A European Union initiative supported by the IOCCG (International Ocean-Colour Coordinating Group) and FARO (Fisheries Applications of Remotely-Sensed Ocean Colour), a GEO Task supported by the Canadian Space Agency.

Handbook of Satellite Remote Sensing Image Interpretation: Applications for Marine Living Resources Conservation and Management

Edited by:
Jesus Morales, Venetia Stuart, Trevor Platt and Shubha Sathyendranath

In conjunction with the EU PRESPO Project for sustainable development of the artisanal fisheries in the Atlantic area, within the INTERREG IVB Programme (a Community Initiative to stimulate inter-regional cooperation in the European Union)

This handbook is based on contributions from (in alphabetical order):

J. Acker, S. Alvain, R.J.W. Brewin, R. Cajal-Medrano, M.E. Callejas-Jiménez, J. Cannizzaro, K.L. Carder, J. Dachs, D. Dagorne, H. Demarcq, L. Duforêt-Gaurier, L. Escudero, M-H. Forget, C. Fuentes-Yaco, A. González-Silvera, N.J. Hardman-Mountford, M-X. He, T. Hirata, N. Hoepffner, C. Hu, E. Jurado, T. Kuroyama, Z. Lee, D. Li, X. Li, J. Liu, Z. Liu, H. Loisel, F. Mélin, R. Millán-Núñez, P.I. Miller, J. Morales, R. Mugo, F.E. Muller-Karger, A. Nihira, C. Paulino, W.G. Pichel, T. Platt, A.I. Prados, V. Rivera, A. Rodríguez-Verdugo, S-I. Saitoh, E. Santamaría-del-Ángel, S. Sathyendranath, R. Simó, I. Soto, V. Stuart and F. Yu.

Published by the EU PRESPO Project and IOCCG (International Ocean-Colour Coordinating Group)

The printing of this handbook was sponsored by the Canadian Space Agency, which is gratefully acknowledged.

Correct citation for this publication:

Morales, J., Stuart, V., Platt, T., Sathyendranath, S. (Eds.) (2011). Handbook of Satellite Remote Sensing Image Interpretation: Applications for Marine Living Resources Conservation and Management, EU PRESPO and IOCCG, Dartmouth, Canada.

Investing in Our Common Future

Contents

Theme: Air/Water Quality

Case Study 1

Remote-Sensing Case Study of the Chesapeake Bay Region During Drought (2002) and Flood (2003) Years

James Acker*[1] **and Zhong Liu**[2]

1.1 Background Information

The location of this study is the Chesapeake Bay estuary on the eastern Mid-Atlantic coast of the United States. The Chesapeake Bay system is the largest estuary in the United States and one of the largest in the world. Chesapeake Bay is approximately 320 km long, with its mouth located in Virginia near Norfolk and Hampton Roads, to the upper part of the Bay at Havre de Grace, Maryland. The headwaters of the Susquehanna River (one of the major rivers entering the bay) are located near Cooperstown, New York. The Chesapeake Bay watershed is approximately 166,000 square kilometers, and the Bay itself has over 18,000 km of shoreline. The average depth of the Chesapeake Bay is about 6.5 meters, though it can be deeper than 45 meters in some locations.

Fresh water from five major rivers enters the Bay - these rivers are the Susquehanna, Potomac, James, York, and Rappahannock. Although there are many other rivers and streams feeding into the Bay, about 90% of the fresh water input to the Bay comes from these five rivers. Due to the large amount of fresh water delivered by the Susquehanna River, the upper portion of the Bay has much lower salinity than the lower portion of the Bay, where tidal flow from the Atlantic is significant. It is estimated that a roughly equal volume of salt water enters the Bay from the Atlantic compared to the volume of fresh water entering the Bay from river systems.

Due to the size of the estuary and the volume of fresh water that enters it, the physical characteristics of Chesapeake Bay water and the biological dynamics of the Bay are strongly connected to the flow of water and the quality of the water entering it from land. A large percentage of the Bay's watershed land is used for agriculture, particularly in Pennsylvania and the Eastern Shore of Maryland. This land usage

[1]Goddard Earth Sciences Data and Information Services Center, Wyle IS LLC, NASA GES DISC Code 610.2, Greenbelt, MD 20771, USA. **Email address:* james.g.acker@nasa.gov

[2]Goddard Earth Sciences Data and Information Services Center, George Mason University, USA

results in large amounts of nutrients derived from agricultural fertilizer and animal wastes entering the Bay in runoff from fields. A further influence on the Bay waters is the increasing population and urban development in major cities, which include Washington D.C., Baltimore (Maryland), Richmond (Virginia) and Scranton/Wilkes-Barre (Pennsylvania), and many other smaller cities and towns in the watershed. Developmental sprawl means that an increasing area of the watershed is impervious to water penetration, resulting in increased runoff and additional input of nutrients and pollutants, as well as input from the growing human population. Therefore, the general quality of Bay waters and the ability to host marine flora and fauna, which is subject to increasing environmental stress, is directly connected to the hydrological system of the Chesapeake Bay watershed.

During the year 2002, much of the United States experienced severe to extreme drought conditions. These conditions were acute in two locations: most states west of the Dakotas, Nebraska, Kansas, Oklahoma, and Texas; and the eastern seaboard from southern Georgia to New Jersey. On the eastern seaboard, the central portion of North and South Carolina, Virginia, and Maryland were subject to particularly acute conditions; the situation worsened in Virginia and Maryland during summer and autumn 2002, with some communities in these states imposing severe water use restrictions, and reservoirs dropping to very low capacities. One reservoir serving Baltimore dropped to 16% capacity and was estimated to have only a 30-day supply of water remaining.

Rain in late autumn began to alleviate the drought conditions, and the rain pattern persisted and became much stronger in the spring of 2003. Rainfall in March and April was particularly heavy in Virginia and Maryland. Over the course of the entire year of 2003, the Baltimore region set an annual precipitation record – a very distinct contrast from the dry conditions that had characterized much of 2002.

Due to these significantly different hydrological conditions, it was expected that the waters of the Chesapeake Bay would exhibit distinctly different bio-optical characteristics, related to the volumes of fresh water and associated nutrient transport during low- and high-flow conditions. The availability of ocean-colour radiometry data in the online data analysis system created by the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) provided the opportunity to investigate the effects of the "drought and flood" precipitation pattern on the waters of the Chesapeake Bay, which is the subject of this case study (Acker et al. 2005).

