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Investigating potential agricultural-related causes of eutrophication in the Tsimlyansk Reservoir through GIS and remote sensing

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Author’s declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by**:**
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Algal blooms can cause disturbances for the many services reliant upon a reliable source of freshwater, threatening water security. Investigation into the underlying causes of eutrophication and related algal blooms can be done through the use of ICTs including remote sensing, GIS, and highly underutilized data portals. Potential agricultural-related causes of eutrophication in the Tsimlyansk Reservoir in Southern Russia were investigated with the intention of conducting the preliminary groundwork for future research to be done in the area. The other primary aims of this research included developing a set of deliverables to be made available for interested stakeholders and exploring how these ICTs can be used in a practical application for the region. Eutrophication in the reservoir was investigated through the development of a detailed land use classification, identification and assessment of algal blooms through satellite imagery, and exploration into the causal relationship between these two elements through precipitation. A relationship was found between precipitation and algal blooms, indicating a potential link between eutrophication and land use in the region around the reservoir. Further research can build upon this study to conclude on the set of underlying causes of harmful algal blooms in the reservoir, upon which policies can be based to mitigate the effects of future occurrences.

Keywords: ICTs, GIS, remote sensing, data portals, land use classification, Tsimlyansk Reservoir, eutrophication, algal blooms

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List of Abbreviations

ETM+	Landsat 7 Enhanced Thematic Mapper Plus
GIS	Geographic Information Systems
IAMO	Leibniz Institute of Agricultural Transition Economies
ICT	Information and Communication Technologies
MLC	Maximum likelihood classification
MODIS	Moderate Resolution Imaging Spectroradiometer (satellite sensor)
NASA	National Aeronautics and Space Administration
NIR	Near infrared (electromagnetic spectrum)
SPOT	Satellite Pour l'Observation de la Terre (satellite)
SWIR	Short wave infrared (electromagnetic spectrum)
TM	Landsat 5 Thematic Mapper
UN	United Nations
UNEP	United Nations Environment Programme
USGS	United States Geological Survey

1. Introduction

1.1. Problem Definition and Background

Issues regarding water security and water quality have garnered attention on an international level for many years. The threatened status of freshwater in many areas of the world is of great concern and has been a key focal point of international, national, and local policies around the world. Eutrophication remains one of the most pressing issues in the protection of freshwater ecosystems (Schindler 2006). Extensive episodes of eutrophication, e.g. in the form of algal blooms, is one of the many parameters that affects water quality. Algal blooms can produce toxins harmful to human health and can disrupt the ecosystem services that are dependent on a reliable source of freshwater.

The Tsimlyansk Reservoir in Southern Russia is of great environmental and economic importance to the region in which it is located. It is relied upon as a source of freshwater in an area that is densely populated, is used extensively for irrigation of the region's agricultural lands, and is a source of cooling water for a nuclear power plant in the area, among a variety of other uses (Lagutov and Lagutov 2012). But in recent years, harmful algal blooms have been reported and associated with a number of environmental and economic concerns. Major fish kills have occurred in the past few years, including one in 2010 in which approximately 900,000 fish were found dead in the reservoir. Similar instances of fish kills occurred in May 2007 and June and August 2009 (Vesti 2011). In October 2009, a particularly bad algal bloom occurred, clogging filters at a water treatment plant and leaving about 170 thousand people without water for 3 days (Nikanorov *et al.* 2010). These major events were caused by algal blooms occurring as a result of increased eutrophication in the reservoir. In order to address this issue to be able to develop policies and practices to mitigate future occurrences of this kind, research must be conducted to determine the underlying causes of these harmful algal blooms in the reservoir.

Agricultural runoff containing nitrogen and phosphorus is a well-recognized source of eutrophication in freshwater systems (Serediak *et al.* 2014; Ferreira *et al.* 2011). The Tsimlyansk Reservoir is in a region of high agricultural importance, deemed the nation's "breadbasket" (Lagutov and Lagutov 2012). Because of the developed agriculture in the area, it is reasonable to assume there is a connection between the agricultural lands and the eutrophication events in the reservoir, but preliminary research must be conducted to determine if the agricultural lands in the region are indeed related to these events, which will set the foundation for how to address the problem on a higher level.

Remote sensing and geographic information systems (GIS) are two types of technologies among the ever-increasing pool of information and communication technologies (ICTs) that have proven to be useful to study environmental problems such as this, for both land (Kuemmerle *et al.* 2013) and water applications, including investigation into eutrophication of freshwater ecosystems (Ritchie *et al.* 2003; Kitsiou and Karydis 2011; Barnes *et al.* 2014; Brivio *et al.* 2001; Farag and El-Gamal 2011). Furthermore, there are numerous large repositories devoted to data derived from remote sensing technologies (e.g. data portals) that are available online and that provide free access to tremendous amounts of data. These resources, the number of which is constantly increasing, are highly underutilized, despite the wealth of information they contain. This research is using the opportunity to combine remote sensing and GIS technologies and the vast amount of available data and explore how they be used to investigate the problem of eutrophication in the area around the Tsimlyansk Reservoir.

In order to investigate this issue using the aforementioned methods, an important step is to accurately determine the state of land cover (used interchangeably with "land use" in this study) in the region at the time these large-scale algal bloom events were taking place (around 2010). Detailed land cover data is a critical part of investigating environmental phenomena (Heinl *et al.* 2009). As such, a large portion of this research is aimed at developing detailed and accurate land cover data for this region, which will serve as a foundation for future research and analysis. Next, eutrophication in the reservoir is investigated to identify when and to what extent algal blooms have occurred in recent years. Lastly, the relationship between land use and eutrophication is investigated through precipitation data, providing an example of how to use the data that has been gathered to attempt to determine a causal link between the two elements.

