**NASA DEVELOP National Program**



Patrick Henry Building

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Virginia Water Resources

*Utilizing NASA Earth Observations to Monitor the Extent of Harmful Algal Blooms in Lower Chesapeake Bay Watersheds*

 **Technical Report**

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# I. Abstract

Harmful algal bloom (HAB) species such as *Alexandrium monilatum* and *Cochlodinium polykrikoides* have had an increasing ecological impact on the Chesapeake Bay watershed where they disrupt water chemistry, kill fish, and cause human illness. In Virginia, scientists from Virginia Institute of Marine Science (VIMS) and Old Dominion University (ODU) monitor HABs and their effect on water quality; however, these groups lack a method to track HABs in real time. This limits the ability to document associated water quality conditions and predict future blooms. Band reflectance values from Landsat 8 Surface Reflectance data obtained from USGS Earth Explorer and Moderate Resolution Imaging Spectroradiometer (MODIS) imagery collected from NOAA CoastWatch were cross-calibrated to create a regression model to estimate concentrations of chlorophyll in the Bay. Calculations were verified with *in situ* measurements from the Virginia Estuarine and Coastal Observing System. Imagery produced with the Chlorophyll-a calculation model will allow VIMS and ODU scientists to better assess the timing, magnitude, duration and frequency of HABs in Virginia’s Chesapeake watershed and to predict the environmental and water quality conditions that favor bloom development.

**Keywords**

Harmful Algal Bloom, Remote Sensing, Virginia, James River, York River, Chlorophyll A, Landsat 8 OLI, Lower Chesapeake Bay, Hampton Roads, Total Suspended Matter, Algae

# II. Introduction

**Background:**

A harmful algal bloom (HAB) is a high concentration of phytoplankton in a river, lake or other aqueous system that has a harmful effect on life and the environment. In the Chesapeake Bay watershed, HABs affect water quality by disrupting water chemistry, reducing oxygen levels in the water, and blocking the passage of sunlight through the water column. The species *Cochlodinium polykrikoides* and *Alexandrium monilatum* are of particular concern because these species also produce toxins that kill fish, cause deformities in shellfish, and are associated with human illness. These HABs have a negative economic impact on Virginia fisheries and on the tourist industry.

HABs are most common between May and October when the water is warm and large amounts of nutrients from agriculture and industry are washed into the Bay. Industrial discharge of nutrients is currently limited by the Virginia Pollutant Discharge Elimination System (VPDES) Permit. The permit was modified in 2012 to require a four-year reduction of industrial discharge to reduce HABs and improve water quality in the James River and York River. As a result, these rivers are regularly monitored to determine the effect of the permit modifications and measure HAB occurrence.

Monitoring is the responsibility of Virginia’s Harmful Algal Bloom Task Force, a collaboration of the Virginia Department of Health, Virginia Institute of Marine Science (VIMS), Virginia Department of Environmental Quality (DEQ), the Marine Resource Commission, and Old Dominion University (ODU).

ODU uses a fixed track boat to measure chlorophyll levels in the Lower James River. ODU also collects weekly water samples from seven fixed stations on the James River. Additional samples from the James River are collected by the Hampton Roads Sanitation District during routine water quality activities. VIMS samples water from the western Chesapeake Bay, as well as from fixed stations in the York River. However, many of parts of the Bay are not routinely monitored. Virginia relies on public reporting to track algal blooms in unmonitored areas.

Unfortunately, real-time monitoring of algal blooms is not possible as a complex series of DNA tests are required to separate and identify harmful algal species from the benign microorganisms that are also present. Therefore, water quality data is not available until the end of the bloom season. This limits the ability to predict HAB occurrence and document associated environmental and water quality conditions.

Remote sensing allows imaging of the entire Bay at regular intervals. Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) has a sensor that is calibrated for chlorophyll, a proxy for algal blooms. However, Aqua MODIS chlorophyll products have 1.4 kilometer resolution. This resolution is too large to adequately image chlorophyll in Virginia’s rivers.

Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) and Landsat 7 Enhanced Thematic Mapper (ETM) do not have chlorophyll sensors, but provide real-color images with 30 meter resolution imaging of the Chesapeake Bay. At this resolution, it is possible to see HABs.

We cross-calibrated Aqua MODIS chlorophyll measurements with Landsat band reflectance to create a chlorophyll and total suspended matter (TSM) imaging tool with 30 meter resolution. This tool will allow the Virginia Harmful Algal Bloom Task Force to better monitor the effect of the permit modifications and will influence decision-making regarding immediate and long-term response to HABs in the Chesapeake Bay watershed.

