimation with Multispectral Data

The multispectral data are used to estimate the chlorophyll-a with different indices. In this study, the Landsat-7 ETM+ data were used to the chlorophyll-a estimation study. First four ETM+ bands were used in this study as they are in visible and NIR spectral region.

4.3.1.1 Band ratio Model with Multispectral data

In chlorophyll estimation using multispectral data, bands in visible and VNIR spectral region (400 nm to 800 nm) are used. The water quality parameters in inland water bodies were estimated with multispectral data and band ratio model. In the case of Band ratio models and derivative models, bias in the measurement instrument and method are cancelled or reduced. In this study, Landsat-7 ETM+ first four bands were used for chlorophyll-a estimation. The ratios of six possible band combinations were calculated. These ratios were correlated with measured chlorophyll-a values and the determinant coefficient (R^2) for each band combinations were calculated. In this
study, the band ratio TM3/TM4 provided maximum correlation ($R^2=0.596$) with measured Chl-a values. The correlation results are provided in the Figure 4.3.

![Figure 4.3 Band ratio vs. Chl-a (Linear) Mx data (KRPuram)](image)

The $R^2$ values were calculated with Linear, Quadratic and Cubic regressions and found that the Cubic regression provided high correlation with measured chlorophyll-a values. The Quadratic regression study with measured chlorophyll values were carried out and result is shown in Figure 4.4. The Figure 4.4 provides the relation between the band ratio values and the measured chlorophyll-values as equation, determinant coefficient and Root Mean Square Error.

![Figure 4.4 Band ratio vs. Chl-a (Quadratic) Mx data (KRPuram)](image)
The Cubic regression study between TM3/TM4 values and measured chlorophyll values were carried out and result is shown in Figure 4.5. The cubic correlation provides the $R^2$ value of 0.7274.

![Figure 4.5 Band ratio vs. Chl-a (Cubic) Mx data (KR Puram)](image)

**Figure 4.5 Band ratio vs. Chl-a (Cubic) Mx data (KR Puram)**

It was seen from the comparison of these three regression results, the band combination providing high correlation in linear regression only gives high correlation in quadratic and cubic correlation methods. As the same band combination provide high correlation in all three regression methods and the linear regression is simple in calculation, in further studies only band ratio model with linear regression method was used. Different ratio models and the determination coefficient obtained with each method with KR puram Lake data are provided in the Table 4.1. The closeness of the measured and estimated values is obtained by calculating the SSE and RMSE as explained in section 3.4.2.
Table 4.1 $R^2$, SSE & RMSE obtained from KR Puram Lake

<table>
<thead>
<tr>
<th>Determinant coefficient ($R^2$)</th>
<th>Linear</th>
<th>Quadratic</th>
<th>Cubic</th>
</tr>
</thead>
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<tr>
<td>TM1/TM2</td>
<td>0.042</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>TM1/TM3</td>
<td>0.148</td>
<td>0.1611</td>
<td>0.7059</td>
</tr>
<tr>
<td>TM1/TM4</td>
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<td>0.5966</td>
<td>0.6339</td>
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<td>0.2076</td>
<td>0.3437</td>
</tr>
<tr>
<td>TM2/TM4</td>
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<td>0.5426</td>
<td>0.673</td>
</tr>
<tr>
<td>TM3/TM4</td>
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<td>0.637</td>
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<table>
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<td>9.569</td>
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<tr>
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<td>8.759</td>
<td>3.073</td>
</tr>
<tr>
<td>Cubic</td>
<td>4.222</td>
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<td>3.822</td>
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</thead>
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<td>1.17</td>
<td>1.263</td>
</tr>
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<td>0.7157</td>
</tr>
<tr>
<td>Cubic</td>
<td>0.7265</td>
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</tr>
<tr>
<td></td>
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<td>0.7358</td>
<td>0.687</td>
</tr>
</tbody>
</table>

4.3.2 Chlorophyll-a Estimation with Hyperspectral data

The hyperspectral data were obtained using spectroradiometer and the reflection spectra were derived using the procedure explained in the section 3.3.8. As the performance of multispectral and hyperspectral data are to be compared, same model was to be used for both data. The two band ratio model was selected for this study because the multispectral data has only four bands and utilisation of multi band models are not possible. The band ratios of various possible band sets were calculated and they were correlated with measured values. The band set providing high correlation coefficient was selected for study and the results are shown in the Figure 4.6. In the case of KR Puram lake the ratio of reflectance at 724 nm to 524 nm provided maximum correlation ($R^2$ =0.867).
Figure 4.6 Band ratio vs. Chl-a using Hyperspectral Data (KR Puram)

The $R^2$ value obtained with hyperspectral data was higher than the value obtained from multispectral. This shows that the hyperspectral data with narrow spectral bands provide high estimation accuracy.