To date, very little work has been done to research this issue and determine the underlying causes of it, especially with the use of ICTs and data portals. Furthermore, the deliverables that will be created as a result of this research, which do not yet freely exist, will be made publicly available to provide useful data to interested stakeholders in the region. Not only will this research contribute to the limited literature on the topic, especially literature in the English language in which there is little written currently, but it will set the foundation for future research to be conducted, which will be able to be used as a scientific basis for policymaking and decision-making in the future. It will also provide an example of how the vast amount of data available can be utilized using available technologies in a practical and useful manner.

1.2. Research Aim

Since there has been little to no work done in this field so far for the region, one of the main goals of this study is to conduct the preliminary groundwork for future research and to generate a set of deliverables that can be used and expanded upon for environmental assessments, environmental monitoring, and policymaking regarding land use around and water quality of the Tsimlyansk Reservoir in the future. In addition to developing the foundation for future research and making some data publicly available, another primary goal of this research is to make use of remote sensing and GIS technologies as well as to utilize and explore the tremendous amount of data freely available through data portals.

1.3. Research Questions and Objectives

The aforementioned research aims will be pursued through the lens of the following research questions (RQ) and corresponding objectives (OB):

RQ1: What was the state of land use around the Tsimlyansk Reservoir around the time of reported harmful algal blooms? Has it changed much over the past 15 years?

- OB1: Obtain data indicating land use in the area around the reservoir in 2010.
- OB2: Develop a land use thematic map of land use in 2010 that can be used as a basis for future research in the region.
- OB3: Determine how land use in the area around the reservoir has changed in the past 15 years.

RQ2: When and to what extent have algal blooms occurred in the Tsimlyansk Reservoir in the past 15 years?

- OB1: Identify instances of algal blooms in the reservoir.
- OB2: Determine the extent of identified blooms and develop a catalogue of available data that can be used for future research.

RQ3: How can this data be used to investigate the relationship between land use and eutrophication in the Tsimlyansk Reservoir?

- OB1: Investigate the link between land use and eutrophication through precipitation data and determine if algal blooms occur after large episodes of precipitation.

1.4. Research Considerations and Approach

1.4.1. Limitations

A limitation for this study was that the researcher does not speak Russian and was thus not able to access a wide variety of information that could have been useful and interesting to the research. But as this limitation was identified at the beginning of the research period, efforts were taken to focus on study methods that would not require Russian language skills, namely remote sensing and GIS. Furthermore, as mentioned above, this limitation provided the opportunity to utilize some of the ever-increasing amount of data and ICTs to address a real environmental problem in the region.

Another limitation was the availability of region-specific data (data that cannot be derived from remote sensing) for the topic and for the study area. As will be discussed in Section 2 of this study, there is a very limited amount of information regarding water quality in the reservoir. Furthermore, government statistics on land use and agricultural productivity are not readily accessible for certain regions within the study area. This limitation was addressed by focusing on the use of readily available data (e.g. satellite imagery of the region) and data from trusted sources (e.g. statistics that were able to be obtained from government databases and GIS datasets from researchers in the region), all of which can be used and analysed with remote sensing and GIS technologies.

1.4.2. Methods

This study will address the aforementioned research questions through a combination of a brief literature review, a study visit to learn remote sensing techniques and how to perform land use classification, the gathering of data from data portals, and the use of remote sensing and GIS technologies and analysis of statistics.

1.4.3. Audience

As mentioned in Section 1.2, one of the primary aims of this research is to conduct the preliminary data preparation and analysis on the issue of agricultural-related eutrophication in the Tsimlyansk Reservoir using remote sensing and GIS. This research is intended for use by stakeholders in the Azov Sea basin, particularly environmental and water practitioners and policymakers. Those individuals and organizations could use this research as a basis for further research and analysis on the causes of eutrophication in the reservoir, which would serve as a basis for mitigation efforts to combat harmful algal blooms in the future and preserve the reservoir. Some of the deliverables produced as a result of this research will be made publicly available on the Azov Basin Center website (http://azovcenter.ru/), a website devoted to promoting the sustainable development of the region, so they can be of immediate use to interested stakeholders.

1.4.4. Outline

Section 2 (*Literature Review*) of this study includes a literature review covering 5 topics: the importance and relevance of water security in current policy discussion and the role eutrophication plays; an overview of the study area and the importance of the Tsimlyansk Reservoir to the region and economy; the suitability of remote sensing for both land and water applications; and an overview of the GIS software packages and data portals used for research. **Section 3** (*Methodology*) provides the research design and describes the basic methodological steps that will be taken to conduct the research, broken down into each research question. **Section 4** (*Results and Analysis*) discusses the specific steps taken to conduct the research, what exactly was done, and what results were obtained. **Section 5** (*Discussion*) provides a discussion of the results, limitations, and highlights a number of pathways for further research. **Section 6** (*Conclusion*) concludes the research by providing an overview of what work was performed and what was achieved.

2. Literature Review

2.1. Water Security: an International Concern

Water security is an important issue on the international policy agenda and is a focal point across all levels of government and interests, from global environmental publications to national and local agreements and legislation. Freshwater is an increasingly finite resource and there are a number of parameters that threaten the quality of freshwater ecosystems including eutrophication, which can lead to harmful algal blooms and pose threats to human health and damage to infrastructure. This section will introduce the concept of water security, highlight its importance in the current political arena, and discuss how it relates to water quality.

2.1.1. Freshwater: a Finite Resource

Freshwater ecosystems provide a myriad of services that help sustain human existence. They include both provisioning services and supporting services, as defined by the Millennium Ecosystem Assessment (Reid *et al.* 2005). Freshwater ecosystems *provide* people with water for a variety of uses, including drinking, sanitation, industry, and agriculture, among others. But the existence and availability of freshwater also *supports* other ecosystem processes, making life on Earth possible (Reid *et al*. 2005).