**Project Objectives:**

While high levels of chlorophyll can indicate the presence of algal blooms, high levels of TSM indicate increased runoff of nutrients that contribute to bloom development. Therefore, our project objective was to create tools that will allow our partners to easily process Landsat 8 scenes to show both chlorophyll and TSM at 30 meter resolution.

During the first term of the project, we had two main goals. The first was to introduce our partners to historical map products (MODIS Aqua, daily and weekly chlorophyll-a and TSM) available from the National Oceanic and Atmospheric Administration’s (NOAA) CoastWatch East Coast Node website (<http://coastwatch.chesapeakebay.noaa.gov/cb_composite.php>).

Our second objective was to cross-correlate measurements from Aqua MODIS and Landsat 8 OLI and TIRS to generate algorithms that allow estimated chlorophyll and TSM to be calculated for the lower Chesapeake Bay at 30 meter resolution. Tools using these algorithms will be created during the second term of the project.

**Study Area:**

HABs are a concern throughout Virginia’s Chesapeake Bay. Our analysis focused on Landsat Path 14 - Row 34, which includes Virginia’s Lower Chesapeake Bay, including the James River, York River, Elizabeth River, and Mobjack Bay.

**Study Period:**

Data was collected and analyzed for May through October of the years 2011 to 2014, as well as May, June and July 2015. (Appendix 1)

**National Application(s) Addressed:**

The project addressed the NASA Earth Science Water Resources application area. The study addresses water quality issues related to harmful algal blooms.

**Project Partners:**

The Virginia Water Resources project partners include Russ Baxter, Virginia Deputy Secretary of Natural Resources for the Chesapeake Bay, the Virginia Institute of Marine Science (VIMS), the Virginia Department of Environmental Quality (DEQ), Old Dominion University (ODU), and the Hampton Roads Sanitation District (HRSD). These agencies are responsible for detecting and responding to HABs and ensuring the health of Virginia’s water resources.

VIMS, located in Gloucester Point, Virginia, is a marine research and education center mandated by the Code of the Commonwealth of Virginia. Its role is to conduct research and advise Virginia’s policy makers on matters of coastal and estuarine science, including HABs. VIMS monitors HABs in the Chesapeake Bay with the assistance of ODU researchers. HRSD also routinely monitors water in the Lower Chesapeake Bay. DEQ responds to public reports of algal blooms.

Current HAB monitoring methods are expensive and limited in both geographic and temporal scope. The goal of this project is to create tools that will allow VIMS and ODU scientists to use remote sensing to target monitoring and data collection efforts. The project’s end-tools will enable our partners to better predict the environmental and water quality conditions that favor bloom development in the Lower Chesapeake Bay.

# III. Methodology

**Data Acquisition:**

*Landsat Data*

Landsat Surface Reflectance products from Landsat 8 and Landsat 7 were downloaded using the United States Geological Survey’s Earth Explorer System for dates between May and October 31 of 2011, 2012, 2013 and 2014 as well as data for May, June and July 2015. Path 14 - Row 34 was used as the search criteria and “Landsat CDR” (Landsat Surface Reflectance) was selected as the preferred dataset in the Earth Explorer interface. This search resulted in scenes showing the James, York and Elizabeth rivers; the Mobjack Bay (Mathews, Va); and the Chesapeake Bay (Appendix 1).

*Aqua MODIS*

Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) Level 2 data for the Chesapeake Bay Watershed were obtained from NOAA’s CoastWatch’s East Coast Node. NOAA’s Chesapeake Bay Chlorophyll-a product was generated using the NOAA 3-band ocean color (OC3) algorithm combined with the Near Infrared (NIR) and Short Wave Infrared (SWIR) atmospheric corrections and the regionally tuned NASA OC3 NIR algorithm. Total suspended matter (TSM) was processed using the algorithm referenced in Ondrusek, et al., 2012. Daily chlorophyll-a and TSM estimates were downloaded as .hdf files and imported into ArcGIS.

*Ancillary Data*

*In situ* water sampling data were provided by Dr. Todd Egerton from the Department of Biological Sciences at Old Dominion University. Samples were obtained from the lower James for years 2011 to 2014 and included measures such as annual corrected Chlorophyll-a ((µg/L) and biomass (µgC/L) by algae division.

Additional *in situ* data for Landsat dates was obtained from the Virginia Estuarine and Coastal Observing System (VECOS) website (<http://web2.vims.edu/vecos/>). The site, which maintained by VIMS, includes historical data from continuous water stations, fixed long term stations and data cruises.

