Spatial Analysis of the Impact of Dredging Induced Increased Water Turbidity on the Visual Acuity of Great Cormorants in Poyang Lake, China

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Spatial Analysis of The impact of Dredging Induced Increased Water Turbidity on the Visual Acuity of Great Cormorants in Poyang Lake, China

by

Wu Hao

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Abstract

Dredging has a strong influence on water turbidity. Turbidity has strong impacts on the primary production by phytoplankton and aquatic plants, and aquatic animals foraging visually. The conceivable reason for the latter is that the turbid water will reduce luminance and target contrast, which influences the reactive distance of the animals. The great cormorant (*Phalacrocorax carbo*) is a common fish eating bird species occurring throughout Euro-Asia and often considered to be in conflict with human economic interests. They are pursuit divers and regarded as a visually-guided forager which can dive to considerable depths, but often feed in shallow water. The recent dredging induced increased water turbidity in Poyang Lake is likely to have influenced the visual acuity of cormorant. This in turn may influence their ability to encounter and capture prey, which together determine their predation success as well as their foraging behavior. So far however, there has been no attempt to map the distribution of visual acuity of aquatic animals. Nowadays, remote sensing and GIS techniques offer the possibility to solve this problem.

We developed a physical model to predict the visual acuity of great cormorant by using Secchi disk depth (representing water clarity) and water depth as input variables. Secchi disk depth was predicted from MODIS imagery with an accuracy of 90%. The spatial variation in visual acuity was predicted from satellite imagery based on the above model. This result shows a positive relation between sand dredging and Secchi disk depth in Poyang Lake. The dredging induced increase water turbidity reduced the visual acuity of great cormorants. Time series visual acuity maps revealed a significant increase trend in Poyang Lake national nature reserve from 2000 to 2005 after the dredging actives started. In this research, domesticated cormorants have been used to investigate the relation between visual acuity and capture rate by making use of the services of old fishermen who still use cormorant to fish in Poyang Lake. Regression analysis of visual acuity, search volume and capture weight per unit time which represent capture rate of cormorants also corroborate the statement that the cormorants’ capture rate should more relate to the prey density rather than their visual acuity.

We concluded that the dredging induced increased water turbidity reduce the detectability of visual feeding animals. The research also shows that it is a promising technique for the research on ecosystem modeling by using the remote sensing data as the inputs.

Key words: visual acuity, great cormorants, water turbidity, Secchi disk depth, dredging impact, MODIS, Poyang Lake
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Finally, I would like to thank my parents. Dear mother and father, with out you, I can not go so far. I love you.
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## Abbreviations

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<th>Full Form</th>
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<tr>
<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer</td>
</tr>
<tr>
<td>Landat TM</td>
<td>Landsat Thematic Mapper</td>
</tr>
<tr>
<td>WWF</td>
<td>World Wildlife Fund</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>EOS</td>
<td>Earth Observation Satellite</td>
</tr>
<tr>
<td>SDD</td>
<td>Secchi Disk Depth</td>
</tr>
<tr>
<td>PLNNR</td>
<td>Poyang Lake National Nature Reserve</td>
</tr>
<tr>
<td>SSC</td>
<td>Suspended Sediment Concentration</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>NTU</td>
<td>Nephelometric Turbidity Units</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>s.e.</td>
<td>Standard Error</td>
</tr>
<tr>
<td>AOI</td>
<td>Area of Interest</td>
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</table>
1. Introduction

1.1 Background

Water turbidity is increasing in freshwater ecosystems in China. Under natural conditions turbidity fluctuates because of natural processes, such as erosion induced by wind or running water, resuspended bottom sediments or fish migration. Nowadays however, human activities increase sediment loads: turbidity maxima are due to erosion from land or dredging. As a result, water turbidity increases.

Dredging has a strong impact on the fresh water environment, especially the water turbidity. Dredging operations, such as excavation, transportation and disposal of soft-bottom material stir up bottom sediments and lead to various adverse environmental impacts (Anchor Environmental, 2003). The physical water environment, such as the bathymetry, current velocities and wave conditions, can be affected by dredging (Angelidaki et al., 2000). It also changes the sedimentary regime in the lake bottom and may cause erosion under sea grass beds (MacInnis-Ng & Ralph, 2003). Erftemeijer and Lewis (2006) mentioned that dredging and disposal of dredged material can lead to a significant decrease in water transparency, while increasing concentrations of suspended matter and sedimentation rates.

Water turbidity is one of the most important factors which can affect the water environment. Dredging induced increased water turbidity has a number of negative environmental impacts. A great number of mostly laboratory studies had reported the effects of turbidity on a variety of aquatic organisms in the last 40 years. Turbidity is important the aquatic ecosystem, such as the primary production by phytoplankton and aquatic plants, aquatic animals foraging visually and any aquatic organism that has a visual sensory system (Anchor Environmental, 2003). In general, it is known that primary production slows in waters where light penetration is limited by turbidity including production by both phytoplankton and aquatic plants (Short & Neckles, 1999). It is also reported that sea bird foraging success rate may be affected by the dredging induced turbid waters in Southern California. A dredging activity that near the habitat of California Least Tern may force these visual feeders to feed further away from their nests than they normally would (Anchor Environmental, 2003). Hence, the time cost which spent on the way from their nests to the region of foraging should be longer and the risk of predation should increase (USFWS, 2002). Consequently, we also suggest that dredging induced increase in water turbidity also influences the relation between predator and prey, as there is ample literature on the influence of water turbidity on aquatic predator prey relations.

Water turbidity influences the visual acuity of predators foraging in aquatic environments. This in turn
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of
great Cormorants in Poyang Lake, China

influences their ability to encounter and capture prey, which together determine their predation success
as well as their foraging behavior and ultimately their distribution. Eriksson (1985) for example
demonstrated that detectability of prey by pursuit divers was affected by fish density and water
transparency. Hecht and Lingen (1992) reported that feeding rate of pursuit divers was reduced in
estuaries with high water turbidity. Henkel (2006) mentioned that some pursuit –diving species, such
as Brandt's Cormorants (*Phalacrocorax penicillatus*), occurred most often in the clearest water where
Secchi disk depth is deeper than 5 meters. The conceivable reason for that is the turbid water will
reduce available light and their visual acuity, thus reducing the reaction distance of the bird. The above
descriptive field studies reveal relations which do not necessarily prove that turbidity influences visual
acuity.

The relation between turbidity and visual acuity has also been investigated in the laboratory. Such
experimental studies have resulted in models which relate visual acuity of animals to the underwater
light regime and water turbidity. Vogel and Beauchamp (1999) quantified reactive distance of some
visual feeding birds including adult lake trout (*Salvelinus namaycush*), rainbow trout (*Oncorhynchus
mykiss*) and cutthroat trout (*Oncorhynchus clarkii*) at different light intensity, prey size and turbidity.
The experimental shows reactive distance declined as a decaying power function of turbidity. White *et
al.* (2007) for example presented a model which predicts visual acuity of cormorants from light
intensity, and the distance and contrast of the object. They tested the visual acuity thresholds of
free-swimming cormorants under a range of conditions. The light condition is simulated according to
the natural environment at different levels. The target is at different contrasts and also at different
viewing distances. They then built the model which shows the diversification of visual acuity when
cormorants catch a typical target fish at a range of distances, target contrasts, and illuminations. This
3D model represented and simulated how these conditions affect the visual acuity in a simulant nature
environment. The result shows visual acuity was positively related to target illumination and contrast,
and negatively related to viewing distances.

The great cormorant (*Phalacrocorax carbo*) is a common fish eating bird species which occurs
throughout Euro-Asia. It is a pursuit diver which can dive to considerable depths, but often feeds in
shallow water. It feeds in the sea, in estuaries, and on freshwater lakes and rivers. Northern birds
migrate to winter in the south. Humans have historically exploited cormorants' fishing skills.
Fishermen domesticate cormorants to catch fish for long time in China (Gudger, 1926). The fishermen
used a snare to tie the cormorant's throat near their base. It only allows the birds to swallow small fish.
When the bird captures a large one and tries to swallow it, it will be caught in the bird's throat. The
fisherman will use a long pole to force the cormorant return to the boat and remove the fish from its
throat. Figure 1-1 shows the situation that fisherman call the cormorant back to the boat. Nowadays
the method has become rare, since more efficient methods of catching fish have been developed (Wiki,
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

2007).