Of all the water available on Earth, freshwater makes up only 2.5%, the majority of which is inaccessible because it is perennially frozen. Most of the world's liquid freshwater is groundwater. A mere 0.26% makes up the rivers, lakes, and reservoirs around the globe. Approximately 75% of human water withdrawals (e.g. for drinking, agriculture, industry, and other uses) come from surface freshwaters in this 0.26% (Carpenter *et al.* 2011). Human activities and human-induced climate change are changing freshwater ecosystems and threatening to cause problems for the world’s population in the future. Freshwater is an increasingly finite resource and its importance for sustaining human life and its uneven distribution in both space and time has made water scarcity a permanent issue on the political agenda.

2.1.2. Water: a Top Policy Agenda Item

Issues regarding water availability and quality have consistently been a focal point of both international and national policy in recent years. Having access to water of an acceptable quality for drinking and sanitation was declared a human right by the United Nations (UN) General Assembly in 2010 (UN General Assembly 2010).

Water is a recurring theme in a number of global policy documents and reports. The UN’s Millennium Development Goals incorporate water access into Target 7.C, part of Goal 7, which aims to “Ensure Environmental Sustainability”. The target, aiming to halve the "proportion of the population without sustainable access to safe drinking water and basic sanitation” by 2015 was met in 2010 (UN 2013). But despite this progress, millions will still be without safe drinking water by the end of the target’s time period (UNEP 2012).

In addition, water is a main theme in the United Nations Environment Programme’s (UNEP) Global Environmental Outlook 5 report, which was released in 2012. This report notes the need for improved governance of water resources to combat competing water uses and overexploitation from various actors (UNEP 2012).

Many international agreements and policy documents have been developed over the past few decades (e.g. Johannesburg Plan of Implementation, the Dublin Principles, the UN Millennium Declaration) that deal with water issues from various angles: the importance of water ecosystems, water’s impact on human well-being, how to use water the most efficiently, how to improve and sustain water quality, and how to adequately manage water resources (UNEP 2012). But there have also been many declarations and pieces of legislation on the regional and national level, like the European Union's (EU) Water Framework Directive (EU Directive 2000) that have similar goals.

Because of water's transboundary nature, the only way to effectively manage the resource is through cross-border, cross-sectoral and multi-actor coordination. The concept of Integrated Water Resource Management, based on the Dublin Principles, began to garner attention after the Earth Summit in 1992. The concept stresses the importance of coordination and cooperation across all levels (Agarwal *et al.* 2000).

To conclude, water is a top priority item in the international policy arena. It is reflected in legislation on all levels of government and is a well-recognized issue of importance.

2.1.3. Water Quality: a Prerequisite for Water Security

"Water quality" can be hard to define because it depends on the ultimate use of the water: water intended for human consumption would inevitably have a different definition than water intended for agricultural or industrial purposes (Ritchie *et al.* 2003). An attempt to define water quality (referred to as "ecological status") is made in Annex V of the EU Water Framework Directive, which takes into consideration a number of factors in its definition: biological (e.g. flora and fauna) hydromorphological (e.g. dynamics associated with water flow), chemical (e.g. presence of pollutants), and other characteristics like thermal conditions, oxygenation, salinity, acidification, and nutrient conditions (EU Directive 2000).

Water quality is a necessary prerequisite to attaining water security, but similar to "water quality", developing an accepted definition for "water security" has been difficult (UNEP 2012). For the purposes of this study, the definition of water security will come from the Ministerial Declaration of The Hague, agreed to in 2000, which was relied upon by the UNEP Global Environmental Outlook 5 report. The Declaration defines water security as:

> "ensuring that freshwater, coastal and related ecosystems are protected and improved; that sustainable development and political stability are promoted, that every person has access to enough safe water at an affordable cost to lead a healthy

> and productive life and that the vulnerable are protected from the risks of water related hazards" (World Water Council 2000).

Water security is inherently associated with water quality in the aforementioned definition, as ecosystems need to be protected and improved, which denotes a certain level of quality, and people need to have access to safe water, indicating an even higher level of quality necessary.

2.1.4. Eutrophication

While there are many indicators of water quality as discussed earlier in this section (e.g. hydromorphology, salinity, thermal conditions), eutrophication remains one of the most pressing issues in the protection of freshwater and marine ecosystems (Schindler 2006). Eutrophication is a predominantly anthropogenic-caused phenomenon that occurs when surface waters are enriched with nutrients, mainly nitrogen and phosphorus (Serediak *et al.* 2014; Ferreira *et al.* 2011). It is widely accepted that agriculture and urban activity are the two major causes of eutrophication from non-point sources in aquatic ecosystems. Agricultural runoff is rich in both nitrogen (N) and phosphorus (P) from fertilizers and pesticides applied to crops. Runoff from these lands is known to cause problems associated with eutrophic water conditions, like harmful algal blooms, oxygen depletion, and fish kills, among others (Carpenter *et al.* 2011; Carpenter *et al.* 1998). But the factors involved in the development of eutrophic algal blooms are inherently complex. Regarding agricultural runoff, there are numerous factors involved in if, how, and when an algal bloom occurs including, for example, the presence of limiting nutrients; episodes of precipitation; thermal stratification in the body of water; the particular species of algae; when, how much, and what type of fertilizer was applied; among many other components (Bellinger 2014).

The nutrient enrichment of freshwater ecosystems caused by eutrophication diminishes water quality and threatens its ability to be used for human consumption, agriculture, and industry. In freshwater ecosystems, eutrophication is often exhibited through blooms of cyanobacteria (blue-green algae), which can pose a health risk to humans (Carpenter *et al.* 1998). This research will focus on problems associated with eutrophication in a freshwater reservoir. While eutrophication is just one aspect of water quality, and quality only part of water security, it is still important to address because of the economic and environmental consequences that can, and have been, arising from it in the area of study.

2.2. Area of Study: Tsimlyansk Reservoir

As major eutrophication events have been occurring in recent years and causing disturbances in the region, this research is focused on eutrophication in the Tsimlyansk Reservoir. The following section will describe the region in which the reservoir is located and highlight important economic and environmental characteristics.