4.4 COMPARISON OF HYPERSPECTRAL INDICES IN CHLOROPHYLL-a ESTIMATION

4.4.1 Chlorophyll-a Estimation

The chlorophyll-a was estimated using various hyperspectral optical models such as single band reflectance, two band reflectance ratio, three band model, four band model, first order, second order derivative of reflectance etc. The model values calculated from reflectance spectra were correlated with measured Chl-a value. The band combination providing highest correlation was selected and the relation between the index values and chlorophyll-a concentration was established with regression study. This relation (equation) was used to estimate the chlorophyll concentration in other locations.

4.4.1.1 Single band reflective Model

In the single band reflective model the reflectance values of different spectral bands were correlated with measured chlorophyll-a concentration. The spectral
band that provides high correlation was selected for further study[76]. The general relation between the single band reflectance to the Chl-a is written as Equation (4.9)

\[ \text{Chl-a} = m_{\lambda,1} \times R_{\lambda,1} + n_{\lambda,1} \]  

(4.9)

Where \( R_{\lambda,1} \) is the reflectance at the wavelength of \( \lambda_1 \) and \( m \) & \( n \) are coefficients which can be obtained by correlation studies. The single band reflectance values were correlated with measured values of Chl-a but in this study, the correlation was found poor and the maximum \( R^2 \) value found in the UV/Blue region was 0.151.

### 4.4.1.2 Area above baseline method

In the area above the baseline method, an imaginary line was drawn from ~680 nm to ~750 nm (nearest troughs to the ~700 nm peak)[75]. The area between this imaginary line and the spectral curvature was measured and correlated with measured values of Chl-a. The area above baseline method also provided poor correlation with Chl-a. The relation between the area and the Chl-a values are presented in the Figure 4.7.

![Figure 4.7 Area above baseline vs. Chl-a.](image)

### 4.4.1.3 Peak magnitude above baseline method

In the peak magnitude above baseline method, peak magnitude from the imaginary line (drawn from ~680 nm to ~750 nm) to maximum reflection value near ~700 nm was correlated with measured values of Chl-a[75]. The area above baseline
method and peak magnitude above baseline method are simple in calculation and analysis but they provided poor correlation with Chl-a in this study. The study result is shown in Figure 4.8.

![Figure 4.8 Peak value above baseline vs. Chlorophyll-a](image)

**Figure 4.8 Peak value above baseline vs. Chlorophyll-a**

4.4.1.4 Three band Model

Three-band model was developed with three spectral bands that provide better accuracy in Chl-a estimation by removing the effect of back scattering, Coloured Dissolved Organic Matter (CDOM) and pure water effects. Originally, the three band reflectance model was developed and used to estimate the Chl-a in vegetation. Same concept was employed to estimate the Chl-a in turbid water. The general form of three band model for Chl-a estimation is presented in Equation (4.10)

\[
\text{Chl-a} = m \ast \left( \frac{1}{R_{\lambda_1}} - \frac{1}{R_{\lambda_2}} \right) R_{\lambda_3} + n
\]  

(4.10)

Where, \(R_{\lambda_1}, R_{\lambda_2}\) and \(R_{\lambda_3}\) are the reflectance of water at \(\lambda_1, \lambda_2\) and \(\lambda_3\). \(m\) and \(n\) are regression constants that can be obtained from regression analysis. As the CDOM and tripton effects are relatively less beyond 650 nm, it is recommended that selecting \(\lambda_1\) in red region near 670 nm, \(\lambda_2\) near 710 nm and \(\lambda_3\) near 750 nm for estimation of Chl-a concentration [148,33]. Iterative correlation study was carried out and maximum correlation (\(R^2 = 0.891\)) was obtained with band set of \(\lambda_1 = 651, \lambda_2 = 699\) and \(\lambda_3 = 703\)
nm. The estimation was studied with and without spectral region restrictions and results are shown in Figure 4.9.