Three remotely-sensed variables, chlorophyll-*a* concentration (chl-*a*), the diffuse attenuation coefficient at 490 nm (K490), and remote-sensing reflectance at 555 nm (R_{rs}555) will be used to examine the bio-optical characteristics of the Chesapeake Bay waters. Chl-*a* reflects the concentration of phytoplankton, the floating photosynthetic plants that form the base of the marine food chain. Phytoplankton are primary producers, creating carbon biomass through the process of photosynthesis. The photosynthetic pigment, chlorophyll, contained in their cells enables this process, and thus chl-*a* is an indicator of the prevalence of phytoplankton. Since, in addition to sunlight, phytoplankton require dissolved nutrients (primarily nitrate and phosphate) in seawater to grow, phytoplankton populations will grow more rapidly and abundantly in the presence of elevated nutrient concentrations. When this happens, an overabundance of phytoplankton can cause increased deposition of dead phytoplankton organic material on the estuarine bottom or seafloor. The digestion ("respiration") of this organic matter by bacteria uses dissolved oxygen in the water, which is important for most organisms living in the water. Increased bacterial respiration of organic matter can reduce dissolved oxygen so much that the water cannot support aquatic life.

Remote sensing estimates the concentration of chl-*a* by detecting the absorption of light by the chlorophyll in phytoplankton cells. It should also be noted that in turbid waters, remotely-sensed chl-*a* can be overestimated due to the absorption or reflection of light by other substances. This is an important point in many areas, but will be less important here.

K490 is simply a measure of how much the intensity of light entering the oceanic water column is attenuated (reduced) by interaction with substances either dissolved or suspended in the water, either through light absorption, light scattering, or light reflection. High values of K490 thus indicate more turbidity, and low values of K490 indicate less turbidity. Turbidity can be caused by increased concentrations of phytoplankton, suspended sediments, or dissolved substances, and usually is a combination of all three of these factors.

R_{rs}555 indicates light reflection, as there is very little absorption of light at this wavelength in marine waters. Thus, R_{rs}555 is sensitive to the presence of suspended sediments, which reflect and scatter light without absorbing much light. Light at a wavelength of 555 nm will also be reflected off the seafloor when the water depth is sufficiently shallow for the light to penetrate to the bottom and reflect back toward the surface.

1.2 Materials and Methods

The primary data set for this investigation is ocean-colour radiometry (OCR) data acquired by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). SeaWiFS has been in nearly continuous operation since September 1997 and provides an exemplary calibrated remotely-sensed data set of ocean-colour variables, including chlorophyll-*a* concentration (chl-*a*) and the diffuse attenuation coefficient at 490 nm (K490).

The algorithm for the chl-*a* retrieval, OC4V4, is an empirical algorithm based on ratios of reflectances for the SeaWiFS bands at 443, 490, 510, and 555 nm (O'Reilly et al., 2000). The K490 algorithm uses data from the SeaWiFS band at 490 nm (Mueller and Trees, 1997).

SeaWiFS ocean-colour data will be analyzed utilizing the GES DISC Interactive Online Visualization ANd aNalysis Infrastructure (Giovanni) (Acker and Leptoukh, 2007). Giovanni will be used to generate maps of data products over the Chesapeake Bay during the spring months of 2002 and 2003, to contrast the low-flow conditions of 2002 with the high-flow conditions of 2003. The three data products that will be examined are chl-*a*, K490 and R_{rs}555. To use Giovanni, a region of interest is selected either by clicking-and-dragging the display cursor on an interactive map, or by providing latitude-longitude corner points defining a specific region of interest. For this study, the corner points are provided to ensure uniformity of output visualizations. The time period of interest is specified for the spring months of 2002 and 2003.

Additional images are provided for context of the Chesapeake Bay region. URLs for these images are provided below. The MODIS images show the Chesapeake Bay, highlighting the major rivers and urban areas, and also demonstrating differences in land use patterns. The watershed image shows the regional extent of the Chesapeake Bay watershed. The impervious surface maps show that urbanization increases impervious surface area around the Chesapeake Bay (these are numbered Figures 1.6 to 1.8.)

Chesapeake Bay watershed:
http://veimages.gsfc.nasa.gov/20832/image04162006_1km.jpg
Impervious surface, State of Maryland:
http://www.dnr.state.md.us/watersheds/surf/indic/md/md_pctimp_indmap.html
Impervious surface, urban areas in the Chesapeake Bay watershed:
http://www.whrc.org/midatlantic/mapping_land_cover/products/impervious_surfaces.htm

1.3 Demonstration Section

The use of Giovanni provides the capability for users to generate their own images, rather than relying on previously-created images. Thus, the instructions in this demonstration section and the associated images will show how to create the images, and subsequently how to interpret them. There are no large image files that have to be opened; small images will be shown here to demonstrate what the end result should look like.

Step 1: Go to the Giovanni Ocean Color Radiometry Interface:
http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_month

Step 2: Enter the geographical coordinates below the interactive map. West: -77.5 North: 40.0 South: 36.5 East: -75.0. Click the "Update Map" button. This will show the highlighted region, with the Chesapeake Bay inside the box defined by the coordinates.

Step 3: In the SeaWiFS.R2009 data set (the first data set listed), select the following parameters by clicking in the boxes on the left next to the parameter name:

Chlorophyll-*a* concentration, Diffuse attenuation coefficient at 490 nm, Remote sensing reflectance at 555 nm.

Step 4: In the calendar selection menu below the lists of parameters, select the following time period: Begin Date: Year = 2002, Month = April, End Date: Year = 2002, Month = Jun (June).

Step 5: Click the "Generate Visualization" button. The default option, "Lat-Lon Map, Time-Averaged", is the visualization option that will be utilized here. The Giovanni system will now generate the visualizations for the three selected parameters. When the maps have been generated, click on the "Download Data" tab at the top. Go to the "Output Files" section, and click on each filename listed. This will display the visualization. Download the images into a folder according to the method for image download appropriate to the Web browser that is being used. It may be necessary to add the suffix ".gif" to the filename in order to see the images in the folder. When the image has been downloaded, click the "Back" button on the browser and repeat the process until all the images have been downloaded.