Annual correction equations for chlorophyll estimates from data flow cruises were also provided by Dr. Egerton. This data will be used for verification of the model during the second term.

*Bathymetric Data*

Bathymetric data for the Chesapeake Bay (30 meter resolution) was downloaded as a 30 meter DEM from the National Oceanic and Atmospheric Administration’s (NOAA) estuarine bathymetry website (<http://estuarinebathymetry.noaa.gov/bathy_htmls/M130.html>).

**Data Processing**

*Landsat 8 Data*

Approximately 22 percent of the data in Landsat 7 images is missing due to the 2003 failure of the Scan Line Corrector (SLC) in the Landsat 7 Enhanced Thematic Mapper (ETM). Therefore, we limited our initial analysis to Landsat 8. Landsat 8 data for Path 14 - Row 34 is available in .hdf format and is projected in the WGS84 UTM Zone 18N coordinate system. The .hdf files were opened in ArcGIS. True color composites of Landsat 8 images were compiled using band 4, band 3, and band 2. The composite images were saved as .tif files.

We created a tool in ArcGIS Model Builder to process the .tif images in preparation for later spectral reflectance models. The pixel values for band 1 through 5 were divided by 10,000 in order to rescale the integer band values to floating point numbers between 0 and 1.

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Next, the Normalized Difference Vegetation Index was calculated using bands 4 and 5 in order to determine the density of plant growth.

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After the NDVI was calculated, the conditional evaluation tool (con, spatial analyst, input condition: “NDVI<=0”, input true raster or constant value = “1”) was used to create a water mask that uniquely identified water and removed land pixels. We used the water mask layer to extract the water pixels from each rescaled band using the ArcGIS “extract by mask” tool.

Clouds were removed using a mask created with the cf\_mask\_conf layer from the Landsat download. Pixel values equal to “2” or “3” were changed to “0” with the “Reclassify” tool. All other pixels were given a value of “1”. Missing values were treated as no-data. The cloud removal mask was created by extracting only pixels (“extract by value” tool) with a value of one.

We created new composites using the extracted water-only layer of bands 1 through 5. The composite image was opened in ArcGIS, where the red band was set to band 4, the green band to band 3, and the blue band to band 2. The images were enhanced using the percent clip stretch (min = 10 and max = 10) to trim off extreme values.

In order to create a chlorophyll estimation tool, we needed to cross-calibrate the processed Landsat data from May through October 2013 with CoastWatch MODIS chlorophyll-a estimations for the corresponding dates. Since MODIS pixels (1.4 km) are larger than Landsat pixels (30m), we used the ArcGIS focal statistics tool to obtain the find the mean pixel value of each 47 pixel by 47 pixel moving window on the Landsat data; null values were removed to prevent underestimation of chlorophyll. This produced a smoothed masked Landsat spectral reflectance raster for each band.

*Aqua MODIS*

Daily CoastWatch MODIS chlorophyll-a estimates were imported into ArcGIS 10.3. The.hdf rasters were converted to point data using the “raster to point” tool. This vector file was imported into to the Landsat map for the appropriate date.

*Bathymetry*

NOAA’s estuarine bathymetric data for the Chesapeake Bay (dataset M130) was available as three DEM tiles. The tiles were joined as a mosaic in ERDAS and exported as a TIFF into ArcMap. The Spatial Modeler “con” function was used to convert all values greater than 0 to 0, so there would be no positive values in the data set. The dataset was projected in the NAD27 UTM Zone 18N coordinate system; it was reprojected in the WGS84 UTM Zone 18N coordinate system before use.

*Preparation for Cross Calibration of Aqua MODIS and Landsat 8 Data*

For each date, the MODIS chlorophyll-a value vector file was used to extract the bathymetric measurement and the values of each smoothed masked Landsat spectral reflectance raster band (ArcGIS “extract values by points”). A table was created of MODIS chlorophyll-a values, corresponding bathymetric measurements, and Landsat spectral reflectance values for bands 1 through 5. The table was saved as a .dbf file that could opened in Excel. This provided the information we needed for our regression equations. The equations were calculated using the R environment for statistical computing.

**Data Analysis:**

Our analysis methods were based on Lim and Choi’s (2015) method for assessing water quality in Korean rivers using Landsat 8 OLI reflectances. However, we cross-calibrated Landsat band data with Aqua MODIS chlorophyll and TSM measurements rather than with in-situ data.

The initial cross calibration of Aqua MODIS and Landsat 8 reflectance data was conducted using only data for July 19, 2013. This date was chosen because there were very few clouds and most of the study area was visible in both the Landsat 8 and Aqua MODIS imagery.