![Figure 4.9 Three band model vs. Chl-a with spectral range restriction](image)

The three band model was tried without any band restriction and the correlation study was carried out. This method provided better correlation ($R^2=0.956$) than the band restricted study. The Chl-a value in this study varies from 35 to 50 mg/m$^3$

The result of the correlation study is provided in Figure 4.10.

![Figure 4.10 Three band model vs. Chl-a without spectral range restriction](image)

4.4.1.5 Two band Model

The two band model utilizes the spectral bands which gives high and low response to the Chlorophyll-a. The ratio method cancels the effect of other constituents
which contribute to both spectral bands to some extent. The algorithm is represented in Equation (4.11)

$$\text{Chl-a} = m_{(\lambda_1, \lambda_2)} \ast z_{(\lambda_1, \lambda_2)} + n_{(\lambda_1, \lambda_2)}$$ (4.11)

Where $z_{(\lambda_1, \lambda_2)} = R_{rs}^{-1}(\lambda_1)/ R_{rs}^{-1}(\lambda_2)$ and the $m$ and $n$ are coefficients. The two-band model presented in Equation (4.5) is a special case of three band model given in Equation (4.4). In this study suitable bands for band ratio model were found by calculating correlation coefficient for all possible band ratio combinations with the constraint of $\lambda_1$ from 650 nm to 690 nm and $\lambda_2$ beyond 710 nm. The band ratio model provided maximum correlation ($R^2=0.803$) with the bands 710 and 650 nm.

In the band ratio model four important combinations are used in chlorophyll-a extraction of ocean water. They are

1. Blue trough/ Green peak
2. Peak near 700 nm and the trough near 670 nm
3. Peak near 700 nm / Green colour peak
4. Red peak / florescence Peak

These four combinations were tried in inland Case-2 water. In the first combination the peak magnitude of green colour and the magnitude of trough near 440 nm are used from the reflective spectra. The ratio of magnitudes at these two wavelengths at different sample locations were correlated with measured values of the chlorophyll-a. This method provided a determinant correlation of $R^2=0.578$ and the result is shown in the Figure 4.11. As chlorophyll-a value increases with the green peak increases but the blue trough remains at same level. Due to this, the ratio provides negative correlation with Chlorophyll-a concentration. Moreover the existence of CDOM in CASE-II water has influence on blue region.
Similarly in the second model, reflectance magnitude at the peak around 700 nm and dip near 672 nm were extracted from the reflectance curve, ratios were calculated and correlated with measured chlorophyll-a values. This model provided determination coefficient of $R^2=0.487$. The correlation study result and fitting curve are provided in the Figure 4.12.
The peak near 700 nm is sensitive to the chlorophyll concentration variation. Similarly the green colour also related to the amount of chlorophyll-a available in the water. The ratios of magnitude of peak near 700 nm to the magnitude of green peak are correlated with the measured values. In this method the correlation value obtained was very low ($R^2=0.2604$). So this model is not suitable to estimate the Chl-a in inland water sources. The correlation study result is shown in Figure 4.13.

![Figure 4.13](image)

**Figure 4.13 ~700 nm peak/green peak vs. Chl-a**

The fourth band combination is the red peak and the small peak between 635 and 670 nm (Refer Figure 3.4). In this study these peaks were at 710 nm and 650 nm. The ratios of this band combination provided a $R^2$ value of 0.8025. The correlation results are presented in the Figure 4.14.

![Figure 4.14](image)

**Figure 4.14 Two band ratio model vs. Chl-a with spectral range restriction**
The band ratio of all possible combinations were calculated and they were correlated with measured chlorophyll-a values and found that the band set 705 nm and 637 nm provided highest determination coefficient ($R^2 = 0.893$). The correlation study results are shown in the Figure 4.15.

![Figure 4.15 Two band ratio model vs. Chl-a without band restriction](image)

From these studies, it can be concluded that the wavelengths used in ocean water quality studies are not suitable for fresh water study but band ratio method provide high coefficient of determination with other band combinations.