Step 6: Click the "Visualization Results" tab. Now use the calendar menu to change the dates to the following. All that is changed is the year, from 2002 to 2003. Begin Date: Year = 2003, Month = April, End Date: Year = 2003, Month = Jun (June). Go to the bottom of the page and click the "Submit Refinements" button. The Giovanni system will now create the visualizations for the same data parameters for this second time period. **The bio-optical and optical parameter visualizations have now been generated.**

Steps 7–11 below will generate the TRMM precipitation maps for two consecutive nine-month periods in the years 2002 and 2003.

Step 7: Go to the Daily TRMM and Other Rainfall Estimate interface:
http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_3B42_Daily

Step 8: Enter the following geographic coordinates: West: -81.0, North: 43.0, South: 36.0, East: -73.0. Click the "Update Map" button. This will show the highlighted region.

Step 9: The only parameter available, "precipitation", should already be selected. Click the box if it is not selected.

Step 10: Enter the following temporal information: Begin Date: Year = 2002, Month = Jan (January), Day = 01, End Date: Year = 2002, Month = Sep (September), Day = 30. Then click the "Generate Visualization" button. The default option, "Lat-Lon Map, Time-Averaged", is the visualization option that will be utilized here. Next to this option, click the "Edit Preferences" button. Scroll down to the "Color Bar" section, and change the "Mode" choice from Pre-Defined to Custom. In the "Min Value" box, enter 0.0. In the "Max Value" box, enter 6.4. Now go to the bottom of the page and click the "Generate Visualization" button. The Giovanni system will now generate the visualization for the precipitation parameter. When the visualization is completed, save the image using the same procedure as in Step 5.

Step 11: Change the temporal information to the following: Begin Date: Year = 2002, Month = Oct (October), Day = 01, End Date: Year = 2003, Month = Jun (June), Day = 30. Go to the bottom of the page and click the "Submit Refinements" button. The Giovanni system will now create the map visualization of the precipitation parameter for this second time period. **The precipitation parameter visualizations have now been generated**.

1.3.1 Image Interpretation

Now that the visualizations have been generated, it is time to examine them for basic interpretation of these results. Each of these images depicts the data values utilizing a false-colour palette. The colour palette used in all cases here is the common "rainbow" palette, in which higher values of the data parameter are expressed in warmer colours (i.e. orange and red), low values are cooler colours (blue and purple), and intermediate values are greens and yellows. For chlorophyll-*a* data, the colour scale is logarithmic, so that the highest values are about 400-800 times greater than the lowest values. The scale for all of the other parameters is linear. Using the colour palette, interpretation of the images is straightforward. Each image shows a map of the values of the parameter averaged over the selected time period. These maps allow easy recognition of where the values were higher and lower in the region during the selected time period.

For the chl-*a* images, the highest values in the orange and red range show areas where phytoplankton chlorophyll concentration was elevated. This usually indicates where phytoplankton populations were thriving. Remotely-sensed chl-*a* can sometimes exhibit erroneously high values if there is a significant concentration of coloured dissolved organic matter (CDOM) also present in the water. Remember that the values of chl-*a*, and also K490 and R_{rs}555, were averaged over a three-month period. The concentrations on any given day during the month could have been much higher or lower than the average calculated over three months.

For the K490 images, higher values indicate where the water was more turbid, i.e., where incoming light was attenuated more strongly due to the presence of interfering substances or particles in the water. For the R_{rs}555 images, higher values indicate where incoming light at this wavelength was reflected more strongly back toward the satellite sensor.

The TRMM precipitation data maps are also easy to interpret using the ‘rainbow’ palette. The warmer colours (higher values) indicate higher amounts of precipitation

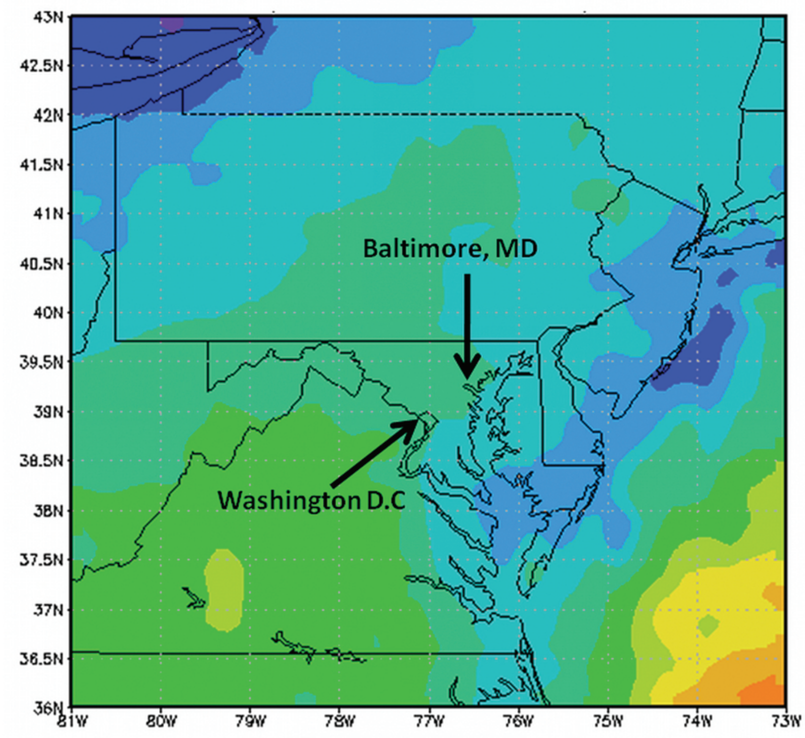

Figure 1.1 Location map of the Chesapeake Bay with TRMM precipitation data, showing location of Washington DC, and Baltimore, MD.

averaged over the nine-month time period. The average amount of precipitation indicates approximately the amount of rain that fell on a per-day basis in a given location over the entire time period. Of course, it is unlikely that there was rain on most of those days, so the average precipitation per day gives a general indication of the amount of rainfall the region received during the specified period of time. If the average value of mm/day is multiplied by the number of days in the period (about 270 days for a nine-month period), this would give the approximate total amount of rainfall for that period. So an average precipitation amount of 3 mm/day means that about 800mm (or 30 inches) of rain fell during that period.

1.4 Training and Questions

Now we will examine each of the image pairs in turn to evaluate the environmental forcing in the Chesapeake Bay watershed and the effects that this forcing had on the bio-optical conditions in the Chesapeake Bay. The first set of images to examine is the pair of TRMM precipitation maps. Examine the labelled precipitation map (Figure 1.1 above) that shows the locations of Washington D.C. and Baltimore (note: this map used a different colour palette scale). Answer questions 1 and 2 below using Figure 1.2 depicting the average precipitation during the period 1 January to 30 September 2002.