It is difficult to investigate the impact of turbidity on free ranging foraging animals from observational studies. Domesticated cormorants could offer a much better opportunity to test hypothesis about the relation between the foraging of birds and water turbidity. In this research, domesticated cormorants have been used to investigate this relation making use of the services of old fishermen who still use cormorant to fish in Poyang Lake. So far no experiments have been done with this domesticated piscivorous bird species.

Figure 1-1. Fisherman use cormorant to fish in Poyang Lake

The above suggest that water clarity influences the visual acuity for pursuit divers. Nowadays, remote sensing and GIS techniques offer the possibility to solve this problem. The model presented by White et al. (2007) offers the opportunity for implementation in a Geospatial environment. Illumination and target contrast can be predicted as the function of Secchi disk depth and water depth. The Secchi disk depth that represents water clarity can be predicted from satellite imagery, such as MODIS and Landsat TM (Wu et al., 2007, in prep.). DEM and historic water level data can provide accurate water depth map. Hence it should be possible to predict the spatial variation in visual acuity from satellite imagery.. So far however, there has been no attempt to map the distribution of visual acuity of aquatic animals.

Wu et al. (2007) also reported that large scale dredging in North Poyang Lake caused a reduction in water turbidity. The dredging boats can be detected by using Landsat TM images. The middle infrared bands of Landsat TM allow accurate detection in ships. Following the logic of the above we postulate
that the dredging influenced the visual acuity of animals in Poyang Lake and that this could be modeled using satellite imagery as an input to monitor historic change in water turbidity. Finally, the historic ship data could be used to investigate the relation between dredging and visual acuity.

1.2 Objective

1.2.1 General objective

In this research, we aim to predict the visual acuity of great cormorant in Poyang lake based on satellite derived estimates of water turbidity and use this model to investigate how dredging influenced visual acuity.

1.2.2 Specific objective

In order to achieve the general objective above, the following specific objectives will be addressed:

- Develop a model which predicts the visual acuity of cormorants which uses water depth and Secchi disk depth as input variables.
- To assess how accurately the model developed by Wu et al. (in press) predicted Secchi disk depth in Poyang Lake in 2007.
- To assess the number of dredging boats by using Landsat TM images.
- To apply the visual acuity model using the MODIS derived Secchi depth estimates to analyze the dynamics in visual acuity and assess the effect of the dredging on this.
- To investigate whether the foraging behavior of cormorants was related to water turbidity and depth.

1.3 Questions

Answers for the following questions were sought in this research:

- Is it feasible to predict the cormorant visual acuity by using GIS and RS technique?
- Is there a possibility to improve on the model established by Wu et al. (2007) and how accurately of this improved model?
- How is the relation between the number of dredging boats and visual acuity?
- How did the dredging induced turbidity and visual acuity change in recent years?
- How is the detectability of prey influenced by water turbidity and illumination and how do the detectability affect foraging behavior?
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

1.4 Approach

**MODIS IMAGERY PROCESS**

- MOD09GQ & MOD09GA HDF
- Formal transformation HDF to IMG
- MOD09 images
- Projection Transformation (UTM WGS84)
- MOD09 images (UTM WGS84) Poyang Lake Band 1-7 (250m)
- Layer stacking
- MOD09 images (UTM WGS84) Poyang Lake Band 1-7 (250m)
- Resample band 3-7 to 250m
- MOD09 images (UTM WGS84) Poyang Lake Band 3-7 (250m)
- Subset images via Poyang Lake MOD09 images (UTM WGS84) Poyang Lake Band 1-7 (250m)
- MODIS IMAGERY PROCESS

**SDD MAP PROCESS**

- Field SDD data
- Regression analysis
- SDD model
- Secchi disk depth map of PLNNR

**VISUAL ACUITY MAP PROCESS**

- Secchi disk depth map of PLNNR
- Illiminance
- Visual acuity model
- Visual acuity map of PLNNR (1999-2005)
- DEM of PLNNR
- Water depth map of PLNNR (1999-2005)
- Contrast

**EFFECT of DREDGING ON VISUAL ACUITY**

- Landsat TM
- Ship detection
- Dredging ship number
- Regression analysis
- Effect of dredging on visual acuity

**Figure 1-2. Framework and structure of the study**
1.5 Outline

- Chapter 1: General introduction of research background, general and specific objectives, research questions and approach.

- Chapter 2: A description of the study area and other relative research materials. The research methods in detail also explain.

- Chapter 3: The results obtained from this research, some graphs and figures have been used to present the results.

- Chapter 4: Presents the discussion in this research.

- Chapter 5: Presents the conclusions, shortcomings in this research and corresponding recommendations as well as future research possibilities for the area.
2 Materials and methods

2.1 Study area

2.1.1 General description of Poyang Lake NNR

Poyang Lake is located between 115°55′-116°45′E, 28°22′-29°45′N. It is the largest fresh water lake in China. It lies in the northern part of Jiangxi province, south of the Yangtze River. The acreage of lake fluctuates alone with water level and reaches 3,283 km² when the water level at Hukou is 21.71 m. the mean water depth of Poyang Lake is 8.4m, and the inmost depth is about 25.1m (Liu, 2006). Poyang Lake is one of the most important bird sanctuaries in the world. Hundreds of thousands of birds over-winter here every year because of the specific climate and hydrology situation (Wu & Ji, 2002).The lake provides habitat for a half million migratory birds. More than 1500 wild great cormorants come to Poyang Lake every winter (WWF, 2005). Besides local fishermen use domesticated cormorant to fish more than 1000 years. Poyang Lake National Nature Reserve (PLNNR) lies in the north-west part of Poyang Lake (Figure 2-1). The reserve is dominated by 9 lakes: Dachahu (8500 ha), Banghu (7300ha), Dahuchi (3000ha), Shahu (1400ha), Changhuchi (700ha), Zhonghuchi (600 ha), Xianghu (400 ha), Meixihu( 300 ha) and Zhushihu (200 ha). The total area is about 22,400 hectares (Wu and Ji, 2002). The following figure shows the location of Poyang Lake National Nature reserve.

Figure 2- 1. Poyang Lake National Nature Reserve (Source: ICF)
2.1.2 Hydrology

The hydrology data collected from Poyang Lake NNR which is shown in Figure 2-2. The detailed data about water level from 1999 to 2005 in 4 lakes including Dachuchi, Meixihu, Shahu and Sixiahu in Poyang Lake NNR.

Receiving water from five inland rivers and moderating floodwater from the Yangtze River lead to a complex hydrology condition for Poyang Lake. The water level fluctuates seasonally, with lowest water level in winter and highest levels in summer (Wu and Ji, 2002). The maximum and minimum water levels were 17.7 m in July and 14.5 m March in 2004. While in 2005, 18.6 m in September and 14.8 m December instead the maximum and minimum water level. The water level became low from winter to early spring and rose sharply in the late spring and reached the peak in the summer; then it started to fall in autumn and retained a low level in the whole wintertime. It provides the suitable wetland environment for the birds living in winter when the water level is low. The large variation of

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Figure 2- 2. Water level of 4 lakes from 1999 to 2005

Receiving water from five inland rivers and moderating floodwater from the Yangtze River lead to a complex hydrology condition for Poyang Lake. The water level fluctuates seasonally, with lowest water level in winter and highest levels in summer (Wu and Ji, 2002). The maximum and minimum water levels were 17.7 m in July and 14.5 m March in 2004. While in 2005, 18.6 m in September and 14.8 m December instead the maximum and minimum water level. The water level became low from winter to early spring and rose sharply in the late spring and reached the peak in the summer; then it started to fall in autumn and retained a low level in the whole wintertime. It provides the suitable wetland environment for the birds living in winter when the water level is low. The large variation of
water level between low-water season and high-water season together with the wind induced suspended sediment make a great difference of water turbidity situation.