### 4.4.1.6 Four Band Model

The four band index model was developed to improve the Chl-a estimation accuracy[149]. The general four band index form is given in Equation (4.12)

$$\text{Chl-a} = m \left( \frac{\frac{1}{R_{\lambda_1}} - \frac{1}{R_{\lambda_2}}}{\frac{1}{R_{\lambda_3}} - \frac{1}{R_{\lambda_4}}} \right) + n$$

(4.12)

Where, $R_{\lambda_1}$, $R_{\lambda_2}$, $R_{\lambda_3}$ and $R_{\lambda_4}$ are the reflectance at $\lambda_1$, $\lambda_2$, $\lambda_3$ and $\lambda_4$. $m$ and $n$ are spectral coefficients that can be obtained by regression analysis.

All possible combinations of $(1/R_{\lambda_1} - 1/R_{\lambda_2}) / (1/R_{\lambda_3} - 1/R_{\lambda_4})$ and their correlation with measured values were calculated. The maximum correlation (R= 0.872) was obtained with band set $\lambda_1=655$ nm, $\lambda_2=709$ nm, $\lambda_3=654$ nm and $\lambda_4=711$ nm. The relation between the indices and chlorophyll-a, determination coefficients are presented in Figure 4.16.
The four band index was calculated with all possible permutation combinations of 400 bands i.e. \((400 \times 399 \times 398 \times 397)\) and the index values were correlated with the measured values. Maximum correlation coefficient \(R^2 = 0.989\) was achieved with the band combination of \(\lambda_1 = 568\) nm, \(\lambda_2 = 587\) nm, \(\lambda_3 = 545\) nm and \(\lambda_4 = 722\) nm. The relation between the index values and chlorophyll-a for that combination is shown in the Figure 4.17.
4.4.1.7 Normalized Difference Chlorophyll Index (NDCI)

Normalized Difference Chlorophyll Index was developed based on the Normalized Difference Vegetation Index\[87]\ . The general form of the NDCI is given in the Equation (4.13)

\[
\text{Chl-a} = m \times \frac{R_{\lambda_1} - R_{\lambda_2}}{R_{\lambda_1} + R_{\lambda_2}} + n
\]  

(4.13)

Where, \(R_{\lambda_1}\) and \(R_{\lambda_2}\) are the reflectance at the selected spectral bands, \(m\) and \(n\) are constants obtained by regression analysis. All possible combination of ratio \((R_{\lambda_1} - R_{\lambda_2} ) / (R_{\lambda_1} + R_{\lambda_2} )\) calculated and they were correlated with measured values. The maximum correlation \(R^2 = 0.895\) was found with 637 nm and 705 nm. The results are shown in the Figure 4.18.

![Figure 4.18 Normalized Difference Chlorophyll Index (NDCI) vs. Chl-a](image)

4.4.1.8 First order Derivative Method

The first order derivative values are also used to estimate the water quality parameters \[88,90]\ . The first order derivative data were calculated with the procedure explained in the section 3.1.1.4. The derivative values were correlated with measured chlorophyll-a and maximum correlation value of \(R^2 = 0.694\) was found at the wavelength of 678 nm. The relation between the derivative data and the Chl-a are shown in Figure 4.19.
4.4.1.9 Second order derivative Method

The second order derivative data also used to estimate chlorophyll-a concentration in many studies [91]. The second order derivative data were derived from the first order derivative values using the procedure explained in the section 3.1.1.5. In this study the second order data provided maximum correlation ($R^2=0.655$) at the wavelength of 661 nm. At this wavelength the second order derivative values varies from $6.5 \times 10^{-3}$ to $11 \times 10^{-3}$ across the samples. The Chlorophyll-a values also varies from 35 to 50 mg/m$^3$. The relation between the second order data and the chlorophyll-a concentrations are shown in the Figure 4.20.
4.4.1.10 Comparison of Models

The single band chlorophyll estimation models provided less determination coefficients ($R^2$) values. The determination coefficient was computed with different bands in the spectral region (650 to 750) as suggested in earlier studies [33]. This spectral region was recommended mainly due to two reasons: First is reflection at the peak near 700 nm and the absorption at the dip near 670 is high. Second reason is reflection of CDOM and water is low in this region. The two band model or band ratio is ratio of reflectance at two bands. The ratio increases the effect due to the chlorophyll and reduces the effect due to other constituents. The Normalised Difference Chlorophyll Index (NDCI) provides chlorophyll-a value in normalized index value. In this study the band ratio method and Normalised Difference Chlorophyll Index (NDCI) method provided similar regression results. The three band and four band models provided high correlation with chlorophyll-a. In general, the results are in accord with the sensitivity analyses of the two-band and three-band models [33].