Q 1: What was the average daily precipitation for the region including Washington D.C. and Baltimore?

Q 2: What was the approximate total precipitation for this region?

For the map depicting the average precipitation during the period of 1 October 2002 to 30 June 2003 (Figure 1.2b):

Q 3: What was the average daily precipitation for the region including Washington D.C. and Baltimore?

Q 4: What was the approximate total precipitation for this region? Now consider the potential implications of the different rainfall amounts for the region.

Q 5: What would be the effects of the markedly different rainfall amounts on the volume of water flowing in the streams and rivers in the Chesapeake Bay watershed?

Q 6: What differences would be expected on the amount of fresh water entering the Chesapeake Bay during the two periods that were depicted in the precipitation maps?

The next pair of images to examine is the pair of chl-*a* maps of the Chesapeake Bay. Examine the two maps side-by-side. Figure 1.3a depicts chl-*a* during April – June 2002, and Figure 1.3b depicts chl-*a* during April – June 2003.

Q 7: During which period are the chl-*a* values in the Bay significantly higher?

Q 8: Does this period of time correspond to the period when precipitation in the Chesapeake Bay watershed region was low (January – September 2002) or high (October 2002 – June 2003)?

Q 9: Given that higher chl-*a* values likely indicate higher values of phytoplankton productivity, what relationship may exist between precipitation, stream-flow, and phytoplankton productivity in the Chesapeake Bay? What could be the cause(s) of that relationship?

The next pair of images to examine is the pair of K490 maps of the Chesapeake Bay. Also examine the two maps side-by-side. Figure 1.4a depicts K490 during April – June 2002, and Figure 1.4b depicts K490 during April – June 2003.

Q 10: During which period are the K490 values in the Bay significantly higher?

Q 11: Does this period of time correspond to the period when precipitation in the Chesapeake Bay watershed region was low (January – September 2002) or high (October 2002 – June 2003)?

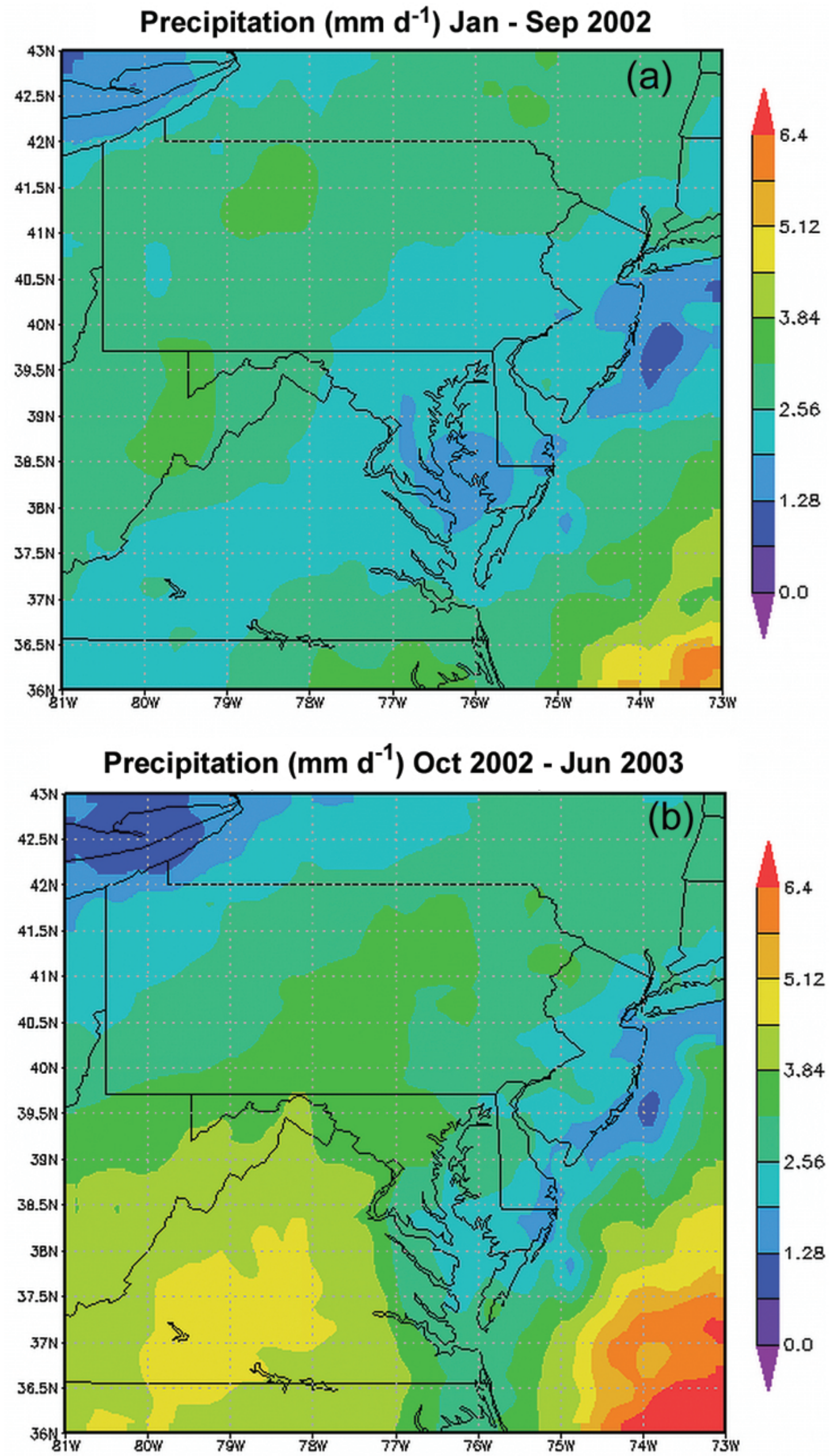

Figure 1.2 (a) Average daily precipitation over the Chesapeake Bay watershed region, January – September 2002, (b) Average daily precipitation over the Chesapeake Bay watershed region, October 2002 – June 2003.