2.2.1. Reservoir Characteristics

The Tsimlyansk Reservoir is located in Southern Russia, northeast of the Black Sea and the Azov Sea, as seen in **Figure 1**. It falls between two regions, called "oblasts", Rostov to the west and Volgograd to the east. It is the largest freshwater body in the basin of the Azov Sea (Gilfanova 2012), measuring 260 kilometres in length and having a surface area of 2,702 square kilometres (Novikova *et al*. 2012). At full capacity, the volume of the reservoir is 23.9 cubic kilometres and it has a maximum depth of 36 meters (Lagutov and Lagutov 2012).

2.2.2. Historical Importance of the Reservoir

The reservoir was formed as a result of the Tsimlyansk dam, which was built as a part of the 'Great Construction Projects of Communism' and began operation in 1953. The dam was built to regulate the Don River, the largest river in the Azov Sea basin. The Don River is characterized by extreme variability in its annual water distribution. About 70% of the total river flow in the Don is comprised of snowmelt, causing tremendous discharge in the spring months as compared with the rest of the year. The Tsimlyansk dam was built to regulate this extreme variability. The main purpose of the dam was to allow for a reliable navigation route through the Don River and to secure access to the Volga-Don Shipping Canal, an important shipping canal linking the Don River and the Volga River and allowing access to the Caspian Sea (Lagutov and Lagutov 2012).

Today, a number of ecosystem services are derived from the existence of the Tsimlyansk dam and reservoir, including hydropower generation, a more reliable source of freshwater for both municipal and agricultural uses, and navigation (Lagutov and Lagutov 2012).

Figure 1. Map of the Tsimlyansk Reservoir in Southern Russia. (Map created by author).

2.2.3. The Azov Sea Basin: Economic Importance

The region in which the reservoir is located, the Azov Sea basin, is a notably important economic region in both Russia and Ukraine. The basin encompasses a high level of agricultural development, including both cropland and livestock farming. The majority of the watershed is covered in cultivated lands. The region is known for its fertile soils (called chernozem) and favourable climate, making it the "breadbasket" of Russia. But the region is semi-arid and there is low precipitation in the entire basin and even less in the eastern areas, necessitating high amounts of freshwater abstraction for irrigation (Lagutov and Lagutov 2012). In the lower Don River are, there are approximately 323,000 hectares of irrigated lands, requiring a volume of about 2 cubic kilometres of water each year (Shavrak *et al*. 2012), or approximately 8% of the total capacity of the reservoir itself (calculated by author).

As mentioned above, transportation is another important economic factor in the region. The basin is located in the middle of many important shipping and transportation routes in the region (Lagutov and Lagutov 2012). The use of the reservoir for shipping and transportation is increasing: a total of 5,022 ships passed through the reservoir in 2000, which increased to 6,799 ships in 2007 (Shavrak *et al*. 2012). The increasing traffic cannot be supported by the existing Volga-Don Shipping Canal and there are two canal construction proposals currently under discussion (Lagutov and Lagutov 2012).

Additionally, power generation is important in the region. The Tsimlyanskaya hydropower station generates energy, albeit a relatively small amount compared to other stations in Southern Russia. The reservoir is also used to provide cooling water to the Volgodonsk Nuclear Power Plant located there. The basin is densely populated, particularly along the rivers, and is one of the most densely populated regions in both countries. The Azov Sea used to be an important fishery, but overexploitation and unsustainable fisheries management caused the regional fishing industry to collapse, turning what was once touted as one of the most productive seas in the world to one in which fish stocks are at critical levels (Lagutov and Lagutov 2012).

The freshwater in this region, particularly that of the Don River and Tsimlyansk Reservoir, allows all of these things to happen – the agricultural productivity, shipping transportation, power generation, and supporting a large population with drinking water and other important services. The region is dependent on the availability of this freshwater.

2.2.4. Importance of Freshwater in the Region

The Tsimlyansk Reservoir is a very important source of freshwater in the region, but the climate in which it is located is not ideal to begin with and climate change has been putting additional pressures on the reservoir. The reservoir is located in a semi-arid climate, characterized by its warmth and dryness. Water is lost to evaporation and much of it is abstracted for agricultural, industrial, and municipal purposes. Approximately 20% of the total Russian freshwater withdrawal comes from the Azov Sea basin, yet the basin accounts for less than 1% of the total water runoff in the country. Despite having a low amount of available water resources, it is a highly utilized basin (Lagutov and Lagutov 2012).

Water security is an important issue to consider in the basin. The Tsimlyansk Reservoir is the only freshwater source for many of the municipalities that surround it (Lagutov and Lagutov 2012). Approximately 457.5 thousand people depend on the freshwater it supplies (Shavrak *et al.* 2012). So many people in the region depend on these surface water bodies for drinking water, but availability is often variable and existing resources are becoming strained due to the variety of ecosystem services that depend on it. Approximately 30-40 million m^3 of water in the Tsimlyansk Reservoir is extracted for municipal purposes, which is a small amount compared to the 10-12,000 million m^3 of freshwater used for hydropower generation (up to 80% of the total water used in the Tsimlyansk multipurpose water scheme) *(Shavrak et al.* 2012; Gilfanova 2012). As discussed above, a great deal of water is also used for irrigation purposes. Additionally, much water is lost through evaporation due to the semi-arid climate and the reservoir's large surface area (Lagutov and Lagutov 2012). The amount of water being lost through evaporation is increasing as well. Between 1953-1987, evaporated water amounted approximately 11% of the water input. From 2000-2009, that amount had increased to 14%, signifying an increasing trend. This is consistent with increasing air temperatures in the region, which have increased by 1.7ºC in the last 25 years (Shavrak *et al*. 2012).

Furthermore, freshwater in the region has been found to contain high levels of pollution. About 7.6% of samples in the region contained biological contaminants. Approximately 10,000 people in the area drink untreated water from the surface water bodies, often exposing themselves to these contaminants. There are already public health threats arising in the area (Lagutov and Lagutov 2012).