4.4.2 TSM Estimation

In TSM estimation, empirical models are based on band ratio or derivative methods to reduce the background noises [90, 150]. Integrated surface reflectance is also used to estimate TSM [151]. Earlier studies show that the bands that best predict TSM vary with water conditions and concentrations of other constituents [150, 151]. In this study a computer program with Visual Basic was developed to compute all possible ratios from hyperspectral bands from 350 to 800 nm and correlated them with the TSM values to select a band ratio that is most sensitive to the TSM. The linear regression method used to establish the relation between the index and parameters may be represented by Equation 4.8.

\[ Y = A(X) + B \quad (4.8) \]

Where, $Y$ is water quality parameter, $X$ is the band ratio and $A$ and $B$ are regression coefficients. The value $A$ provides the slope of the curve fitting line and the value $B$ provide the bias value. The $Y$ is the value of the water quality parameter for the given band ratio($X$).
4.4.3 Estimation of Turbidity

The turbidity in water is measured with nephelometer in the units NTU. Generally the turbidity is estimated by correlating the reflectance values at a wavelength with the measured turbidity values. In many studies, the turbidity in the water is estimated using the spectral reflectance at a band near 750 nm[152]. The turbidity values measured at lab are correlated with the reflectance values of different bands.

4.4.4 Estimation of Chlorophyll-a with Hyperion data

The water quality parameter of Kalale lake and Varthur lake were estimated with the data collected by hyperion instrument onboard EO-1 Satellite. The water samples were collected and the concentration of chlorophyll-a was measured with Laboratory method. The results obtained from the Kalale lake are presented in the Figure 4.21. The Determination coefficient obtained with Hyperion data was $R^2=0.776$ with the bands B36 and B32. The wavelengths corresponding to the Band 36 and Band 32 are 711 nm and 671 nm respectively. The Chl-a concentration in the Kalale lake was between 20 to 30 mg/m$^3$. The chlorophyll-a concentration in the Kalale lake was less than other urban lakes.

![Figure 4.21 Chlorophyll-a Estimation using Hyperion data](image)
Chlorophyll-a in varthur lake was estimated with the hyperion data. The hyperion data was noisy and had strips. After processing the data with the methods explained in the chapter-3, it was used to Chl-a estimation. As the western part of Varthur Lake was covered with floating vegetation the samples were collected only in eastern portion of the lake. The Chl-a concentration varied from 20 to 37 mg/m$^3$. The results are shown in Figure 4.22.

![Graph: Band ratio vs. Chl-a (Hyperion)](image)

**Figure 4.22 Band ratio vs. Chl-a (Hyperion)**

**4.5 SPATIAL AND TEMPORAL VARIATION OF WATER QUALITY PARAMETERS**

**4.5.1 Inter-lake variation of water quality parameters- Hyperspectral data**

The chlorophyll-a concentrations in different lakes were measured and compared using the hyperspectral and multispectral data. As the performance comparison between hyperspectral and multispectral data has to be done with same model, the two band ratio model was used for both the data. As multispectral data has only four bands, higher band models are not suitable. In this study two band models were used to estimate the chlorophyll-a and TSM while the turbidity was estimated with single band model i.e the reflectance at different bands were correlated with turbidity and relation between the reflectivity and turbidity were established. In order to study
variation of water quality parameters with seasons, data were collected in two different seasons i.e January and August. To avoid the repetitive similar presentations, only one season data and calculations are shown. However the result and discussion chapter compares both season data.

4.5.1.1 Chlorophyll-a variation between lakes

The chlorophyll-a concentration in KR Puram Lake was measured with laboratory methods. The band ratio values of various band combinations were calculated and correlated with measured chlorophyll-a values. The relation established between the band ratio and the chlorophyll-a concentration may be used for mapping the chlorophyll-a in the lake. The study results are given in Figure 4.23.

![Figure 4.23 Band ratio vs. Chl-a using Hyperspectral data(KR Puram Lake)](image)

Similarly the chlorophyll-a concentration in the Ulsoor Lake was estimated and the results are shown in the Figure 4.24. It was observed that the chlorophyll-a concentration in Ulsoor Lake is higher than the KR Puram Lake. The range of the concentration also higher in Ulsoor Lake.
The chlorophyll-a in the Madiwala lake is estimated with two band method. The $R^2$ value obtained in the Madiwala is less than the value obtained in Ulsoor. The result of Madiwala lake is provided in the Figure 4.25.