2.2 Materials

2.2.1 MODIS imagery

MODIS (Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites (NASA, 2001). With its sweeping 2,330-km-wide viewing swath, MODIS can see every point on our earth every 1-2 days in 36 discrete spectral bands (Hook et al., 2000). MODIS Surface Reflectance product (MOD09) is produced by the Land Surface Reflectance Science Computing Facility of University of Maryland and NASA GSFC. It is a seven-band product computed from the MODIS Level 1B land bands 1, 2, 3, 4, 5, 6, and 7. It has been corrected by NASA for the effects of atmospheric gases, aerosols and thin cirrus clouds. The product affords an estimate of the surface spectral reflectance as it is measured at ground level as if there were no atmospheric scattering or absorption. The images can be downloaded from the website of Earth Observing System Data Gateway (EOS, 2006). Table 2-2 shows the basic characteristics for MODIS band 1 to band 7. Figure 2-3 shows the color composite of band 3, 2 and 1 of MODIS.

Figure 2-3. The color composite of band 3, 2 and 1 of MODIS image
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

<table>
<thead>
<tr>
<th>Primary Use</th>
<th>Band</th>
<th>Bandwidth(µm)</th>
<th>Spectral Radiance</th>
<th>Required SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land/Cloud/Aerosols Boundaries</td>
<td>1</td>
<td>620 - 670</td>
<td>21.8</td>
<td>128</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>841 - 876</td>
<td>24.7</td>
<td>201</td>
</tr>
<tr>
<td>Land/Cloud/Aerosols Properties</td>
<td>3</td>
<td>459 - 479</td>
<td>35.3</td>
<td>243</td>
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<tr>
<td></td>
<td>4</td>
<td>545 - 565</td>
<td>29.0</td>
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<td>5</td>
<td>1230 - 1250</td>
<td>5.4</td>
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<td></td>
<td>6</td>
<td>1628 - 1652</td>
<td>7.3</td>
<td>275</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2105 - 2155</td>
<td>1.0</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 2-1. Basic characteristics for MODIS band1 to band 7 (Source: NASA)

Spectral Radiance values are (W/m² -µm-sr) SNR = Signal-to-noise ratio
NE(delta)T = Noise-equivalent temperature difference

MOD09 images of 6 years which from 2000 to 2006 were selected and 30 cloud-free images were downloaded at the frequency of one image per month. Table 2-2 shows the date of the MOD09 images selected and finally used in the study.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<tr>
<td>2000</td>
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<td>16</td>
<td></td>
<td>14</td>
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<td></td>
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<tr>
<td>2004</td>
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<td>30</td>
<td>08</td>
<td></td>
<td>04</td>
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<td>28</td>
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<tr>
<td>2005</td>
<td>21</td>
<td>07</td>
<td>05</td>
<td></td>
<td>09</td>
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<td>31</td>
</tr>
<tr>
<td>2006</td>
<td>17</td>
<td>11</td>
<td>12</td>
<td></td>
<td></td>
<td>26</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2-2. The MOD09 images selected and finally used in the study

2.2.2 DEM and historical water level data

Digital elevation model (DEM) is used to refer to any digital representation of ground surface topography or terrain (WIKI, 2006). The DEM of PLNNR and historical water level is required to calculate water depth in this research. The acquired DEM of Poyang Lake was made in 1998. The spatial resolution is 20 m and vertical accuracy is around decimeter. It covers the whole Poyang Lake NNR and the north and south parts of the Poyang Lake where near sand hill. The historical water level data from 1999 to 2005 were acquired from the Bureau of Poyang Lake NNR. Normally, water level increases from February to July and it decreases form November to February of next year. But the
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

precipitation can affect water level in some situation. Figure 2-4 shows the DEM map of PLNNR.

Figure 2-4. DEM of PLNNR

2.2.3 Landsat TM imagery

The Landsat Thematic Mapper (TM) is a sensor has acquired images of the Earth nearly continuously from July 1982 to the present, with a 16-day repeat cycle (NASA, 2000). The image data consist of seven spectral bands with a spatial resolution of 30 meters in the blue-green (band 1), green (band 2), red (band 3), near-infrared (band 4), mid-infrared (bands 5 and 7), and the far-infrared (band 6). All of these 6 bands are 8 bit data. Table 2-3 shows the basic characteristics for Landsat TM band1 to band 5 and band 7. Six Landsat TM images which cover the north part of Poyang Lake from 2000 to 2006 are used for the dredging ships detection in this research.

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength Resolution (micrometers)</th>
<th>Spatial Resolution (meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1 (Blue-Green)</td>
<td>0.45 - 0.52</td>
<td>30</td>
</tr>
<tr>
<td>Band 2 (Green)</td>
<td>0.52 - 0.60</td>
<td>30</td>
</tr>
<tr>
<td>Band 3 (Red)</td>
<td>0.63 - 0.69</td>
<td>30</td>
</tr>
<tr>
<td>Band 4 (Near-IR)</td>
<td>0.76 - 0.90</td>
<td>30</td>
</tr>
<tr>
<td>Band 5 (Middle-IR)</td>
<td>1.55 - 1.75</td>
<td>30</td>
</tr>
<tr>
<td>Band 7 (Middle-IR)</td>
<td>2.08 - 2.35</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2-3. The basic characteristics for Landsat TM band1 to band 5 and band 7
2.2.3 Field data

During the field work, 33 sample points were taken from the Dahuchi and lower Hukou. The Secchi disk depth, surface and underwater irradiance were measured at every sample point. The longitude and latitude were recorded by GPS. Four domesticated cormorants were used to collect the diving parameters and capture detail. The collection and analysis methods are described specifically in later section.

2.3 Methods

2.3.1 Field data collection and analysis

The field data was collected in the middle of September and the end of November to the middle of December. The whole data set can be divided into three parts, cormorant observation data, SDD data and underwater irradiance data. The equipments required during the field work are listed in the appendix. All the measurements were performed on a flat-water surface and cloud-free condition. The sample points are shown with red dot in figure 2-5.

![Field Survey Samples](image)

Figure 2-5. Field survey samples
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

2.3.1.1 Cormorant observation

One fisherman was hired with more than 20 years cormorants fishing experience. Four cormorants were chosen for the observation. The cormorants were taken into different water area with variation in water depth and Secchi disk depth. The cormorants were allowed free foraging at each site for 30 minutes. Diving characteristics, such as diving time and recovery time, were recorded to build the diving model. The capture detail, such as fish weight, fish size and capture success rate, were also recorded to investigate the relation between visual acuity and water turbidity. Figure 2-6 shows the histogram of diving time and recovery time. The diving time are normal distribute.

![Figure 2-6. Histogram of diving time and recovery time](image)

2.3.1.2 SDD measurement

A Secchi disk is a disk, usually 20 cm in diameter, painted in black/white quarters. It is lowered into the water and the depth at which the disk is no longer visible is recorded as the Secchi Disk Depth (SDD, in units of meters). Because the SDD sample will be related to the reflectance of the MODIS images with spatial resolution MODIS is 250 meters, we choose each SDD sample point at least 500 meters form the lake shore. Grid sample site were choose in the satellite image before the field work. The longitude and latitude of each sample point was inputted into a Garmin GPS device which spatial resolution within 10 meters. 33 sample points were measured.

2.3.1.3 Underwater irradiance measurement

LI-COR Quantum Sensors can measure photosynthetically active radiation (PAR) in the 400 to 700 nm waveband and are available in terrestrial configurations and underwater configurations. In this research, two sensors and a data logger were used in the sample points. The models of them are LI-192 Underwater Quantum Sensor, LI-190 Quantum Sensor, LI-1400 Data Logger.
2.3.2 Remote sensed data pre-processing

MOD09GQK/MYD09GQK contains MODIS bands 1 and 2 which spatial resolution is 250 m, while MOD09GHK/MYD09GHK stores MODIS bands 1 to 7 which spatial resolution is at 500 m. These corrected products can be downloaded from Geo Gateway directly. After downloading the satellite imagery, some pre-processing should be done. All images should be projected into WGS84/ UTM zone 50N, which are coherent with the projection system of DEM. Then MOD09GHK/MYD09GHKs’ bands 3-7 will be re-sampled from 500 to 250 meters using nearest-neighbor re-sampling to preserve the original reflectance values. After that, these re-sampled bands which resolution is 250 m will be stacked together. Because the great difference of water lever, the areas of Poyang Lake vary during different season in each year. The time series image will be used in this research. It is very important to subset the water bodies from MODIS images. Land areas and small water bodies were removed using a binary mask derived from the Modified Normalized Difference Water Index (MNDWI), which effectively discriminates soil and vegetation from open water (Xu, 2005). The Flowchart is showed specifically in Figure 2-9.