In summary, the reservoir is depended upon for many purposes. Recent algal blooms and associated problems have threatened the services it provides, threatening water security in the region overall.

2.2.5. Eutrophication in the Reservoir

Eutrophication is an important issue for the Tsimlyansk Reservoir. As defined earlier in the chapter, when a water body becomes eutrophic, which occurs when it receives excess nutrients, it often results in the development of blue-green algae, sometimes creating algal blooms. This can often occur because of agricultural runoff that contains phosphorus- and nitrogen-based fertilizers and organic matter (Novikova *et al*. 2012).

The nutrient content, predominantly nitrogen and phosphorus, in the Tsimlyansk Reservoir is high enough that the water body can be considered 'hypertrophic'. But there is not reliable or consistent water quality or nutrient concentration data for the reservoir. There was some testing done in the 1980s, some in 1990, and some between 2006-7, but the data is inconsistent. From the testing that has been done, it was found that nutrient concentrations exceeded the maximum permissible concentration every year in 38-100% of the samples (Nikanorov *et al.* 2012).

There are typically two peaks during the year of blue-green algae in the reservoir as a result of eutrophication, the first in the spring (*Bacillariophyta*) and the second in the late summer (*Cyanophyta*). The algae are highly productive and a bloom can reach up to 80% of the reservoir's surface area (Nikanorov *et al.* 2012). As mentioned in Section 1 of this study, a number of problems resulting from algal blooms have occurred in recent years, including fish kills (Vesti 2011) and damage to water treatment infrastructure, the latter of which left about 170 thousand of people without water to drink for 3 days during a particularly large algal bloom in October 2009 (Nikanorov *et al*. 2010).

Eutrophication is a major problem in the reservoir and there has not been adequate work done to address the issue in order to mitigate problems from future occurrences.

2.2.6. Importance of this Study for the Region

The Tsimlyansk Reservoir is located in a region characterized for its semi-arid climate and low precipitation. The reservoir is heavily utilized and is relied upon for a multitude of services, from providing drinking water to area inhabitants to irrigating the highly developed agricultural areas in the region. Eutrophication and resulting algal blooms are causing problems in the region, necessitating the need for research into the underlying causes of the blooms so mitigation options can be pursued. Remote sensing and GIS are two ICTs that can be used to learn more about the problem and get closer to finding solutions to address it.

2.3. Technology: Remote Sensing

Remote sensing and subsequent processing and analysis made up a large portion of this research. This section will describe the technology and how it can be used in land and water applications.

2.3.1. The Technology

Remote sensing can be defined as the acquisition of information about an object without being in direct contact with that object (Chuvieco and Huete 2010; Gibson and Power 2000; Weng 2013). In essence, it is the act of "sensing" and recording information about an object while being at a distance (e.g. a place that is "remote") from it (Weng 2013).

The human eye can only perceive a small part of the electromagnetic spectrum, which can be defined as the range of all of the various types of electromagnetic radiation that exist. The small portion we can perceive is called the visible spectrum and ranges from 0.4 to 0.7 micrometers (μm), as seen in **Figure 2**, based on Chuvieco and Huete (2010). Through remote sensing technology, we can expand the portion of the electromagnetic spectrum that we can perceive beyond this visible region. Different portions of the electromagnetic spectrum have different uses in remote sensing. For example, the near-infrared (NIR) portion is often used to study green vegetation, while the short wave infrared (SWIR) portion of the middle infrared range is often used in soil vegetation studies (Chuvieco and Huete 2010).

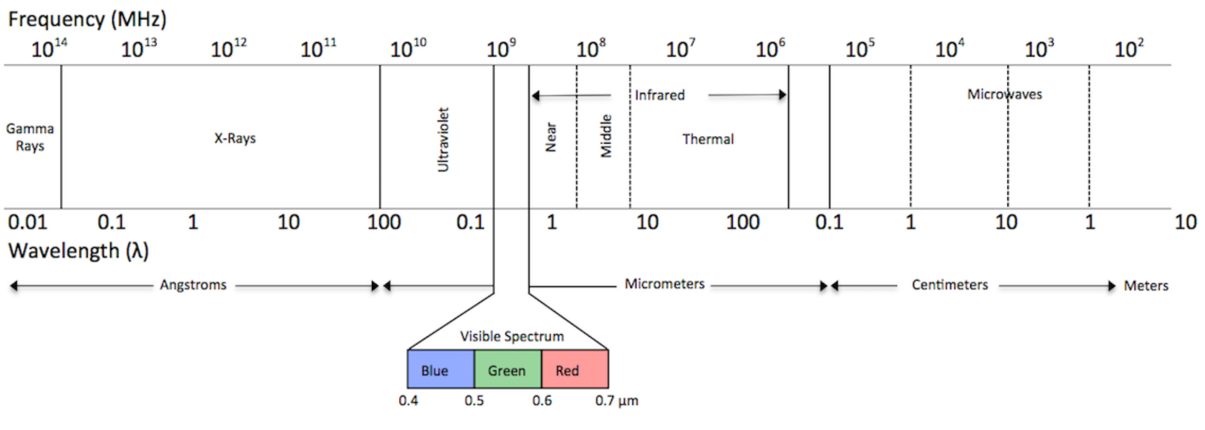


Figure 2. Electromagnetic spectrum. (Created by author based on Chuvieco and Huete 2010).

Objects on the Earth's surface (as well as different types of land cover) act differently in the various parts of the electromagnetic spectrum. They have unique "spectral signatures", which is a term that means the amount of reflectance an object gives off at different parts of the spectrum. Water, for example, has a completely different spectral signature than green vegetation because it has different levels of reflectance at various wavelengths in the spectrum (Chuvieco and Huete 2010). Because of these spectral differences, it is possible to use remote sensing to detect the type of land cover on the Earth's surface based on the land cover's specific spectral signature.