The chlorophyll-a concentration in the Madiwala lake was higher than other two lakes. The Chl-a concentration range also was higher than other two lakes. From
the Figure 4.23, 4.24 and 4.25, it can be seen that the range of chlorophyll concentration is directly proportional to the concentration of chlorophyll-a.

4.5.1.2 TSM variation between lakes

Total Suspended Matter in the lake water is based on the soil type and the vegetation cover of catchment area. The total suspended matter in the Krishnarajapuram Lake was estimated with Hyperspectral and Multispectral Data. The TSM had been estimated accurately with band ratio method by many studies. Two band model was used in TSM estimation. The TSM concentration in the K.R.Puram Lake was in the range of 24 to 30 mg/l and the regression study is shown in the Figure 4.26.

![Figure 4.26 Band ratio vs. TSM (K.R Puram Lake) with regression details](image)

Figure 4.26 Band ratio vs. TSM (K.R Puram Lake)

The TSM in the Ulsoor lake was measured using the gravity method and the band ratio values were correlated with these measured values. The relation between the band ratio indices and the TSM concentration were derived using regression methods. In the KR puram lake, the TSM values varied from 44 to 60 mg/l. The results of the regression study are shown in the Figure 4.27.
The TSM values measured in Madiwala lake were in the range of 50 to 70 mg/l and higher than the values observed in both KR Puram and Ulsoor TSM values. The band ratio values are in the range of 0.63 to 0.68. The measured TSM values, the relation between the band ratio and TSM concentration and the determination coefficient value obtained in the Madiwala lake are shown in the Figure 4.28. The correlation value obtained in Madiwala Lake was higher than the correlation value obtained from Ulsoor Lake and KR Puram Lake.
4.5.1.3 Turbidity variation between lakes

The turbidity is the cloudiness of water in light path caused by the suspended materials. It is an important water quality parameter that indicates the foreign particles in water. Using turbidity measurements, the solid loads in water bodies can be roughly estimated. The optical properties of the suspended particulates are affected by three important factors namely, particle concentration (mg/m$^3$), particle size (microns) and particle composition. If the particle size is constant, high correlation between the turbidity and the TSM is observed.

In many studies the single band reflectance values have been used to estimate the turbidity. In the single band model, the turbidity was estimated by correlating the reflectance magnitude of different wavelengths with measured turbidity value. The maximum determinant coefficient ($R^2=0.535$) was found with the reflectance at 746 nm. Turbidity of the KR Puram lake water was in the range of 20 to 24 NTU. The reflectance at the spectral wavelength 746 nm varied from 1.15 to 1.5. The reflectance magnitude values and the turbidity values are shown in the Figure 4.29.

![Figure 4.29 Reflectance at 746 nm vs. Turbidity (KR Puram Lake)](image)

The turbidity in the Ulsoor lake was estimated with single band reflectance magnitude method. In this method the reflectance at different spectral bands were correlated with the measured values. The reflectance variation the sampling locations
are between 1.15 and 1.45. The turbidity level in Ulsoor lake is in the range of 24 to 36 NTU and the $R^2$ obtained is 0.624. The results of the study are provided in Figure 4.30.

![Figure 4.30 Reflectance at 741 nm vs. Turbidity (Ulsoor Lake)](image)

The Madiwala Lake showed a high turbidity value than other two lakes. The turbidity values in Madiwala Lake were in the range of 40 to 65 NTU. The reflectance observed in the Madiwala Lake was higher than other two lakes. The $R^2$ value obtained in turbidity estimation studies were less than that of chlorophyll measurement. The result of the correlation study is shown in the Figure 4.31.

![Figure 4.31 Reflectance at 758 nm vs. Turbidity (Madiwala Lake)](image)
4.5.2 Inter-lake variation of water quality parameters- Multispectral data

The multispectral data was collected by Landsat-8 OLI and the data is available in radiance 16 bit compressed form. Also the data is available in spectral reflectance form which was also collected and analysed.

4.5.2.1 Chlorophyll-a variation between lakes

The water quality parameters were estimated in the three study areas. The ratio of different band combinations were correlated with measured values of water quality parameters and band combinations providing high correlation was selected for further studies. In Ulsoor Lake the reflectance ratio and the Chl-a measured values were in the range of 1.3 to 1.5 and 35 to 50 mg/m$^3$ respectively. The obtained determinant coefficient $R^2$ was 0.779. The results are presented in Figure 4.32.