*Chlorophyll estimation*

Initial graphing of MODIS chlorophyll estimates with band data showed that data could easily be divided into two clusters: data from the ocean (no bathymetry) and data from the Chesapeake Bay (with bathymetry).

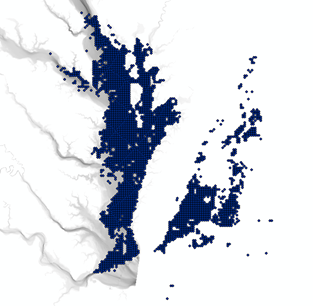
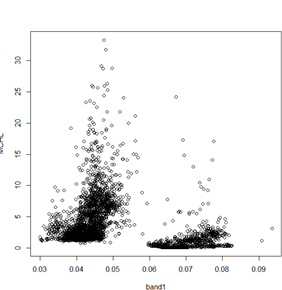


Figure 1 – MODIS Points

Figure 2 - Initial graph of Aqua MODIS chlorophyll measurements (y-axis) vs. Landsat 8 reflectances (x-axis)

We initially used the formula MCHL ~ band1 + band2 + band3 + band4 + band5 for our regression models. With this formula, Landsat data from the ocean was well correlated to MODIS chlorophyll values with an R-squared value of 0.6872866. When outliers were removed, the R-squared value increased to 0.8633691 indicating a very high degree of correlation in oceanic waters.

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| --- | --- |
| **Depth** | **R-squared** |
| 0 to -5 | 0.25 |
| 0 to -20 | 0.49 |
| < -5 | 0.34 |
| < -10 | 0.31 |
| < -15 | 0.54 |
| < -20 | 0.69 |
| Deep ocean | 0.86 |

In the Chesapeake Bay, initial results differed. In water with depths greater than 20 meters, the initial formula provided an r-squared value of 0.5831518; when outliers were removed the r-squared equaled 0.6910601indicating a strong correlation.

Table 1 - R-squared values decreased wit

However, in depths shallower than 20 meters, the initial equation resulted in an r-squared value if only 0.49018. We calculated r-squared values for the initial formula at a variety of depths and determined that depth was a factor that needed to be accounted for in our model. We tested regression models using all linear combinations of bands 1 through 5 and water depth, as well as several combinations of logarithmic and exponential equations.

A total of 78 equations were tested (Appendix 3).

*TSM Estimation*

A similar process was used to create a regression model for total suspended material. However, we added Band 8 after reading Zhang et al (2015). Zhang’s team used Band 2, Band 3 and Band 8 to estimate TSM in China’s Xin'anjiang Reservoir. A total of forty-six equations were tested (Appendix 4).

*Models*

We chose the regression equations with the highest R-squared values to calculate rough estimates of chlorophyll and TSM. Tools for each model were constructed in ArcGIS Model Builder (Appendix 2).

# IV. Results & Discussion

*Chlorophyll Estimates*

We chose the chlorophyll regression equations with the highest R-squared values to produce calculate rough estimates of chlorophyll and suspended sediment in shallow waters.

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| **Chlorophyll Regression Equations** |
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R-squared values ranged from 0.2379 (MCHL ~ ((band1 + band2 + band3 + band4 + band5) \* exp(depth)) to 0.6223 (MCHL ~ ((band1 + band2 + band3 + band4 + band5) \* exp(-1\*depth))). The equations with the highest r-squared values were negative exponential functions where the bands were raised to a coefficient of depth.

*Total Suspended Matter*

R-squared values for TSM equations ranged from R-squared = 2.38E-05 (TSM~Band 8) to R-squared = 0.5403. We chose the TSM regression equations with the highest R-squared values to produce calculate rough estimates of chlorophyll and suspended sediment in shallow waters.

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| **Total Suspended Matter Regression Equations** |
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These equations were used as the basis for tools in ArcGIS model builder. The tools were used to create a time-series of maps showing estimated chlorophyll and estimated TSM for all Landsat 8 dates during the 2013 bloom season.

**Analysis of Results:**

Our equations produced a wide range of estimated chlorophyll values. For equation 2, relative chlorophyll values ranged from -2987.23 to 1550.38. Although the range is large, most values were within a narrower range (approximately -400 to approximately 20). Although clipping would have made it easier to compare across days, we could not delete outliers because we are interested in abnormally high values that could indicate HABs.

Because different days had different ranges of chlorophyll values, our model cannot be used for comparing across days until it is calibrated with in-situ measurements. However, it can be used to identify areas with relatively high levels of chlorophyll on a given day.