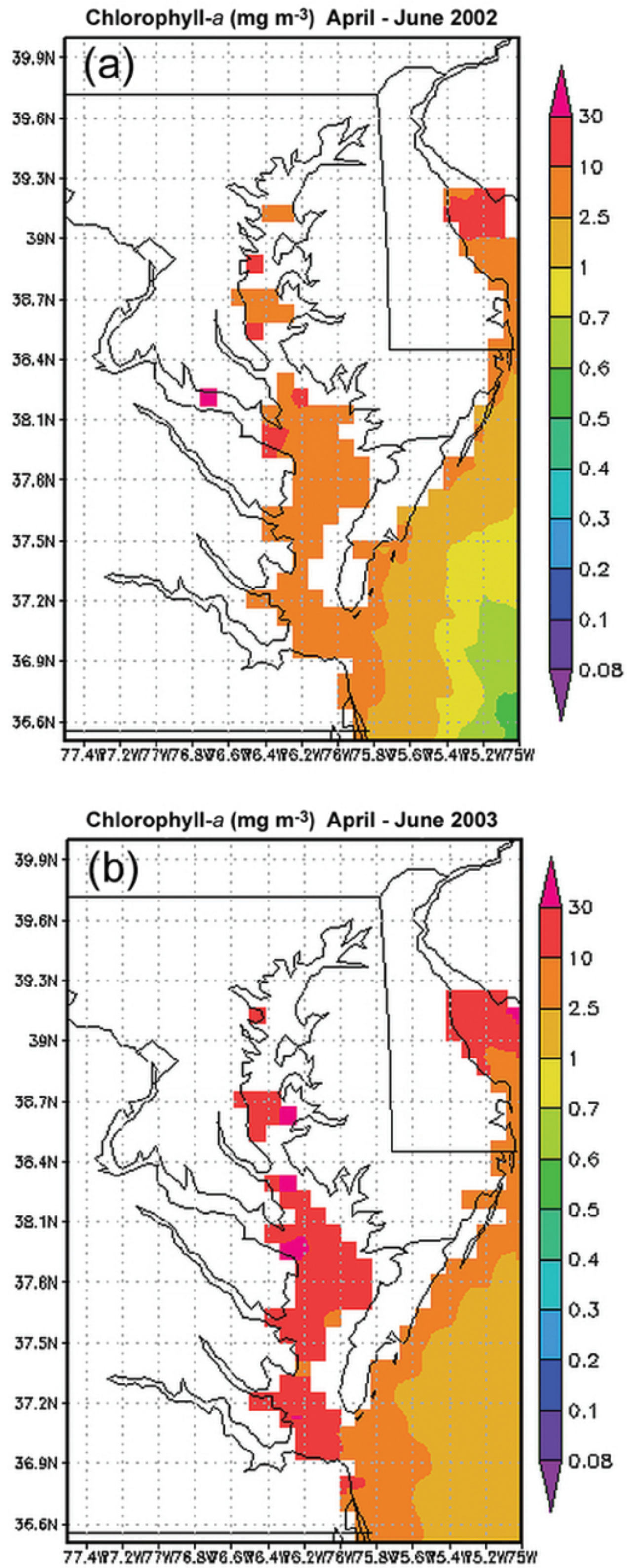

Figure 1.3 (a) Average chl-*a* in the Chesapeake Bay, April – June 2002 (b) Average chl-*a* in the Chesapeake Bay, April – June 2003.

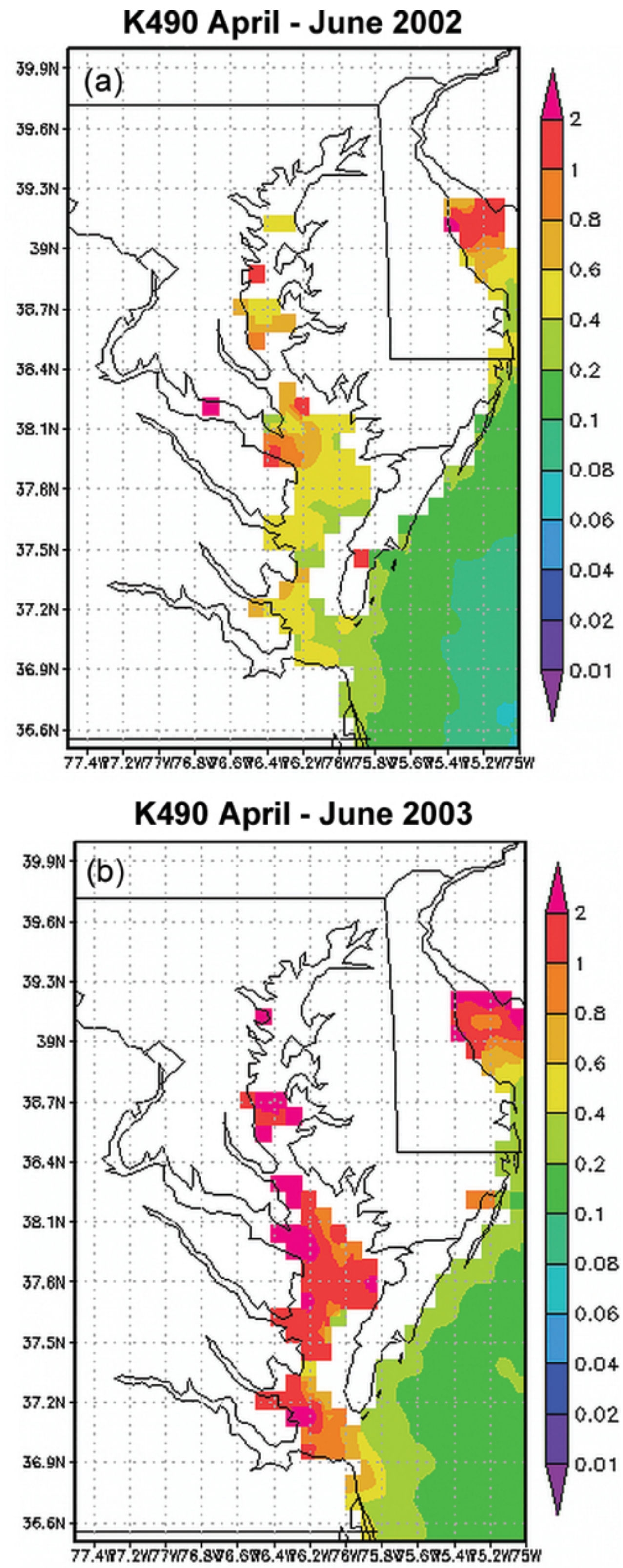

Figure 1.4 (a) Average K490 in the Chesapeake Bay, April – June 2002 (b) Average K490 in the Chesapeake Bay, April – June 2003.