![Flowchart of MODIS images pre-processing](image)

**Figure 2-7. Flowchart of MODIS images pre-processing**

2.3.3 Assessing SDD with MODIS images

Water clarity has often been used as an indicator of a lake's overall water quality for it correlates well with water quality (Shaw et al., 2004). The Secchi disk is one of the most commonly used tools to measure water clarity (Nellis et al., 1998, Gan et al., 2004). SDD provides a simple and convenient method to measure the rate at which light is attenuated with depth. (Chen et al., 2007). However, this
method may be costly for intensive sampling within water bodies in which water clarity fluctuates highly in time and space scale (Kloiber et al., 2002b, Hakanson & Boulion 2003).

The Landsat images had been used to assess Secchi disk depth from 1980’s. Many scientists use different band of Landsat images to estimate Secchi disk depth. Landsat has thus successfully been applied to the mapping of Secchi disk depth, but has its limitations in operational use for regular monitoring. This is because water clarity is a highly dynamic variable, and its variability may not effectively be captured by a satellite with about biweekly overpass. In many parts of the world frequent cloud cover further reduces the actual availability of cloud free images to a level which makes Landsat unsuitable for monitoring purposes of a highly dynamic variable, like Secchi disk depth.

MODIS, with its medium spatial resolution, daily coverage, high sensitivity and cost-free distribution (Li & Li, 2004, Miller & McKee, 2004), would be more suitable to monitor such dynamics. However, this potential has rarely been explored in inland water bodies. For example, Lillesand and Chipman (2001) mentioned using MODIS data to estimate Secchi disk depth of large lakes on a regional basis. The Secchi disk depths of Green Bay, Lake Michigan and eleven other lakes were estimated weekly to biweekly using MODIS blue/red spectral radiance ratio from July of 2001 (Lillesand, 2004). Figure 2-6 shows the flowchart of research methodology for assessing SDD map.

**Figure 2-8. Flowchart of research methodology for assessing SDD map**

Wu et al. (2007) compared these two image sources, MODIS and Landsat TM, for mapping the tempo spatial dynamics of Secchi disk depth in Poyang Lake national nature reserve, China, which is also our study area. After deleting the samples 500 m offshore, 71 samples on 5 points were left to build this model. Two multiple regression model had been developed. The model including blue and red band of Landsat TM explained 83% of the variance of the natural logarithm of Secchi disk depth, and the model of MODIS have a better result, 88% of the variance with estimated s.e. of 0.37 explained by this model. F-tests showed that regression models was statistically significant at p=0.0001. This
multiple regression model is as follow:

\[
\ln(\text{SDD}) = 0.474 + 15.240 \times \text{blue} - 21.130 \times \text{red}
\]

This model was used to access Secchi disk depth in the first step. Then the field measured SDD data in 2007 were used to validate this Model. The accuracy test had been done with 33 sample points. To obtain a better result for this research, we related the Secchi disk depth record from field measure in Nov 2007 to the spectral information of MODIS which taken as the same day as the field work. An improved multiple regression model was developed. The detailed model and validation is described specifically in later section.

2.3.4 Modeling visual acuity

Great cormorants (*Phalacrocorax carbo*) are normally considered as good visually-guided pursuit-dive foragers (White *et al*., 2007). The underwater light environments are quite different from aerial environments in spectral composition, luminance and turbidity (Jerlov, 1976). Some scientists think they may have excellent underwater vision. It is reasonable to expect that cormorants have a visual system which can well adapt to function in water. Vision is regarded as the primary sense that guides their foraging. Thus, there were some reports showed that great cormorant have a highly pliable lens whose curvature is driven by powerful intraocular muscles (Glasser & Howland, 1996) and this is thought to accommodate for the loss of corneal refractive power that accompanies immersion and ensures a well focused image on the retina (Katzir & Howland, 2003). However, it is difficult to provide the demonstration of an anatomical capacity to check the visual change when cormorant foraging underwater (White *et al*., 2007). When they dive into water, corneal refractive power will lose. In order to retain a sharp retinal image, this loss should be compensated for by changes in the lens (Katzir & Howland, 2003). This loss of corneal refractive power will also reduce the object sizes in the visual fields and the brightness of the retinal image (Martin, 1999).

Visual acuity refers to the clarity or clearness of one’s vision, a measure of how well a person or animal sees. The word “acuity” comes from the Latin *acuitas*, which means sharpness. It is determined by a test to check the smallest object distinguishable in a distance normally. The lower value of visual acuity (in the unit: minute of arc), the better vision can be affirmed. The underwater visual acuity of many kind of animals were determined at different levels of water turbidity, such as seals (Weiffen *et al*., 2006), Brandt’s Cormorants (Henkel, 2006). White *et al*., (2007) who empirically modeled the aquatic visual acuity of great cormorants under a range of illuminance (I), target contrast (C), viewing distance (VD) conditions. Provided the following equations:
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

VA (I) = (-0.00168 log(I)^2 + 0.0125 log(I) + 0.0889)^{-1}
VA (C) = (10^{(-1.36+0.38*C)})^{-1}
VA (VD) = (10^{(-0.751–0.151*VD)})^{-1}

We assume that great cormorant always dive to bottom of lake for forging in this research. What we want to put as the input for the visual acuity model is how much light can get to bottom and what is the target contrast at the bottom.

According to Wu et al. (2007), underwater irradiance can be calculated by using Secchi disk depth (SDD) and water depth (WD). We estimated light can reach the water surface is $I_{ss}$, and light entering water body ($I_s$) considering the reflectance rate ($k_r$) by water surface. A value of $k_r$ of 4% was adopted according to Campbell & Aarup (1989) and Joshi (2005):

$$I_s = I_{ss} * (1 - k_r)$$

The change in light intensity caused by the absorption is described by Lambert-Beer’s Law, which is a mathematical means of expressing how light is absorbed by matter. Then the light at water depth (WD) was calculated

$$I_d = I_s * e^{-k_i*WD}$$

Where $k_i$ was derived from Secchi disk depth (SDD). (Poole & Atkins, 1929)

$$k_i = a/SDD$$

According to Wu et al. (2007), $a$ equal to 1.133, so the function of light intensity can be calculated according to above.

$$I_{ds} = I_{ss} * (1 - k_r)* e^{-a*WD/SDD}$$

In our model, the light transmittance (LT) which is a percentage of incidents light that can get to bottom from water surface. The fraction of light transmitted (LT) through water depth (in meters) is related to beam attenuation which is the effect of Secchi disk depth. The formula as follows:

$$LT=(1 - k_r)* e^{-a*WD/SDD}$$

We assume that the irradiance at water surface is a constant at 10000 Lux which is the normal sunlight
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

at an average day. The visual acuity of irradiance can be calculated by this formula.

\[ VA(I) = (-0.00168 \log(10000 \times LT)^2 + 0.0125 \log(10000 \times LT) + 0.0889)^{-1} \]

Contrast is the difference in visual properties. This difference causes the object distinguishable from other objects and its background (WIKI 2007). The difference in the color and brightness of the object and other objects within the same field of view is defined to determine the level of contrast normally (USEPR, 2007). Because the human or animal visual system is more sensitive to contrast than absolute luminance, we can perceive the world similarly regardless of the huge changes in illumination over the day or from place to place. One measure of contrast is Michelson contrast (Michelson, 1927), calculated using the formula

\[ C = \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}} \]

In our research, the object of cormorant is the prey. Base on the lecture review, the cormorant always foraging at bottom and the prey type almost the same in a small region. We assume the ordinary contrast of the prey and the background at water surface are the constants which equal to 0.8 in this research. The ordinary maximum and the minimum luminance (L_{\text{max}}, L_{\text{min}}) will decrease when water come to turbid and deep because of the beam attenuation. As the result, the light transmittance (LT) is the only variable which affects contrast. The maximum and minimum luminance at a specified water depth are defined the product of light transmittance and ordinary luminance. The contrast can be calculated by this formula.

\[ C = LT \times (L_{\text{max}} - L_{\text{min}}) / (L_{\text{max}} + L_{\text{min}}) \]

Then the visual acuity of contrast can be calculated by this formula.

\[ VA(C) = (10^{(-1.36+0.38C)})^{-1} \]

To calculate the final visual acuity, we give these two visual acuity different weight (a, b). The two weights are decided by the preview papers. Then the mean value of them was taken as final output for mapping.

\[ VA = \frac{a \times VA(I) + b \times VA(C)}{2} \]

We assume the water depth scale in the ranges form 0.5 to 12 meter and the Secchi disk depth scale in
the ranges form 0.05 to 3 meter which is the common hydrographic condition in the PYNNR. Then Matlab was used to do the model and present figure based on the above math formula.