TSM equations produced a narrower range of values from -20 to 70 with most values between 0 and 20. Although TSM equations had lower r-squared values, our TSM images reflected Landsat true-color imagery.

|  |  |
| --- | --- |
| May16 - Copy (2).jpg  Figure 3: May 16, 2013 Real color image | C:\Users\develop.admin\Desktop\TSM516.jpg  Figure 3: May 16, 2013 Total Suspended Matter (TSM) Estimate |

*Future Work*

This is a two term project. During the current term, our focus was the calculation and testing of the equations needed to estimate Chlorophyll A from Landsat products. During the second term, the chlorophyll and TSM estimates will be calibrated using in-situ data. Once the models are refined and validated, they will be used to create python-based ArcGIS tools for our partners.

In the future, the project methods could be modified to produce chlorophyll-a estimation tools geographically calibrated for tracking HABs in other bodies of water, including the upper Chesapeake Bay and Delaware Bay.

# V. Conclusions

We cross-correlated MODIS chlorophyll-a and TSM values with Landsat reflectances to calculate regression equations for initial models that estimate chlorophyll-A and TSM at 30 meter resolution. Through conversations with our partners about Landsat 8 and the crossing dates we hope that a few dates of in-situ data collection will coincide with a Landsat 8 crossing. This will allow the Fall 2015 team exact data to calibrate, test, and validate the models created in this term. Once the models are refined and validated, an easy-to-use python-based tool for ArcGIS will be created and provided to our partners.

Our partners will use the resulting chlorophyll and TSM maps to indicate probable locations of harmful algal blooms and guide sampling in Virginia’s rivers, the Mobjack Bay, and the Chesapeake Bay. This will save money and allow monitoring of areas that are not regularly sampled through data flow cruises or fixed sampling stations.

The combination of remote sensing imagery with in-situ water sampling will allow our partners to better understand the factors that contribute to bloom development in the Chesapeake Bay watershed.

# VI. Acknowledgments

We would like to thank the following people for their assistance with this project:

* Dr. Kenton Ross - *National Program Science Advisor*
* Russ Baxter - *Virginia Deputy Secretary of Natural Resources for the Chesapeake Bay*
* Dr. Kim Reece, Dr. Jian Shen, Dr. Wolf Vogelbein - *Virginia Institute of Marine Science*
* John Kennedy, Dr. Tish Robertson, Anne Schlegel - *Virginia Department of Environmental Quality*
* Dr. Todd Egerton - *Department of Biological Sciences, Old Dominion University*
* Will Hunley - *Hampton Roads Sanitation District*

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# VII. References

Lim,J & Choi, M (2015) - Multiple regression models of spectral reflectance and water quality parameters. Environmental Monitoring Assessment 187: 384.

Ondrusek, M et al (2012) - The development of a new optical total suspended matter algorithm for the Chesapeake Bay. Remote Sensing of Environment 119.

Zhang YB, et al (2015) - Remote sensing estimation of total suspended matter concentration in Xin'anjiang Reservoir using Landsat 8 data. Huan Jing Ke XueJan 36:1 [Article in Chinese].

# VIII. Content Innovation

Database Linking Tool

1. Landsat 8 – United States Geological Survey Earth Explorer
   1. <http://earthexplorer.usgs.gov/>
2. NOAA Coastwatch East Coast Node
   1. <http://coastwatch.chesapeakebay.noaa.gov/>
3. Virginia Estuarine and Coastal Observing System
   1. <http://web2.vims.edu/vecos/>

Glossary Viewer

1. Chlorophyll – is a green pigment, present in all green plants and in cyanobacteria which is responsible for the absorption of light to provide energy for photosynthesis.
2. Harmful Algal Bloom (HAB) - is a high concentration of phytoplankton in a river, lake or other aqueous system that has a harmful effect on life and the environment.
3. Landsat 8 – carries two instruments: The Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). Landsat 8 passes over the study area every 16 days at 30 meter resolution.
4. MODIS – or Moderate Resolution Imaging Spectroradiometer. Aqua MODIS views the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths.
5. R-squared - a statistical measure of how close the data are to the fitted regression line.
6. Tiff - computer file format for storing raster graphics images
7. Total Suspended Matter (TSM) – is a water quality parameter that refers to solids in water that can be trapped in a filter.