Q 12: What are the likeliest causes of the elevated values of K490 in the Chesapeake Bay, and what is the potential relationship to stream-flow and the transport of fresh water into the Bay?

The next pair of images to examine is the pair of $R_{rs}555$ maps of the Chesapeake Bay. You will again examine the two maps side-by-side. Figure 1.5a depicts $R_{rs}555$ during April – June 2002, and Figure 1.5b depicts $R_{rs}555$ during April – June 2003.

Q 13: During which period are the $R_{rs}555$ values in Chesapeake Bay significantly higher?

Q 14: Does this period of time correspond to the period when precipitation in the Chesapeake Bay watershed region was low (January – September 2002) or high (October 2002 – June 2003)?

Q 15: The answer to the previous question may be surprising. Given what you have determined about the bio-optical conditions in the Chesapeake Bay from the previous two pairs of maps (for chl-*a* and K490), what is the likeliest explanation for the relationship between $R_{rs}555$ and stream-flow during periods of high and low precipitation?

The final images that will be examined are the impervious surface maps of the Chesapeake Bay region and urban areas within this region (Figures 1.6 to 1.8) and supplemental material entitled "Breath of Life" (see `http://www.eco-check.org/pdfs/do_letter.pdf`).

Q 16: What do you think would be the effects of increasing areas of impervious surface in the watershed of the Chesapeake Bay on the water conditions in the Bay? (Consider the effects on water clarity, water chemistry, bottom visibility, nutrient concentrations, and phytoplankton productivity.)

1.5 Answers

A 1: The average daily precipitation during this period was 1.9 – 2.6 mm day^{-1}.

A 2: The approximate total precipitation during this period was 500 – 700 mm.

A 3: The average daily precipitation during this period was 3.2 – 3.8 mm day^{-1}.

A 4: The approximate total precipitation during this period was 860 – 1030 mm.

A 5: The markedly different rainfall amounts would result in significant differences in the volume of water flowing in the streams and rivers. Stream flow would be significantly reduced during the low precipitation period and considerably greater during the high precipitation period.

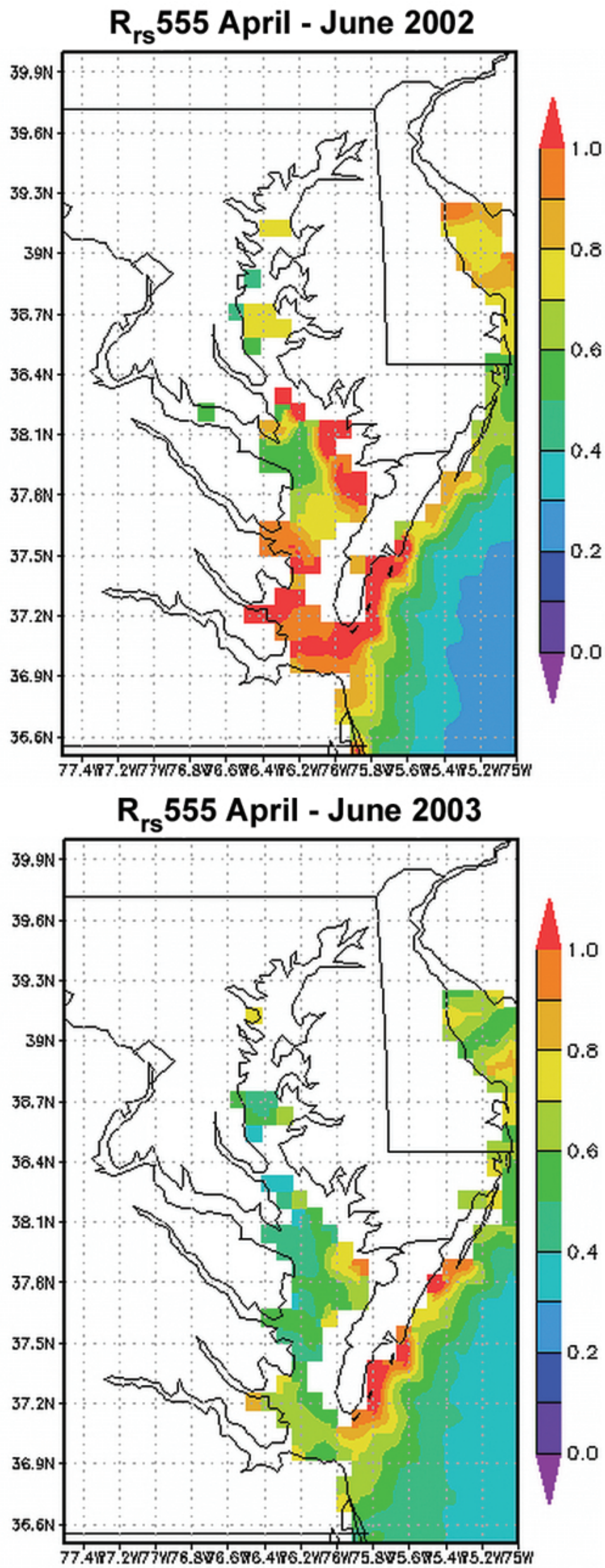

Figure 1.5 (a) Average $R_{rs}555$ in the Chesapeake Bay, April – June 2002 (b) Average $R_{rs}555$ in the Chesapeake Bay, April – June 2003.