### 2.3.5 Modeling prey encounter rate

The prey encounter rate is an important indication of the situation of cormorant forging success rate. The following figure shows the foraging process of cormorant and the factors which may impact it.

![Figure 2-9. Foraging process of cormorants](image)

We will use the field measure data of cormorant capture weight to validate the relation of capture rate and visual acuity. To find an improved relation between cormorants underwater visual acuity and capture rate in the real environment. We measured the capture detail, such as fish weight, fish size and capture success rate per unit time at different Secchi disk depth and water depth. The prey encounter rate is formally defined as the product of search efficiency and fish density (Turesson & Bronmark, 2007). The encounter rate will increase linearly when fish density increases in the simplest situation. But the detailed fish density data is difficult to obtain from field the survey and satellite images. To calculate prey encounter rate, we assume it is a constant in this research. However, different mechanism may affect search efficiency. They will produce a more complex relation between fish density and prey encounter rate. We use the search volume which means the cormorant can search per unit of time to define the search efficiency. The volume searched per unit time (V) is a function according to Reactive distance (R), swimming speed of bottom (BS), bottom time (BT), diving time (DT). Figure 2-10 shows the search volume and the formula as below:

\[ V = \Pi^{*} R^{2} * BS * BT \]
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

Reactive distance has been defined as either the maximum distance at which visual predators can detect their prey (Vinyard & O’Brien, 1976) or the maximum distance at which they will pursue their prey (Ware, 1972). It dependent on several factors, such as light intensities, contrasts, prey size and water turbidity. Water turbidity and light intensity are the most important factors of reactive distance. Generally speaking, the elevated turbidity will reduce the reactive distance.

The visual acuity can be transform into reactive distance. We assume the prey size is the constant of 20 cm which is the normally prey size of great cormorant. The reactive distance (RD) is the trigonometric function of prey size (PS) and visual acuity (unit in min of arc). Figure 2-11 shows the relation of them.

\[ \text{RD} = \frac{\text{PS}}{2 \times \tan(\text{VA})} \]

Bottom time was defined as how much time cormorants can stay in the bottom in one diving time. The more time they can stay in depths where preys occur, the higher prey capture rate they can get. There are several factors can impact bottom time. Generally speaking, they will spend more time dive to the bottom in deeper water. Some pursuit diver can maximize the relative time spent at the foraging depth by minimizing the commuting time taken to reach these depths. However, the speed that they can use to reach a given depth can be limited by the body size (Wardle, 1975), mode of propulsion and...
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

buoyancy (Wilson and Wilson, 1995). We assume that cormorants always dive to the bottom to feed. Thus, for our research, we will use the dive angle, swimming speed, and the relation between water depth and diving time to build the cormorant diving model. Knowledge of them enables the bottom time to be calculated.

The diving time (DT) of cormorant relate to the water depth. We recorded the water depth of their each diving. The maximum diving time is about 30 s, it’s the longest time for cormorant to stay in the water during field observation. Regression analysis had been done between them. A strong logarithm relation was found with these data. The diving time can be calculate as a formula of Water depth.

\[ DT = \int (WD) \]

Base on the preview paper (Yan Ropert-Coudert et al., 2004), the diving angle of both male and female cormorants relate to the diving depth. Dive angles were constant until 12 m depth. But there was a clear, positive, linear relationship between dive angle and maximum depth beyond 12 m. The formula of descent angle (DA) of inland lake cormorants are as the follows:

- \[ DA=40 \] if WD<12
- \[ DA=4.61*WD-21.19 \] if WD>12

The swim speed is also a very important factor. It can be dived into two phases, descent phase and foraging phase. The average descent speed (DS) of descent phase is 1.67 m/s, and the bottom speed (BS) of foraging phase is 0.7 m/s. Based on the above knowledge, bottom time can be calculate by the formula as follow:

\[ BT=DT-2* WD*/ \sin(DA)*DS \]

Based on the field observation, fish density is one important factor which will impact the cormorants foraging in the natural environment. The prey type of cormorant was recorded during the field work. Base on the expert knowledge of local fisherman who making life by cormorants for decades, the main food for cormorants in Poyang lake and Rao river is the yellow catfish (Pelteobagrus fulvidraco), Chinese perch (Siniperca spp) and carp. The distribution of these fish relate to water turbidity and water depth. Yellow catfish is often called mud cat in various regions of North America. They like to hide in the mud of shallow and turbid water. The Chinese perch and carp are totally different situation. They always stay in the bottom of deep and clear water. But it is too difficult to model the real fish distribution, we assume it is a constant in our research. The following figure shows the possible
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

situation of prey distribution.

![Fish distribution diagram](image)

**Figure 2-12. Fish distribution**

### 2.3.6 Assessing visual acuity map with DEM and SDD map

Because the spatial resolution of SDD map is 250 meter which as same as the MODIS images. All SDD time series images should be re-sampled from 250 to 20 meters using nearest-neighbor re-sampling to preserve the original values, which are coherent with the spatial resolution of DEM. After that, the water level data which fit the date for each SDD image were selected. The DEM image was subtracted from these water level data to achieve water depth time series images. These re-sampled SDD images which resolution is 250 m and water depth images will be stacked together for the next step processing. Then we subset the region of Poyang Lake national nature reserve form the stacked map, the visual acuity model was used to assess the visual acuity map series. Figure 2-6 shows the flowchart of research methodology for assessing visual acuity map.

![Flowchart](image)

**Figure 2-13. The flowchart of research methodology for assessing visual acuity map**
2.3.5 Assessing dredging ships with Landsat TM

The potential of Landsat TM bands for ship detection is related to the contrast in reflectance of the pixels with ships and their adjacent water. Wu et al. (2007) reported the visible and near infrared bands of Landsat TM has limitation in ship detection while the middle infrared bands hold great potential. An unsupervised classification is applied to the band 7 of Landsat TM image at first. Then we use a NDWI mask to pick up these water bodies and convert these raster images into polygons. Finally the area numbering threshold was used to count the number of ships. Figure 2-14 shows the flowchart of research methodology for assessing number of ships.

One small area with high ship density in our study area is displayed in Figure 2-14. The highly veracious detection can be observed through the comparison of ship information from band 7 of Landsat TM image and the area numbering results from this figure.

Figure 2-14. Flowchart of research methodology for assessing number of ships

Figure 2-15. Comparison of ship information from band 7 of Landsat TM image and the area numbering results
3 Results

3.1 Multiple regression model of MODIS and SDD

We obtained green and red band reflectance value from MODIS image which correspond to the day of field measurement with Secchi disk depth at first. Then the correlation between Secchi disk depth and these reflectance values was calculated. Figure 3-1 shows the relation of individual band of MODIS and Secchi disk depth (SDD) and the natural logarithm of Secchi disk depth (ln(SDD)). Both two bands correlate negatively with SDD and ln(SDD). The natural logarithm of Secchi disk depth present higher correlation with red and blue band reflectance value than the original Secchi disk depth. The variance of ln(SDD) was best explained by the MODIS red band. The R Sq is 0.901.