![Figure 4.32 Band ratio vs. Chl-a using Mx data (Ulsoor lake)](image)

The chlorophyll-a in the Madiwala lake was estimated with band ratio linear regression method. The band ratio and the measured chlorophyll values were in the range of 1.2 to 1.7 and 42 to 70 mg/m$^3$ respectively. The determination coefficient obtained was 0.6775. The linear regression curve and $R^2$ values are shown in Figure 4.33.
4.5.2.2 TSM variation between lakes

In many studies the TSM has been estimated with band ratio method because, the effect of background noises are reduced [57]. In TSM estimation with multispectral data, the TSM is measured from the water samples collected at sampling locations and the measured values were correlated with the band ratio values. Different combination of band ratio and band indices were calculated and correlated with measured values of TSM. In the study it was found that the OLI5/OLI11, OLI5/OLI4 ratios are providing higher correlation. The linear regression method was used to establish the relation between the ratio and TSM. The TSM values in the KR Puram lake varies 24 to 34 mg/l. The reflectance values are in the range of 0.8 to 1 and the maximum determinant coefficient $R^2$ obtained is 0.382. The TSM result obtained from KR Puram lake is shown in the Figure 4.34. The lowest $R^2$ value is due to the contribution of other constituents.
Similarly, the TSM in the Ulsoor lake was estimated using the band ratio and linear regression methods. The TSM values measured in the Ulsoor Lake is in the range of 43 to 62 mg/l. The Band Ratio OLI1/OLI4 varies from 0.63 to 0.68. TSM values in Ulsoor lake was higher than that of KR Puram lake. The $R^2$ value obtained was 0.620. The study results are given in the Figure 4.35.

Figure 4.34 Band ratio vs. TSM using Mx data (KR Puram lake)

Figure 4.35 Band ratio vs. TSM using Mx data (Ulsoor lake)
The TSM was estimated with the data collected from the Madiwala lake. The absolute TSM values measured were higher than that of KR Puram and Ulsoor lake values. The maximum $R^2$ value obtained from Madiwala lake was 0.657. The correlation study results are presented in the Figure 4.36

![Figure 4.36 Band ratio vs. TSM using Mx data (Madiwala lake)](image)

**4.5.2.3 Turbidity variation between lakes**

The reflection data were correlated with measured values of turbidity from the lab and the spectral band providing high correlation was selected for regression study. The relation between reflectance value of the spectral band and the turbidity of the water was derived. The derived relation was used to estimate and map the turbidity in the water body.

Multispectral Landsat-8 data was used to map the Turbidity. The reflectance values of different spectral bands were correlated with the measured turbidity values. In KR Puram lake the measured turbidity values were in the range of 20 to 28 NTU. The determinant coefficient $R^2$ obtained in this study was 0.192. The turbidity estimation study results are provided in Figure 4.37. This low correlation may be due to constituents that contribute reflection at the selected wavelengths but not contributing to the turbidity.
In the Ulsoor lake the turbidity was varying from 24 to 36 NTUs. The reflectance at different spectral bands were correlated with the measured turbidity values and found that the OLI5 provide higher correlation ($R^2=0.597$). The correlation results are provided in the Figure 4.38
Turbidity of the Madiwala lake was measured with the collected samples it was varying from 45 to 68 NTU. The determination coefficient $R^2$ was equal to 0.498. The Reflectance of OLI5 varied from 0.8 percentage to 0.84 percent. The measured turbidity values and the result of correlation study are given in the Figure 4.39.

![Figure 4.39 Band reflectance vs. Turbidity using Mx data (Madiwala lake)](image)

4.5.3 Water quality parameters distribution in Lakes

The distribution of water quality parameter in the lakes were studied and mapped. As a sample spatial variation of chlorophyll-a, Total suspended matter and turbidity concentration in the Krishnarajapuram lake is shown in Figure 4.40, 4.41 and 4.42. The pixel size of the data used in mapping the Chl-a, TSM and Turbidity is 30m x 30 m.