Remote sensing is not a new concept: it has been used since the early 1960s to acquire information about the Earth from aerial photography (Chuvieco and Huete 2010). But the term has evolved to cover many more technologies and platforms since then. Images can be obtained through instruments aboard aircraft or balloons or instruments mounted on space-borne platforms, like satellites (Weng 2013). And the data these instruments acquire have become much more sophisticated, spanning a wider range of the electromagnetic spectrum well beyond the visible part of it.

This study will focus on satellite remote sensing because of the advantages space-based observations have over other platforms. According to Chuvieco and Huete (2010), some of these advantages include:

- A comprehensive and consistent view of the entire Earth
- A variety of space-based instruments that have a wide range of technological capabilities (e.g. spatial resolution)
- The ability to obtain information from the non-visible parts of the electromagnetic spectrum
- The ability to have repeat observations, allowing analysis of dynamic phenomena
- Very little delay in transmission, allowing for near real-time observations

There are a number of satellite programs in existence today, developed by nations and commercial entities around the world. The Landsat program, developed by NASA, is one of the most notable satellite remote sensing missions, providing over 30 years of consistent, high-quality data. Other programs include the SPOT Satellite (Systeme Pour l'Observation de la Terre), developed collaboratively by France, Belgium, and Sweden; NASA's Terra-Aqua platforms that include a number of sensors, including MODIS (Moderate Resolution Imaging Spectroradiometer) for both land and oceanic applications; and a number of private commercial satellites including IKONOS-2, originally developed by a company called Space Imaging, Inc. (Chuvieco and Huete 2010). These satellites and sensors vary in spatial resolutions, number of spectral bands, swath coverage size, frequency of repetition, and image availability.

2.3.2. Applications for Land Use

In this research, *RQ1* addresses using remote sensing to determine the current state of land use. The effectiveness and usefulness of remote sensing to determine and map land use and land cover is well recognized and documented (Kuemmerle *et al.* 2006). According to Kuemmerle et al. (2013), remote sensing is "arguably the most important technology available" to map the current state and changes of land use and land cover over large expanses of land. It can also be used to assist in the differentiation of subtle differences in spectral signatures of land type, e.g. to identify abandoned cropland from actively used cropland (Schierhorn *et al.* 2013).

Remote sensing analysis is not constrained by space or time, unlike the use of *in situ* measurements or on-site ground-truthing (the act of physically going to a location to verify what is on the ground) (Prishchepov 2014), and the number of available images is continually increasing, ever-expanding the period of time that can be studied. Additionally, it allows for consistent and reliable information across administrative and political borders, unlike many other methods of data collection.

As mentioned earlier in this section, a number of remote sensing satellites have been launched by nations around the world for the past few decades. Of these programs, Landsat has been one of the most successful, providing high-quality satellite images of Earth's land areas for over thirty continuous years, making it the most consistent set of data available (Chuvieco and Huete 2010). For this reason, this study will use satellite images from NASA's Landsat program to assess land use and land cover change for the area of study.

It is important to note that a malfunction of the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite in 2003 affected the availability of data for this research. In May 2003, an important hardware component of the satellite failed, causing blank stripes of missing data on all of the images taken by the scanner. Because of this, images from only the Landsat 5 mission are usable for the period under study (Chuvieco and Huete 2010). Landsat 8, originally called the Landsat Data Continuity Mission, was launched in February of 2013 to, as the name suggests, ensure the continuity of data coming from the Landsat program after the Landsat 5 satellite was decommissioned in January 2013 (NASA 2013b).The period of study is fully covered by the Landsat 5 mission and the successful use of remote sensing using the Landsat 5 Thematic Mapper (TM) images is well documented. Examples from the Nile Delta (Elhag *et al.* 2013), Oregon, USA (Oetter *et al.* 2001), and Yunnan, China (Zhang *et al.* 2014) all discuss the successful utilization of Landsat TM images to develop land use and land cover maps for various purposes.

2.3.3. Remote Sensing Applications for Water

As will be addressed by *RQ2*, remote sensing has proved to be a useful technology for use in water applications, including the assessment eutrophication as an indicator of water quality (Ritchie *et al.* 2003; Kitsiou and Karydis 2011; Barnes *et al*. 2014; Brivio *et al.* 2001; Farag and El-Gamal 2011). Techniques to assess water quality using remote sensing started being developed in the early 1970s (Ritchie *et al.* 2003) and have been used to monitor the quality of inland water bodies since the 1980s (Brivio *et al.* 2001). Remote sensing of satellite imagery can be used to monitor a variety of water quality parameters, including chlorophyll, an indicator of eutrophication (Ritchie *et al.* 2003). It can also be used to detect phytoplankton and cyanobacteria blooms that occur during eutrophic events (Barnes *et al*. 2014).

Similar to land use applications, remote sensing for water allows for greater spatial and temporal analysis. *In situ* measurements provide data for a specific location at a specific time. But the use of satellite imagery allows for a much broader analysis of an area, both spatially and temporally (Brivio *et al.* 2001; Ritchie *et al.* 2003). This broader perspective, and the ability to continually monitor as time goes on, is a necessity for the proper management of water bodies (Ritchie *et al.* 2003).

In summary, remote sensing is a valuable and effective tool that will be used to study the relationship between land use and eutrophication in the Tsimlyansk Reservoir.

2.3.4. Applicability of Remote Sensing for the Region

As discussed earlier in this section, there is a lack of representative data on the water quality of the Tsimlyansk Reservoir due to inconsistencies in collection and inaccessibility from the necessary organizations (Novikova *et al.* 2012; Nikanorov *et al.* 2012). As such, this region is a good candidate for assessment using remote sensing for both land use and water quality.

2.4. Technology: Geographical Information Systems (GIS)

In addition to remote sensing, much of the work done on this research was conducted using GIS technologies. This section provides a basic description of the different software packages used by the researcher.