# VIII. Appendices

**Appendix 1: Landsat Dates**

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| --- | --- | --- | --- |
| **Year** | **Month** | **Landsat 8 Dates** | **Ancillary Data** |
| 2011 | May | 11, 27 |  |
|  | June | 12,28 |  |
|  | July | 14,30 |  |
|  | August | 15,31 |  |
|  | September | 16 |  |
|  | October | 2,18 |  |
| 2012 | May | 13,29 |  |
|  | June | 14,30 |  |
|  | July | 16 |  |
|  | August | 1,17 |  |
|  | September | 2,18 |  |
|  | October | 4,20 |  |
| 2013 | April | 30 | 30 - James River (mesohaline) |
|  | May | 16 | 16 - James River (PH) |
|  | June | 1,17 | 17 - Elizabeth River  17 - James River |
|  | July | 3,19 | 3 - James River (mesohaline) |
|  | August | 4,20 | 20 - Elizabeth River  20 - Lafayette River |
|  | September | 5,21 |  |
|  | October | 7,22 |  |
| 2014 | May | 3,19 |  |
|  | June | 4,20 |  |
|  | July | 6,22 |  |
|  | August | 7,23 |  |
|  | September | 8,24 |  |
|  | October | 10,26 |  |
| 2015 | May | 6, 22 |  |
|  | June | 7, 23 |  |
|  | July | 9,25 |  |

**Appendix 2: Model Builder Tools**

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| --- | --- |
|  | Step 1: Landsat 8 Composite Images (ArcGIS Image Analysis Tool) – After the composite is created, Band1, Band2, Band3, Band4, Band5 are inputted into this model. The Divide tool is applied to the band. The “Double” variable is applied, value 10,000 The ending result is a rescaled band raster.  Example: Landsat 8 band  ->**tool: Divide** -> Input raster or constant value 1: Band1 Input raster or constant 2: Double ->**output**-> rescaled Landsat 8 band |

|  |  |
| --- | --- |
| NDVI.JPG | Step 2: This is the process to create NDVI. |
|  | Step 3: This step creates the water mask. |
|  | Step 4: The water mask created in the previous step is applied to the Rescaled Bands using the “Extract by Mask” tool. The bands are then combined with the “Composite Band” tool to create a new composite image that has the water masked out. |

|  |  |
| --- | --- |
|  | This model shows Chlorophyll Regression #2. Each band has the appropriate coefficient applied. The depth exponent is applied to the sum of the bands. The y-intercept is added to the product to create the calculated chlorophyll. |
|  | This model is the depth portion for the Chlorophyll Model. For each Chlorophyll regression, the value for “DepthCoeff” will vary depending on the regression. “depthPRJ” is the Bathymetry projected file. |