Figure 3-1. Scatter plots and regressions describing the relation of Secchi disk depth (SDD), natural logarithm of Secchi disk depth (ln(SDD)) and the reflectance value of blue and red bands of MODIS
The spatial resolution of red band of MODIS image is 250 meter and blue band is 500 meter. To obtain a better visual effect, red band should be the main variable in the multiple regression model. The linear regression analyses were used to test the correlation of natural logarithm of Secchi disk depth and these 2 bands. Table 3-1 shows the result of regression models. The both blue band and red band had negative sign in the best fitting multiple regression models. The model can explain 90% of the variation of the natural logarithm of Secchi disk depth with estimated standard error (s.e.) of 0.26. F test showed the regression model was statistically significant at p=0.001. Figure 3-2 shows the relation of the original and natural logarithm of measured Secchi disk depth against the predicted one from the best fitting models. Compare to the model of Wu et al. (2007), this new model can explain higher variation of the natural logarithm of Secchi disk depth. The R Sq increased from 0.88 to 0.901. Table 3-1 shows the comparison of these three models.

<table>
<thead>
<tr>
<th>Regression model</th>
<th>R Sq</th>
<th>s.e.</th>
<th>F</th>
<th>P</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(SDD) = 2.186 – 69.242*blue</td>
<td>0.634</td>
<td>0.49</td>
<td>53.643</td>
<td>&lt;0.001</td>
<td>33</td>
</tr>
<tr>
<td>ln(SDD) = 0.813 – 16.829*red</td>
<td>0.901</td>
<td>0.25</td>
<td>282.169</td>
<td>&lt;0.001</td>
<td>33</td>
</tr>
<tr>
<td>ln(SDD)=0.474+15.240<em>blue-21.130</em>red (Wu et al. 2007)</td>
<td>0.83</td>
<td>0.20</td>
<td>60.51</td>
<td>&lt;0.001</td>
<td>71</td>
</tr>
</tbody>
</table>

Table 3-1. Regression models between the natural logarithm of Secchi disk depth (ln(SDD)) and the blue and red bands of MODIS

Figure 3-2 shows the distribution of the residual which subtracting from filed measured SDD. The regression residuals are normally distributed.

![Figure 3-2. Normal P-P Plot of Regression Standardized Residual for SDD](Image)
We also used the measured SDD data of the field work in 2007 to validate the Model of Wu et al. 2007. The analysis result is showed in Figure 3-3. The scatter plots revealing the agreement of measured and predicted SDD. This model explain 80.6% of the variation of the measured Secchi disk depth with estimated s.e. of 0.26. F-tests showed that this regression models was statistically significant at p=0.001 (F= 128.68, d.f. =1). Figure 3-4 shows the distribution of the residual which subtracting from filed measured SDD. The regression residuals are normally distributed. Compare to the result of Wu et al. (2007), the correlation reduced from 88% to 80.6%. The possible reason for the reduced accuracy is described specifically in later section.

![Figure 3-3. Scatter plots describing the measured and predicted Secchi disk depth](image1)

![Figure 3-4. Normal P-P Plot of Regression Standardized Residual for validating](image2)
3.2 Temporal SDD variation and distribution maps

3.2.1 Temporal SDD variation in the main part of Poyang Lake

The follow Figure 3-5 shows the average SDD derived from each MODIS image of 5 years. This Figure presents a declining trend of Secchi disk depth in the period between April and October from 2000 to 2006 expect 2002. The higher value occurred in the summer every year when water lever get higher. That is due to the increased water volume. The fit line shows the average SDD value declined from 2001 to 2006. Secchi disk depth fluctuated between 0.4 and 1.5 m and the average value is 0.9 m in 2000 before the dredging started. The average Secchi disk depth dropped below 0.8 m in 2003 and 0.5 m in 2006.

![Figure 3-5. Average Secchi disk depth of Poyang Lake from 2000 to 2006](image)

3.2.2 Time series SDD maps predicted from MODIS

Figure 3-4 display the time series SDD maps which derived from MODIS images. The decline of Secchi disk depth was showed by this time series maps clearly. Comparing these maps, Secchi disk depth of north Poyang Lake was high which display blue and green color in map in the summer of 2000 and 2001. The low value in June should be the nature process. The discharge of Yangtze River leads a mass of sediment flow to lake form the river. The Secchi disk depth declined quickly after 2003. The maps displayed mostly in red color which means low Secchi disk depth in the north Poyang Lake. It was lower than 0.3 m in whole 2004. The same situation happened in the latter half of 2005 and first half of 2006. Thus, we can accept there is a significant decline in Secchi disk depth at Poyang Lake.
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China


November 1st 2000

Secchi disk depth (unit: meter)
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

Figure 3-6. Secchi disk depth predicted from MODIS imagery from 2000 to 2006
3.3 Impact of dredging on Secchi disk depth

Figure 3-7. Time-series maps showing the distribution of Secchi disk depth and ships during summer or autumn from 2001 to 2006 in the northern Poyang Lake and Gan River.

Above figure 3-7 shows the spatial and temporal variations of Secchi disk depth and ships. The map
series confirm the increase trend of ship. Not only the number of ships change but also the spatial distribution of ships. The major part of ship spear over Hukou to Gan River in 2000. They move to the north part of sand hill in next 4 years. Secchi disk depth of the region with ships is lower than the region with out ships.

Figure 3-8 shows the number of ships that detect from Landsat TM images in the northern Poyang Lake and Gan River. Almost 200 ships were detected from Landsat TM images in 2000. The number grew quickly in next four years. It reached 300 in 2002, and 410, 460 in 2003 and 2004. It declined from 460 to 360 in 2005 and back to 450 in 2006.

The regression between Secchi disk depth from MODIS images and the number of ships detected from Landsat TM images is showed in the follow figure 3-9. The relation is negative ($R^2=0.78, F=130.59, P<0.006$). Thus, we can accept that the dredging actives could reduce Secchi disk depth of Poyang Lake.

Figure 3- 9. Relation between average Secchi disk depth and the number of ship (2000-2007)
3.4 Cormorants’ visual acuity

3.4.1 Visual acuity model

Here is a figure to show the effect of water depth and Secchi disk depth on the light transmittance. The scale of light transmittance is in the range from 0 to 0.7. The transmittance present to peak value which almost 0.7 when Secchi disk depth maximize and water depth are minimize. Compare to the deep and turbid lake, more light can arrive to the lake bottom in the shallow and clear lake.

![Figure 3-10. Effect of Water depth and Secchi disk depth on light transmittance](image1)

Figure 3-10. Effect of Water depth and Secchi disk depth on light transmittance

Figure 3-11 shows the effect of Water depth and Secchi disk depth on visual acuity which influence by light transmittance. The peak value of this surface presents to low Secchi disk depth area.

![Figure 3-11. Effect of Water depth and Secchi disk depth on visual acuity (LT)](image2)

Figure 3-11. Effect of Water depth and Secchi disk depth on visual acuity (LT)
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

Figure 3-12 shows the effect of water depth and Secchi disk depth on contrast. The surface is almost as the same the surface of light transmittance. The contrast scale in use ranges from 0 to 0.5.

![Figure 3-12. Effect of Water depth and Secchi disk depth on contrast](image)

The following figure shows effect of Water depth and Secchi disk depth on visual acuity which influence by contrast. The visual acuity decrease abruptly in the shallow water depth.

![Figure 3-13. Effect of Water depth and Secchi disk depth on visual acuity (contrast)](image)

The different weights have been given to these two visual acuities which affect by light transmittance
and contrast. Based on the preview paper, prey contras may have a heavier weight than light for cormorant forging. So we define the weight of visual acuity that affect by light as 0.3 and the other one as 0.7. Figure 3-14 shows the effect of Water depth and Secchi disk depth on the final visual acuity. Cormorants have better visual acuity in the shallow and clear water than depth and turbid water. The visual acuity doesn’t change too much in the mesial water depth and Secchi disk depth.

**Figure 3- 14. Effect of Water depth and Secchi disk depth on the final visual acuity**

Based on the above model, we made the following table to show prey detectability change demonstrating the effects of contrast and light.