2.4.1. GRASS GIS

GRASS GIS (Geographic Resources Analysis Support System) is a free open source GIS software package (GRASS GIS 2012). GRASS GIS 6.4.2 was used for this research. GRASS' interface is not as user-friendly as other GIS software packages, e.g. Esri's ArcGIS products, and it requires some fundamental knowledge about command line syntax to run some of the operations and to troubleshoot. The researcher had no prior experience with GRASS before the study period, but had the opportunity to be taught how to use the software on a study visit to IAMO (the Leibniz Institute of Agricultural Transition Economies) in order to see how the software could be utilized to process both vector and raster data and work with multispectral image data. In addition, tutorials and sections of the GRASS user manual were used to supplement what was learned at IAMO. For this research, GRASS was used primarily for land use classification.

2.4.2. ArcGIS

ArcGIS 9.3 is a commercial GIS software package developed by Esri, one of the world's leading geospatial software companies. It is user-friendly and is particularly good for map development and visualization. The researcher had basic experience with ArcGIS products and was able to supplement existing knowledge with user manuals and tutorials. ArcMap (one of the components of the ArcGIS package) was the main tool used for map generation and visualization.

2.4.3. Quantum GIS

Quantum GIS (or "QGIS") is another type of free open source GIS software that can perform basic data management operations and visualization. For this study, QGIS 1.8.0 Lisboa was used primarily for troubleshooting purposes and to perform basic functionalities when transitioning between GRASS and ArcMap.

2.5. Technology: Data Portals

Data portals are massive repositories of data that are made freely available online. In addition to making a vast amount of data available for download, many data portals provide visualization tools that can be used without working with the underlying data. The number and variety of data portals is continually increasing, providing free access to data in countless categories (e.g. environmental, economic, demographic), often on a global scale. Some of these data portals include the UNEP Environmental Data Explorer (UNEP 2014), The World Bank DataBank (The World Bank 2014), and the EU Data Portal (EU 2013).

A number of remote sensing-based data portals have emerged in recent years and new portals continue to emerge on a regular basis. The Giovanni web portal is a good example of this. The Giovanni web portal was developed by the Goddard Earth Sciences Data and Information Services Center of NASA (disc.sci.gsfc.nasa.gov/giovanni) and provides both visualization and download capabilities for a variety of global remote sensing data, including daily precipitation, air temperature, and soil evaporation, among a multitude of other parameters (NASA 2013a). This source of information is highly underutilized and is considered highly technical, despite its accessibility and simplicity. This research aims to collect and make use of data from this data portal, providing an example of how the source can be used in combination with remote sensing and GIS in a practical application.

3. Methodology

In order to conduct the preliminary groundwork to investigate potential agricultural-related causes of eutrophication in the Tsimlyansk Reservoir, research will be conducted in a series of steps predicated by the aforementioned research questions. Keeping in mind the overall research aims, **Figure 3** illustrates the research plan and **Table 1** details the research objectives and corresponding tasks and methods that will be used to achieve each one.

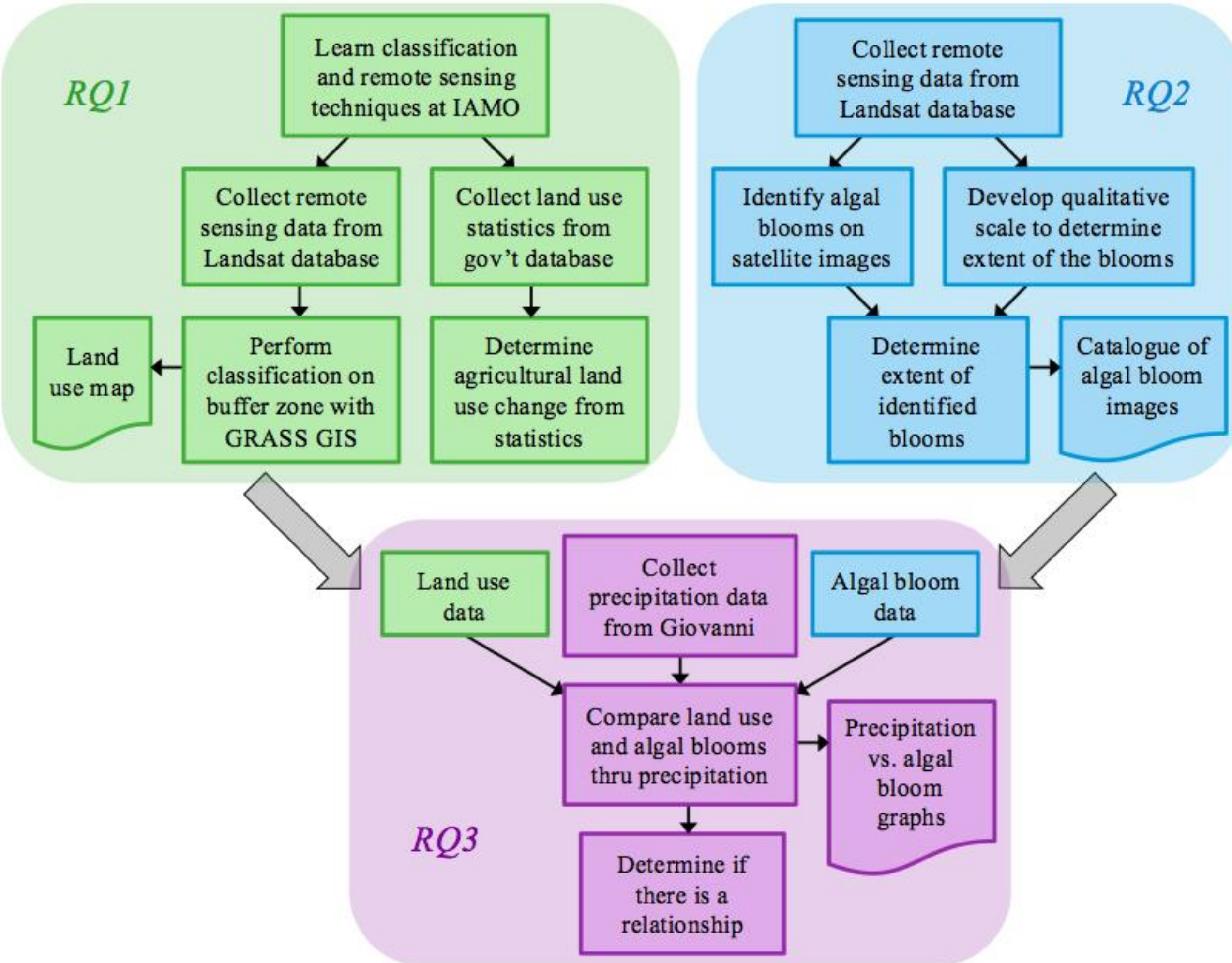


Figure 3. Flow chart illustrating the overall research plan to address the 3 research questions.