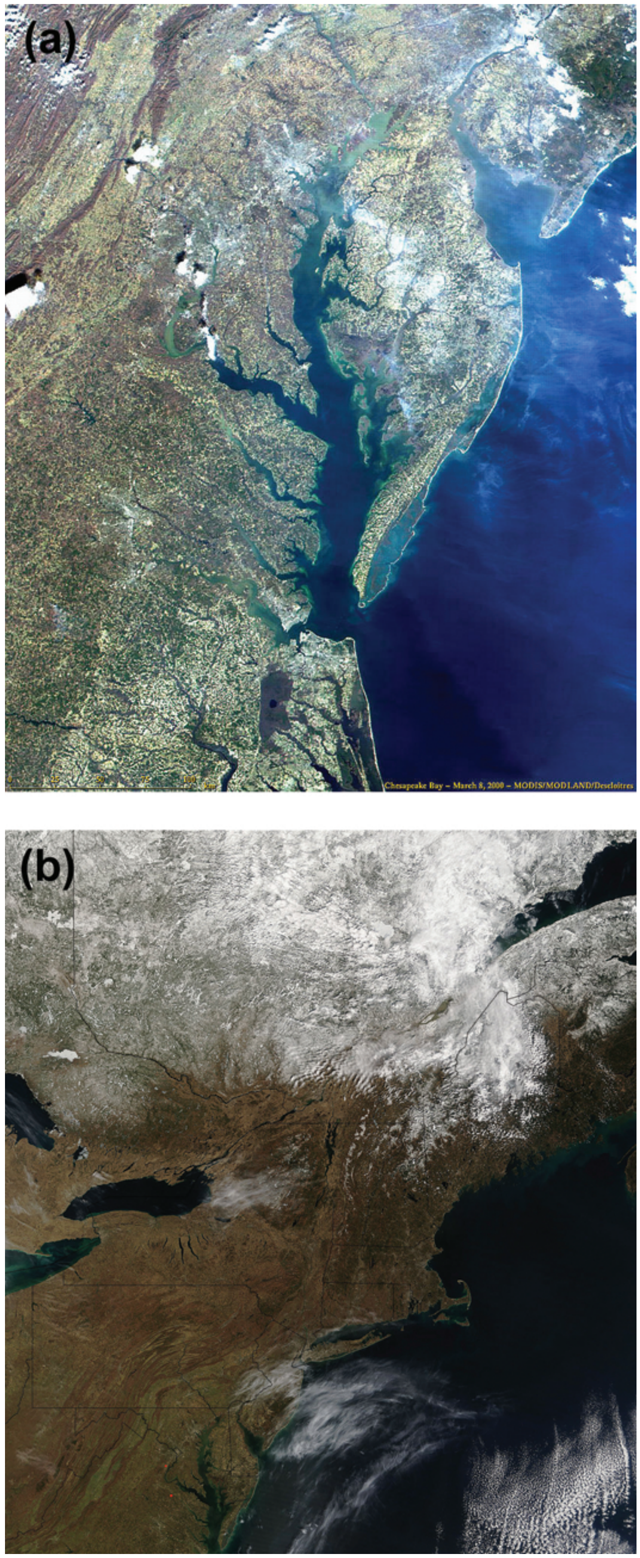

Figure 1.6 (a) MODIS image of the Chesapeake Bay, acquired 20 April 2000 (b) MODIS image of the Chesapeake Bay watershed, acquired 16 April 2006.

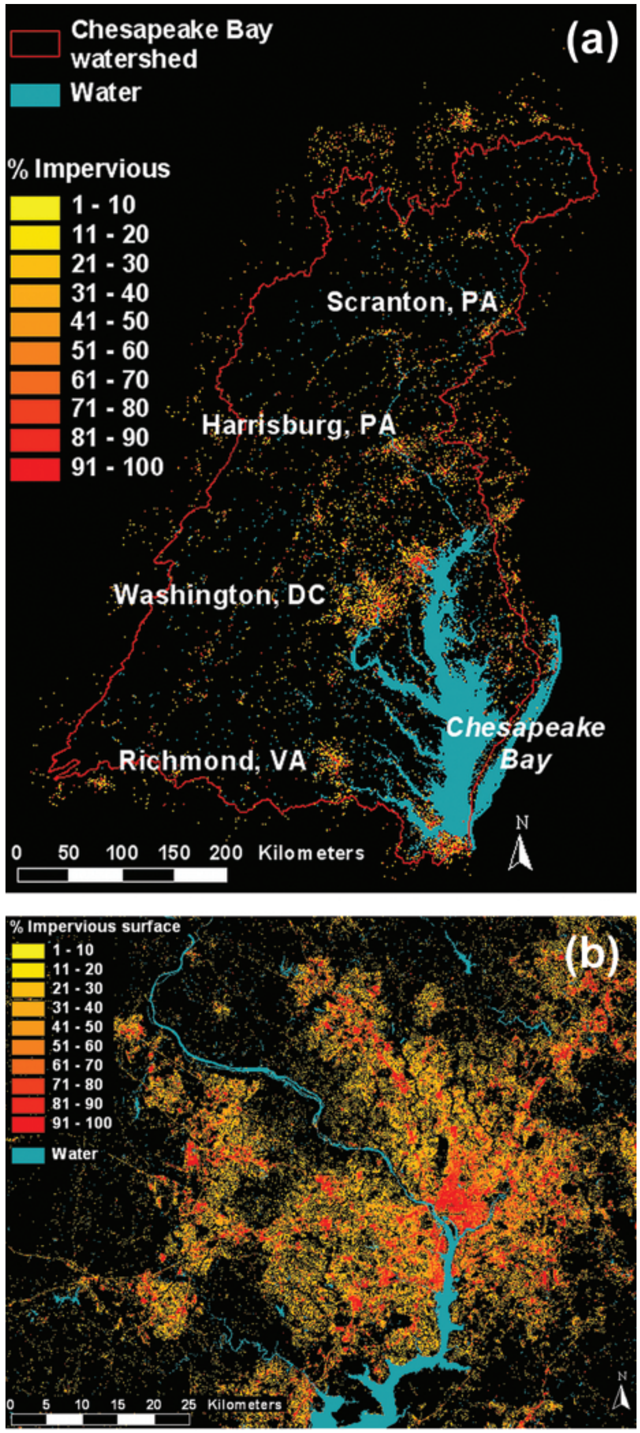

Figure 1.7 (a) Percent impervious surface area in the Chesapeake Bay watershed (b) Percent impervious surface area in the Washington, DC metropolitan area.