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<th>Light</th>
</tr>
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<td></td>
<td>1000 lux (dusk)</td>
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<tr>
<td></td>
<td>70 lux (twilight)</td>
</tr>
<tr>
<td></td>
<td>1 lux (deep twilight)</td>
</tr>
<tr>
<td></td>
<td>0.1 lux (full moon)</td>
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<tr>
<td>100%</td>
<td>![Fish Image]</td>
</tr>
<tr>
<td>80%</td>
<td>![Fish Image]</td>
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<tr>
<td>60%</td>
<td>![Fish Image]</td>
</tr>
<tr>
<td>40%</td>
<td>![Fish Image]</td>
</tr>
<tr>
<td>20%</td>
<td>![Fish Image]</td>
</tr>
</tbody>
</table>

**Figure 3- 15 Effects of contrast and light on prey detectability**
3.4.2 Temporal visual acuity variation and distribution maps

Figure 3-16 show the average visual acuity of PLNNR from 2000 to 2005. An increase trend of visual acuity can be observed from this figure. The fit line shows that average visual acuity was about 17 minutes of arc in 2000 and increased to 17.5 in 2004, and finally reached the peak at 18 in 2005. The differentiation of visual acuity during one year also decreased. It was about 4 minutes of arc in 2000 and down to 2 in 2005.

![Figure 3-16. Average Visual acuity of PLNNR from 2000 to 2005](chart)

Figure 3-17 shows the time series visual acuity maps which derived from time series Secchi disk depth maps and digital elevation model of the region of PLNNR. The decline trend of visual acuity can be observed from these time series maps. A vertical gradient occurred in the region of north part of Sand Hill. The visual acuity is lower than 16 minutes of arc at July 16th 2000 and increase a little at July 24th 2001 before the dredging started. It increased quickly from 2003 when dredging started. The visual acuity is higher than 20 minutes for the whole 2004 and 2005. Dachahu which is the most important lake of PLNNR is located at the north-west of this map. The visual acuity of it is depended on the connection between itself and the north part of sand hill. It will increase at summer when recharged water from the main part of Poyang Lake and decrease during other three seasons. The almost same situation happened in Dahuchi which located at the south east of this map. Visual acuity of this lake fluctuates seasonally with a higher value in both spring and autumn and lower value in summer. Generally speaking, we could observe that the acreage of foraging region with a lower visual acuity which means high detectability is decrease form time series visual acuity maps form 2000 to 2005. Thus, we can accept there is a significant decline in visual acuity at Poyang Lake national nature reserve.
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China
Figure 3-17. Visual acuity predicted from MODIS imagery from 2000 to 2005 (without 2002)
3.4.3 Impact of dredging on visual acuity

Figure 3-17 shows the spatial and temporal variations of visual acuity and ships. The map series confirm the increase trend of visual acuity from 2001 to 2005. The region with higher visual acuity values occurred at the north part of sand hill where present to higher ship densities in all 4 years. The average visual acuity of map increased alone with the increased number of ship. Visual acuity of the region with ships is lower than the region with out ships. These results supported the statement that dredging actives have positive impact on visual acuity.

![Maps showing spatial and temporal variations of visual acuity and ships from July 2001 to July 2005.](image)

**Figure 3-18.** Spatial and temporal variations of visual acuity and ships
The regression between visual acuity and the number of ships detected from Landsat TM images in 4 years is showed in the follow figure 3-19. The relation is positive (\(R^2=0.514\), F=2.12, P<0.008). Although the number of sample points is few and far between, we can confirm the increase trend of visual acuity by increased ship number. Thus, we can accept that the dredging activities could increase visual acuity of Poyang Lake national nature reserve.

Figure 3- 119. Relation between average visual acuity and the number of ships for 4 years

3.5 Cormorants’ encounter rate model

Regression analysis had been done between water depth and diving time. A strong logarithm relation was found with these data. The water depth had negative sign in the best fitting multiple regression models. The model can explain 84.9% of the variation of the natural logarithm of water depth with estimated standard error (s.e.) of 0.31. F test showed the regression model was statistically significant at p=0.001. So the logarithmic function is used in following formula. Figure 3-18 shows the regression relation between diving time and ln (water depth).

\[ DT=8.8667 \times \ln (WD)+6.281 \]
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

Figure 3-20. Scatter plots and regressions describing the relation of natural logarithm of water depth (ln(SDD)) and the diving time

The formula of bottom time can be simulated by water depth

BT=8.8667*Ln(WD)+6.281-2*WD/sin(40)*1.67 if WD<12
BT=8.8667*Ln(WD)+6.281-2*WD/ sin(4.61*WD-21.19)*1.67 if WD>12

Based on the formula and data derived from previous paper and above bottom time formula. Reactive distance (RD) and search volume (V) per diving of cormorants can be calculated as follows:

\[ VA = \int (WD, SDD) \]
\[ RD = \frac{PS}{2 \cdot \tan(VA)} = \int (WD, SDD) \]

Where PS (prey size) is a constant.

\[ V = \prod \cdot RD \cdot BS \cdot BT \]
\[ BT = \int (WD) \]
\[ RD = \int (WD, SDD) \]
\[ V = \int (WD, SDD) \]

Where BS (bottom speed) is also a constant. Then the Secchi disk depth and water depth were used as the input variables to show the 3-D figures of reactive distance and search volume in Matlab. Figure 3-19 shows the effect of water depth and Secchi disk depth on reactive distance. The scale of reactive...
distance is in the range from 0.7 m to 1.2 m. The reactive distance present to peak value when Secchi
disk depth maximizes and water depth minimizes. The valley value present to turbid water.

![Figure 3-21. Effect of Water depth and Secchi disk depth on reactive distance](image)

Then the formula with the parameters which are Reactive distance (R), swimming speed of bottom
(BS), bottom time (BT), diving time (DT) was used to model search volume (unit in cubic meters).
The follow figure shows the complex surface of search volume. The scale of reactive distance is in the
range from 5 to 24 cubic meters. It reaches the peak value when water depth is 4 meter and decreases
when Secchi disk depth decline. The lowest search volume occurred at shallow and deep water. The
reason is that cormorant can not stay in the bottom for long time when water is shallow and the
reactive distance is limited by decreased light transmittance in deep water.

![Figure 3-22. Effect of Water depth and Secchi disk depth on search volume](image)
Finally, the prey encounter rate can be counted as the function of water depth (WD), Secchi disk depth (SDD) and prey density (PD). Because we assume the prey density as a constant in the prey encounter model, the surface of encounter rate will be the same as the search volume.

### 3.6 Effect of visual acuity and encounter rate on capture rate

To find the relation between visual acuity and cormorant capture rate, we use water depth and Secchi disk depth from field measurement when cormorant foraging to predict the visual acuity. The capture rate is simulated by the capture weight of four cormorants per hour (unit in Kg.). The regression analysis has been done. Here is the figure to show the regression between cormorants capture weights per hour and the predicted visual acuity of foraging area. The capture weight is negative relate to visual acuity with a poor pertinence ($R^2=0.241$, $F=279.59$, $P<0.005$).

![Graph showing the relation of capture weights per hour and predicted visual acuity](image)

**Figure 3-23. Scatter plots and regressions describing the relation of capture weights per hour and predicted visual acuity**

The regression analyses also shows poor pertinence when search volume which represent the prey encounter rate was linked to the capture weight per hour. The positive correlation is a little higher than the above ($R^2=0.312$, $F=169.43$, $P<0.002$). Figure 3-19 shows the regression between them.
Figure 3- 24 Scatter plots and regressions describing the relation of capture weights per hour and search volume

The above two figures shows some predicable of cormorant foraging. The weak correlation proved the statement that capture rate should relate to the prey distribution more than visual acuity and prey encounter rate.
4 Discussion

4.1 Secchi disk depth and dredging

This research has shown a positive relation between the intensity of sand dredging and Secchi disk depth in Poyang Lake. The remote sensing images, such as MODIS and Landsat TM images, were used to assess the Secchi disk depth and the number of ships. We reported that the our SDD model can explain 90% of the variation of the natural logarithm of Secchi disk depth with estimated standard error (s.e.) of 0.26 by using the reflectance value of red band of MODIS only (Table 3-1). The middle infrared bands of Landset TM hold great potential in ship detecting. Previous research proved that the dredging induced SDD revealed a significant increase from 2000 to 2005. Our results confirm the significant positive relation between ship numbers and water turbidity reported by Wu et al. 2007. These results imply that sand dredging has a huge impact on water clarity of Poyang Lake.