**Appendix 3: Chlorophyll Equations**

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| --- | --- |
| **Formula** | **R-squared** |
| MCHL ~ band1 + band2 + band3 + band4 + band5 | 0.5947 |
| MCHL ~ band1 + band2 + band3 + band4 | 0.5557 |
| MCHL ~ band1 + band2 + band4 + band5 | 0.5198 |
| MCHL ~ band1 + band3 + band4 + band5 | 0.5297 |
| MCHL ~ band2 + band3 + band4 + band5 | 0.5347 |
| MCHL ~ band1 + band2 + band3 | 0.5554 |
| MCHL ~ band1 + band2 + band4 | 0.3602 |
| MCHL ~ band1 + band2 + band5 | 0.4112 |
| MCHL ~ band1 + band3 + band4 | 0.4497 |
| MCHL ~ band1 + band3 + band5 | 0.5132 |
| MCHL ~ band1 + band4 + band5 | 0.517 |
| MCHL ~ band2 + band3 + band4 | 0.5007 |
| MCHL ~ band2 + band3 + band5 | 0.5208 |
| MCHL ~ band2 + band4 + band5 | 0.511 |
| MCHL ~ band3 + band4+ band5 | 0.5278 |
| MCHL ~ band1 + band2 | 0.3096 |
| MCHL ~ band1 + band4 | 0.3555 |
| MCHL ~ band1 + band3 | 0.4495 |
| MCHL ~ band1 + band5 | 0.2852 |
| MCHL ~ band2 + band3 | 0.5002 |
| MCHL ~ band2 + band4 | 0.3322 |
| MCHL ~ band2 + band5 | 0.4081 |
| MCHL ~ band3+ band4 | 0.4111 |
| MCHL ~ band3 + band5 | 0.5116 |
| MCHL ~ band4+ band5 | 0.5092 |
| MCHL ~ band5 | 0.02467 |
| MCHL~band4 | 0.3163 |
| MCHL~band3 | 0.3959 |
| MCHL ~ band2 | 0.2409 |
| MCHL ~ band1 | 0.1542 |
| MCHL ~ band1 + band2 + band3 + band4 + band5+depth | 0.5962 |
| MCHL ~ band1 + band2 + band3 + band4+depth | 0.558 |
| MCHL ~ band1 + band2 + band4 + band5+depth | 0.5498 |
| MCHL ~ band1 + band3 + band4 + band5+depth | 0.5495 |
| MCHL ~ band2 + band3 + band4 + band5+depth | 0.5478 |
| MCHL ~ band1 + band2 + band3+depth | 0.5579 |
| MCHL ~ band1 + band2 + band4+depth | 0.4482 |
| MCHL ~ band1 + band2 + band5+depth | 0.4747 |
| MCHL ~ band1 + band3 + band4+depth | 0.4838 |
| MCHL ~ band1 + band3 + band5+depth | 0.5312 |
| MCHL ~ band1 + band4 + band5+depth | 0.546 |
| MCHL ~ band2 + band3 + band4+depth | 0.5147 |
| MCHL ~ band2 + band3 + band5+depth | 0.5316 |
| MCHL ~ band2 + band4 + band5+depth | 0.5395 |
| MCHL ~ band3 + band4+ band5+depth | 0.5458 |
| MCHL ~ band1 + band2+depth | 0.4176 |
| MCHL ~ band1 + band4 +depth | 0.4477 |
| MCHL ~ band1 + band3+depth | 0.4836 |
| MCHL ~ band1 + band5+depth | 0.4232 |
| MCHL ~ band2 + band3+depth | 0.5133 |
| MCHL ~ band2 + band4+depth | 0.4421 |
| MCHL ~ band2 + band5+depth | 0.4745 |
| MCHL ~ band3+ band4+depth | 0.4665 |
| MCHL ~ band3 + band5+depth | 0.5279 |
| MCHL ~ band4+ band5+depth | 0.538 |
| MCHL ~ band5+depth | 0.3007 |
| MCHL~band4+depth | 0.4361 |
| MCHL~band3+depth | 0.4646 |
| MCHL ~ band2+depth | 0.3997 |
| MCHL ~ band1+depth | 0.3668 |
| MCHL~log (band1+band2+band3+band4+band5) | 0.2379 |
| MCHL ~ ((band1 + band2 + band3 + band4 + band5) \* exp(depth) | 0.5971 |
| MCHL ~ ((band1 + band2 + band3 + band4 + band5) \* exp(-1\*depth)) | 0.6223 |
| MCHL ~ ((band1 + band2 + band3 + band4 + band5) \* exp(-1\*depth)) | 0.6223 |
| MCHL ~ ((band1 + band2 + band3 + band5) \* exp(-1\*depth)) | 0.6102 |
| MCHL ~ ((band1 + band2 + band4 + band5) \* exp(-1\*depth)) | 0.5819 |
| MCHL ~ ((band1 + band3 + band4 + band5) \* exp(-1\*depth)) | 0.5812 |
| MCHL ~ ((band2 + band3 + band4 + band5) \* exp(-1\*depth)) | 0.5768 |
| MCHL ~ ((band1 + band4 + band5) \* exp(-1\*depth)) | 0.5766 |
| MCHL ~ ((band3 + band4 + band5) \* exp(-1\*depth)) | 0.5759 |
| MCHL ~ ((band1 + band2 + band3 + band4) \* exp(-1\*depth)) | 0.5729 |
| MCHL ~ ((band1 + band2 + band3) \* exp(-1\*depth)) | 0.5722 |
| MCHL ~ ((band2 + band4 + band5) \* exp(-1\*depth)) | 0.5702 |
| MCHL~ ((band5 + band2 + band3) \* exp(-1\*depth)) | 0.554 |
| MCHL ~ ((band2 + band3 + band4) \* exp(-1\*depth)) | 0.5298 |
| MCHL ~ ((band1 + band3 + band4) \* exp(-1\*depth)) | 0.4989 |
| MCHL ~ ((band1 + band2 + band5) \* exp(-1\*depth)) | 0.4967 |
| MCHL ~ ((band3 + band4) \* exp(-1 \* depth) | 0.4796 |
| MCHL ~ ((band1 + band2 + band4) \* exp(-1\*depth)) | 0.4471 |