4.5.3.1 Chlorophyll-a Distribution in K.R. Puram Lake

The Chlorophyll-a distribution in the Krishnarajapuram lake was mapped with the Landsat-7 data. Based on the regression study, the two band ratio method was used to estimate the chlorophyll-a concentration as discussed in the section 4.3.1.5 and the distribution map was generated and presented in the Figure 4.40. Chl-a concentration varies from 33.9 to 39 mg/m$^3$ and the variation is shown as colour
variation. The circular area at the center of the lake is an artificial island with soil and trees. The Chl-a value is high at the middle of the lake than the banks.

Figure 4.40 Spatial variation of Chlorophyll-a (KR Puram lake)

4.5.3.2 TSM distribution in KR Puram Lake

The Total suspended matter was also estimated with bands obtained from the regression study. The TSM in the Krishnarajapuram lake varies from 25 to 34 mg/l. Near the banks and the island TSM concentration was high. The TSM distribution is shown in the Figure 4.41.

Figure 4.41 Spatial variation of TSM (KR Puram lake)
4.5.3.3 Turbidity distribution in KR Puram Lake

The turbidity values were estimated as discussed in with the reflectance of selected bands. The turbidity distribution in the Krishnarajapuram lake is shown in the Figure 4.42. The estimated turbidity varies from 21 to 28 NTU. Similar to the TSM distribution, the turbidity concentration is higher near banks and center island than the values obtained interior.

![Figure 4.42 Spatial variation of Turbidity (KR Puram lake)](image)

4.6 RELATION BETWEEN WATER QUALITY PARAMETERS

4.6.1 Relation between TSM and Turbidity

The turbidity and TSM are representing the suspended matter information in terms of reflection and mass respectively. While the turbidity depends on the total area of the particles and their reflective property, the TSM is based only on the mass of the particles. If the particle size is less the turbidity will be more for a given mass. If the particles are high reflective then turbidity will be more. The relation between Turbidity and TSM was studied and results are provided in the Figure 4.43. While the turbidity varies from 40 to 60 NTU, the TSM varies from 50 to 70 mg/l. The maximum determination coefficient of 0.811 was obtained between turbidity and TSM. The TSM and the turbidity have positive correlation between them.
4.6.2 Relation between Turbidity and Secchi Disk Depth

The secchi disk depth measurement is the oldest method that provides rough estimate of water quality and still it is used in estimation of the turbidity. The relation between the Turbidity, and SDD were studied and the results are provided in Figure 4.44. In madiwala lake the turbidity varies from 40 to 70 NTU and the secchi depth varies from 30 to 40 cm. The maximum $R^2$ achieved was 0.606. As turbidity increases the scattering of light increases and the light penetration distance comes down.
4.6.3 Relation between Water Surface Area and Chl-a

The water surface area was estimated using the Landsat-8 data and the area was correlated with average chlorophyll-a values. The area and Chl-a provide a positive correlation with the determination coefficient of $R^2=0.91$ in studied lake. The result is shown in the Figure 4.45.

![Figure 4.45 Relationship between water surface area and Chl-a](image)

4.6.4 Relation between Chlorophyll-a and TSM

The relation between chlorophyll-a and TSM concentration was studied. It was found the there is no consistent correlation between them. It was not consistent and the correlation values changes between studies. This shows that the parameter influencing the concentration of Chl-a and TSM are different.

4.7 SUMMARY OF DATA ANALYSIS

The locations of the study lakes in Bangalore city are marked and shown in the Figure 4.1 and 4.2. Then lab measurement methods of Chl-a, TSM and Turbidity using the collected water samples were presented in detail. The performances of multispectral and hyperspectral data in water quality parameter estimations were compared. The performance of hyperspectral data is better than that of multispectral data. Various hyperspectral methods were used to estimate the Chl-a, TSM and
Turbidity and their performances were compared. While single band indices gave less $R^2$ between measured and the indices, Multi band indices have provided better $R^2$ Values. The three band and four band model provided highest $R^2$ value. The derivative models also provided appreciable performance.

The spatial & temporal variation of water quality parameters was studied. The regression method was used to derive the relation between the water quality parameters and the indices. Using this relation, Chl-a, TSM and Turbidity distribution in selected lakes were mapped. The relation between these parameters are also studied and presented. The relation between the Chlorophyll -a and the TSM could not be established as the results obtained in different water resources were not consistent. The TSM and the turbidity show positive correlation between them. The relationship between the Water surface area and water quality parameters were studied and found no correlation between them.