Compare to the result of Wu et al. (2007), the correlation between Secchi disk depth and the reflectance value of MODIS reduced from 88% to 80.6%. The reasons for decrease accuracy are both complicated and varied. The model presented by Wu et al. (2007) was based on the data from the Bureau of Jiangxi PLNNR and the International crane foundation recorded in 2004 and 2005. Receiving water from five inland rivers and moderating floodwater from the Yangtze River lead to a complex hydrology condition in Poyang Lake. Diversification of this lake –river interactions can reflect on Secchi disk depth model instable in two years. Climate variations in the region and Three Gorges dam also are very important factors.

4.2 Visual acuity and dredging

The research also revealed that Cormorants’ visual acuity could be mapped reliably using time series of Secchi disk depth map and a DEM in combination with water level data. The remote sensing and Geo-information system had been applied in the field of ecosystem modeling from last two decade. Thus far, most of these researches were focus on the vegetation, such as the grass primary production (GPP) model (LeRoux et al., 1997), carbon exchange model (Willem et al., 2007), canopy density model, etc. Our results indicated that RS and GIS technology offer potential for modeling and mapping the visual acuity of visual feeding animals. We used Secchi disk and water depth as the input variables to build the visual acuity model of cormorants, based on simple physical and optical principles. The results are reasonable. The time series visual acuity map shows a decline trend from 2000 to 2005, but did not reveal its cause.
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

What the argument did the results offer to support the claim that visual acuity increased because of dredging? The increase in number of ship was significantly related to the increase in visual acuity. The positive correlation shown by statistic analysis is the result of the dredging induced increase water turbidity. The increase turbidity will reduce the light transmittance and prey contrast in the bottom of lake. As the result, less light and smaller contrast will cause the prey detection become harder for cormorants. Finally, visual acuity could active to a quite high value near the dredging area where the turbid and deep water located.

Together, research of using the remote sensing and GIS technique to map the spatial and temporal water turbidity and build visual acuity model for cormorants corroborate the statement that the dredging induced increase water turbidity reduce the detect ability. This method could be applied for other visual feeding animals.

The impacts of dredging induced increased water turbidity on aquatic ecosystems have been reported in a wide range, such as aquatic plants and animals, and also noise, pollution etc. (Hossain et al., 2004; Lubke et al.,1984; Nayar et al.,2003; Spencer et al.,2006; Zhong & Chen, 2005). Poyang Lake is an important base of aquatic organisms, such as fishes, waterfowl. Most of these organisms are visual feeding animals. The increase turbidity will reduce their detect ability. As the result, the degraded optical environment may cause a decrease or disappearance of food source of visual feeding animals including fishes, aquatic birds. The balance of ecosystem was seriously broken.

In addition, the dredging activities not only reduce the Secchi disk depth, but also degrade the habitat of aquatic organisms. The noise and oil pollution could seriously affect the propagation, growth and subsistence of fish in the lake ( Zhong & Chen, 2005). Some populations of rare species, such as the Baji and Yangtze finless porpoise, have decreased rapidly because of dredging (Fok & Pang, 2006). The proportion of grass land in the Poyang Lake national nature reserve was also decreased by the increased dredging actives (Wu et al. 2007). Thus we suggest that the dredging of Poyang Lake could have destruction effect on the local aquatic ecosystem.

4.3 Visual acuity and capture rate

This research shows a weak but significant correlation between predicted visual acuity and the capture rate of cormorants as recorded in the field. A somewhat weak relation is understandable, as the cormorants’ capture rate would also be influenced by prey density. The visual acuity is only part of the search volume and the search volume is only part of encounter rate. The prey density presumably plays an important role in the cormorant foraging.

There are still some arguments in this topic. Hecht and Lingen (1992) reported that feeding rate of
pursuit divers was reduced in estuaries with high water turbidity while White et al. (2007) mentioned that the visual acuity is not the main factor of cormorants foraging. Our results confirm the theory report by White et al. (2007). The reason should be that cormorants may use other sensory cues such as touch sensitivity in the bill. When cormorants forage at the bottom, they probably probe the sediment with their beaks and find prey.

The underwater visual acuity of cormorant is not as good as we think. White et al. (2007) had modeled prey detectability in cormorants using a high contrast prey item with low turbidity. The result is not good. The ability of cormorants to resolve visual detail in water is poor, and far below that predicted by analogy with the vision of predatory birds that take prey in aerial pursuit. The cormorants’ highest visual performance is only equal to that of unaided humans in water. And acuity will decline with increasing turbidity in real lake, and the high contrast preys are not the typical food for cormorants. Thus, in turbid conditions, acuity will be further reduced while the field data still present a high capture weight per unit time. The above suggest us that the visual acuity is not the main factor of cormorants foraging.

5 Conclusion and recommendation

5.1 Conclusions

In this research, methodology for predict the visual acuity of great cormorant in Poyang Lake by optical remote sensing and Geo-information system has been derived. Time series visual acuity maps are made by using Secchi disk depth and water depth as the input variables. We also investigated that the dredging induced increase water turbidity could reduce the visual acuity of great cormorants. In addition, we propose the visual acuity is not the main factor of cormorants foraging. The work is in three steps: first, a regression model has been built to map the Secchi disk depth by using the reflectance value of red band of MODIS. Second, a semi physical model has been built to model visual acuity and dive behavior of cormorants by given the Secchi disk depth and water depth as the input, Third, the time series visual acuity maps which derived from above model is compared to the number of ships which derived from the band 7 of Landset TM and the field measured capture weight per unit time. The results show that this method is a promising technique for the research on ecosystem modeling by using the remote sensing data as the inputs. The short time and long time change of visual acuity can be distinguished from time series map with little cost and time. The conclusions can be summarized as follow:
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

(1) Secchi disk depth could be mapped with a highly accuracy by using MODIS images.

(2) The visual acuity and dive behavior models of great cormorant which using the Secchi disk depth and water depth as the input variables are developed.

(3) Time series Secchi disk maps derived from MODIS images revealed a significant decrease trend in north part of Poyang Lake from 2000.

(4) Time series visual acuity maps revealed a significant increase trend in Poyang Lake national nature reserve from 2000.

(5) The dredging induced increase water turbidity could reduce the prey detect ability by increase the visual acuity of great cormorants.

(6) We confirm the vision detection is not the main capture method of great cormorant during foraging.

5.2 Recommendations and future research

So far, the dredging impact of Poyang Lake is not called enough attention. Thus we suggested the effect of dredging actives should be taken an import part in the future research of Poyang Lake. The topic can be summarized as follow:

(1) With more information about the prey density of cormorants, a more accuracy model can be developed to map their capture rate.

(2) The satellite images could be used to access other capture models for the visual feeding animals.

(3) The GPS devices could be attended to cormorants, the recode will help us to research the destitution and relate them to the remote sensing data to find correlation of them.
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

Reference


Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China


Takahashi, T., K. Kameda, et al. (2006). "Food habits of great cormorant Phalacrocorax carbo hanedae at Lake Biwa, Japan, with special reference to ayu Plecoglossus altivelis altivelis." Fisheries
Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

Science 72(3): 477-484.


WWF (2005). Waterbird survey of the middle and lower yangtze river

6 Appendix

Appendix A: The equipments required in the field survey

<table>
<thead>
<tr>
<th>Equipments used in field survey</th>
<th>Quantity</th>
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<td>Ribbon tape</td>
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<tr>
<td>GPS</td>
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<td>Fisher boat</td>
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<td>Cormorants</td>
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Appendix B: The recode of Secchi disk depth, water depth and capture weight during cormorant observation

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Appendix C: Geographical coordinates of field samples

Projection info = {UTM, 50, North, WGS-84, units=Meters}

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Spatial analysis of the impact of dredging induced increased water turbidity on the visual acuity of great Cormorants in Poyang Lake, China

Appendix D: Secchi disk depth and reflectance values of blue and red band of MODIS of field samples

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Appendix E: Diving time, recovery time and water depth of cormorant observation

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