**Appendix 4: TSM Equations**

|  |  |
| --- | --- |
| **Formula** | **R-squared** |
| TSM ~ band1 | 0.08343 |
| TSM ~ band2 | 0.2392 |
| TSM ~ band3 | 0.469 |
| TSM ~ band4 | 0.408 |
| TSM ~ band5 | 0.0248 |
| TSM ~ band8 | 2.38E-05 |
| TSM ~ band3 + band4 | 0.469 |
| TSM ~ band3 + band4 + depth | 0.4883 |
| TSM ~ band1 + band2 + band3 + band4 | 0.5197 |
| TSM ~ band1 + band2 + band3 + band4+depth | 0.5234 |
| TSM ~ band1 + band2 + band3 + band4 + band5 | 0.5367 |
| TSM ~ band1 + band2 + band3 + band4 + band5 + depth | 0.5403 |
| TSM ~ band2 + band3 + band4 + band5 | 0.5291 |
| TSM ~ band2 + band3 + band4 + band5 + depth | 0.533 |
| TSM ~ band2 + band3 + band5 | 0.5241 |
| TSM ~ band2 + band3 + band5 + depth | 0.5276 |
| TSM ~ ((band1 + band2 + band3 + band4) \* exp(-1\*depth)) | 0.5246 |
| TSM ~ ((band1 + band2 + band3 + band5) \* exp(-1\*depth)) | 0.5394 |
| TSM ~ ((band1 + band2 + band4 + band5) \* exp(-1\*depth)) | 0.5424 |
| TSM ~ ((band1 + band3 + band4 + band5) \* exp(-1\*depth)) | 0.5374 |
| TSM ~ ((band2 + band3 + band4 + band5) \* exp(-1\*depth)) | 0.5342 |
| TSM ~ ((band3 + band4) \* exp(-1\*depth)) | 0.4905 |
| TSM ~ band2 + band3 + band8 | 0.5154 |
| TSM ~ band2 + band3 + band8 + depth | 0.5193 |
| TSM ~ ((band2 + band3 + band8) \* exp(-1 \* depth)) | 0.5198 |
| TSM ~ (band2 + band5 + (band5/band3)) | 0.4943 |
| TSM ~ (band2 + band5 + depth + (band5/band3)) | 0.5061 |
| TSM ~ (band2 + band3 + band5 + (band5/band3)) | 0.5242 |
| TSM ~ (band2 + band3 + band5 + depth = (band5/band3)) | 0.5276 |
| TSM ~ (band2 + band5 + (band5/band4)) | 0.4456 |
| TSM ~ (band2 + band4 + band5 + (band5/band4)) | 0.4884 |
| (TSM ~ (band1 + band5 + depth + (band5/band3)) | 0.514 |
| TSM ~ (band1 + band2 + band3 + band4 + band5 + (band5/band4)) | 0.5368 |
| TSM ~ (band1 + band2 + band3 + band4 + band5 + depth + (band5/band4)) | 0.5404 |
| TSM ~ (band1 + band2 + band3 + band4 + band5 + (band5/band3)) | 0.5368 |
| TSM ~ (band1 + band2 + band3 + band4 + band5 + depth + (band5/band3)) | 0.5403 |
| TSM ~ (band1 + band2 + band3 + band4 + depth + (band5/band4)) | 0.5404 |
| TSM ~ (band1 + band2 + band3 + band4 + depth + (band5/band3)) | 0.5403 |
| TSM ~ (band1 + band3 + band4 + depth + (band5/band4)) | 0.5364 |
| TSM ~ (band1 + band3 + band4 + depth + (band5/band3)) | 0.5363 |
| TSM ~ (band1 + band2 + band4 + depth + (band5/band4)) | 0.5382 |
| TSM ~ (band1 + band2 + band4 + depth + (band5/band3)) | 0.539 |
| TSM ~ (band1 + band2 + band3 + depth + (band5/band4)) | 0.539 |
| TSM ~ (band1 + band2 + band3 + depth + (band5/band3)) | 0.5363 |
| TSM ~ (band2 + band3 + band4 + depth + (band5/band4)) | 0.5335 |
| TSM ~ (band2 + band3 + band4 + depth + (band5/band3)) | 0.5333 |

|  |  |
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| **Appendix 5: Resulting Images** |  |
| May 16, 2013 | August 20, 2013 |
| C:\Users\develop.admin\Desktop\May16 - Copy (2).jpg  Landsat 8 Composite | C:\Users\develop.admin\Desktop\LS820.jpg  Landsat 8 Composite |
| C:\Users\develop.admin\Desktop\TSM516.jpg  Total Suspended Matter | C:\Users\develop.admin\Desktop\TSM820.jpg  Total Suspended Matter |
| C:\Users\develop.admin\Desktop\CHL516.jpg  Estimated Chlorophyll | C:\Users\develop.admin\Desktop\CHL820.jpg  Estimated Chlorophyll |