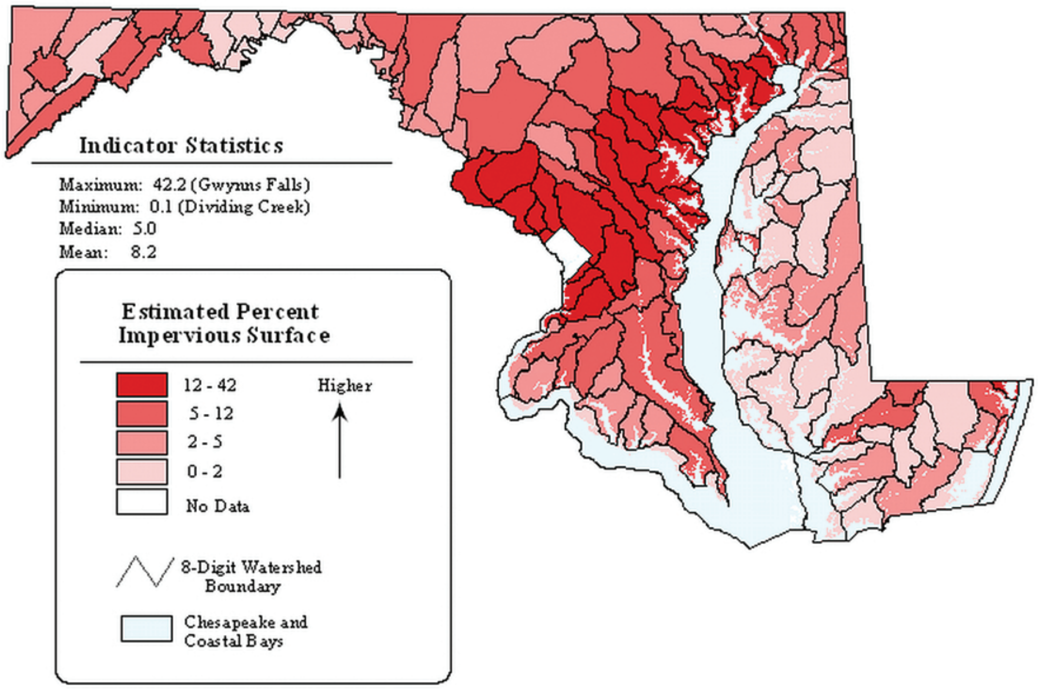

Figure 1.8 Estimated percent impervious surface area in the state of Maryland.

A 6: Due to the increased stream-flow during the high precipitation period, a significantly larger volume of fresh water would enter the Chesapeake Bay, compared to the low precipitation period.

A 7: Chl-*a* values in the Chesapeake Bay are higher during the April 2003 – June 2003 period.

A 8: This period of time corresponds to the period when precipitation in the Chesapeake Bay watershed was high.

A 9: The higher values of chl-*a* corresponding to the period of high precipitation indicate that elevated stream-flow and increased transport of fresh water into the Chesapeake Bay may enhance phytoplankton productivity. This could also be due to increased turbidity (some of which could be more phytoplankton cells in the water). The possible causes are an increased delivery of nutrients in the elevated stream-flow entering the Bay, and also an increased concentration of suspended sediments carried by higher stream-flow volumes.

A 10: The K490 values in the Bay are significantly higher during the April – June 2003 period.

A 11: This period of time corresponds to the period when precipitation in the Chesapeake Bay watershed was high, October 2002 – June 2003.

A 12: The likeliest causes of the elevated values of K490 are directly related to the answer to Question 9. Increased concentrations of phytoplankton and higher concentrations of suspended sediments (and also coloured dissolved organic matter) will all contribute to enhanced light attenuation in the water column. This is the likeliest reason that higher stream-flow and transport of freshwater into the Bay are correlated with higher K490 values.

A 13: The $R_{rs}555$ values in the Bay are significantly higher during the period April – June 2002.

A 14: This period of time corresponds to the period when precipitation in the Chesapeake Bay watershed was low, January – September 2002.

A 15: The surprising result should be related to the difference in the values of chl-*a* and K490 during the high precipitation (high stream-flow) and low precipitation (low stream-flow) periods. Light attenuation is caused by light absorption, light scattering, and light reflection. When the chl-*a* and K490 values are elevated, there are more substances and particles in the water column; thus, the scattering, absorption and reflection of light increases. Simply put, the water is less clear. During the low precipitation/low stream-flow period, the water in the Bay was clearer – and in the shallow depths of the Bay, this allowed more reflection from the bottom of the Bay, which is the likeliest explanation for the increased values of $R_{rs}555$ during the low precipitation period.

A 16: Increased areas of impervious surface will increase both the volume of water entering the Bay at one time during high precipitation events, and will also deliver more undiluted water running off other types of surfaces, such as the lawns of homes or cleared fields. The increased areas of impervious surface can also contribute to erosion when flow volumes are elevated and cause flooding. All of these effects contribute to greater flow of nutrients into the Bay, and can enhance the concentrations of suspended sediments during certain times. These effects will enhance phytoplankton growth and cause decreased water clarity, which affects the survivability of benthic vegetation. Further, the increased growth of phytoplankton leads to increased organic matter deposition on the bottom, causing more bacterial respiration and the spread of areas of low oxygen or no oxygen (hypoxia/anoxia) in the bottom waters of the Bay. In the web document at `http://www.eco-check.org/pdfs/do_letter.pdf` there is a chart (Figure 1.6) of dissolved oxygen levels in the Bay from 1985 – 2006. Note the difference between 2002 and 2003 in this chart. Due to the extremely low stream-flows in 2002, that year was the best overall, in terms of hypoxic and anoxic areal extent, for the entire 22-year period charted.

1.6 References

Acker JG and Leptoukh G (2007) Online analysis enhances use of NASA earth science data. Eos, Trans Am Geophys Union 88(2): 14 and 17

Acker J G, Harding L, Leptoukh G, Zhu T, and Shen S (2005) Remotely-sensed chl a at the Chesapeake Bay mouth is correlated with annual freshwater flow to Chesapeake Bay. Geophys Res Lett 32: L05601. doi:10.1029/2004GL021852 01

O'Reilly JE, Maritorena S, Siegel D, O'Brien MC, Toole, D, Mitchell BG, Kahru, M, Chavez FP, Strutton P, Cota G, Hooker SB, McClain CR, Carder KL, Muller-Karger F, Harding L, Magnuson A, Phinney D, Moore GF, Aiken J, Arrigo KR, Letelier R, and Culver M (2000) Ocean color chlorophyll a algorithms for SeaWiFS, OC2 and OC4: Version 4. In: Hooker SB and Firestone ER (eds) SeaWiFS Postlaunch Calibration and Validation Analyses (Part 3), NASA Technical Memorandum 2000-206892, Volume 10, NASA GSFC, 9-23

Mueller JL and Trees, CC (1997) Revised SeaWiFS prelaunch algorithm for the diffuse attenuation coefficient K(490). In: Yeh, E-n, Barnes RA, Darzi M, Kumar L, Early EA, Johnson BC, Mueller JL and Trees, CC (eds) Case Studies for SeaWiFS Calibration and Validation, E-n. Yeh, R. A. Barnes, M. Darzi, L. Part 4, NASA Tech. Memo. 104566, NASA Goddard Space Flight Center, Greenbelt, Md., Volume 41