Research Question	Research Objective	Individual Task	Method
***RQ1**: What was the state of land use around the Tsimlyansk Reservoir around the time of reported harmful algal blooms? Has it changed much over the past 15 years?*	**OB1**: Obtain data indicating land use in the area around the reservoir in 2010	• Obtain satellite imagery of the region	Remote sensing
	OB2: Develop a land use thematic map of land use in 2010 that can be used as a basis for future research in the region	• Visit IAMO to learn remote sensing and land use classification techniques • Perform land use classification • Transform classification output into thematic map	Study visit, remote sensing, GIS
	OB3: Determine how land use in the area around the reservoir has changed in the past 15 years	• Obtain and analyse land use statistics for the period 1995-2010 • Obtain and analyse crop yield statistics for the period 1995-2010	Analyse statistics
***RQ2**: When and to what extent have algal blooms occurred in the Tsimlyansk Reservoir in the past 15 years?*	**OB1**: Identify instances of algal blooms in the reservoir	• Obtain satellite imagery of the reservoir in which algal bloom activity is apparent	Remote sensing
	OB2: Determine the extent of identified blooms and develop a catalogue of available data that can be used for future research	• Develop a qualitative scale to assess the extent of the algal bloom, based on concentration and size • Scrutinize images to determine extent of algal blooms	Remote sensing
***RQ3**: How can this data be used to investigate the relationship between land use and eutrophication in the Tsimlyansk Reservoir?*	**OB1**: Investigate the link between land use and eutrophication through precipitation data and determine if algal blooms occur after large episodes of precipitation	• Obtain precipitation data for the region for the period the past 15 years • Compare identified eutrophication episodes with precipitation data to determine if a relationship exists	Remote sensing, analyse statistics

Table 1. Research objectives and corresponding tasks and methods.

3.1. Current Land Use and Change (*RQ1*)

As referred to in Section 2, researchers at IAMO have worked extensively with remote sensing of land cover and land use. In order to address the first research question, the researcher conducted a weeklong study trip to IAMO in Halle, Germany, during which remote sensing techniques and proper land use classification procedures were learned and practiced (Prishchepov 2014). Based on what was learned at IAMO, remote sensing and land use classification will be applied to the study area.

To address the first objective, satellite imagery of the region surrounding the Tsimlyansk Reservoir will be obtained for the year 2010. This imagery will be used to perform a land use classification and will provide the basis for the development of a land use thematic map of the region.

After sufficient satellite imagery is obtained, a land use classification will be performed to address the second research objective. Classification is often one of the goals of processing and interpreting remote sensing data (Chuvieco and Huete 2010). To perform the classification, a number of steps will be taken, based on Chuvieco and Huete (2010). These steps are 1) training, 2) classification assignment, 3) accuracy assessment, and 4) repeat iterations, if necessary. The training stage will comprise of essentially "teaching" the classification software what types of land cover appear on the map and where through the creation of a number of polygons in each land cover class. These "trainings" will be run through GIS software and will result in a land use classification containing the predetermined land use class categories, based on the spectral signature of the pixels used in the training development. The next step will be to validate the classification output to ensure that the classification is of a reasonable accuracy. If this accuracy assessment step yields results that are not satisfactory, the trainings will be improved and the process will be repeated until the desired accuracy is achieved. The result will be transformed into a completed thematic map of the study area showing the existing state of land use and land cover, addressing the second objective. From this point, the total percentage of agricultural land within the region will be calculated, based on the land use classification output.

The third objective addresses land use change. Statistics regarding the extent of agricultural lands in the region and how this has changed over time will be obtained. If it is found that agricultural lands have greatly increased in recent years, this could be a factor of recent algal blooms in the region. But if agricultural land area has remained relatively constant, this would likely mean other factors are involved.

3.2. Eutrophication in the Tsimlyansk Reservoir (*RQ2*)

The next step will be to determine what has been happening regarding eutrophication in the reservoir in the past 15 years. To do this, the first objective will aim to identify instances of algal blooms in the reservoir. This will be done by browsing through satellite imagery to identify algal bloom events, which are easily seen via satellite, as seen in **Figure 4**. The result of this search will be a list of dates in which an algal bloom of some extent was present in the reservoir, which will fulfil the first objective.

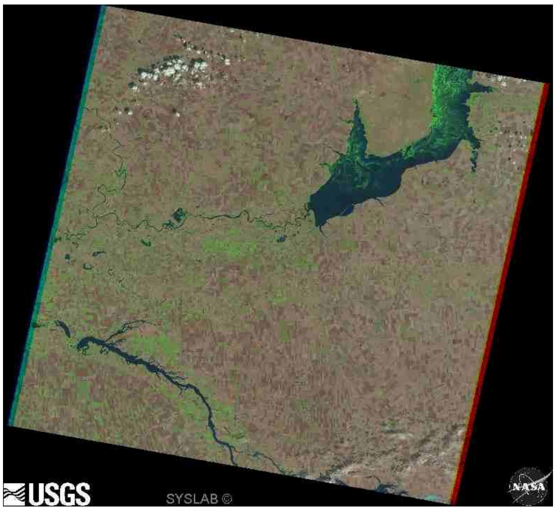


Figure 4. Example of algal bloom in satellite imagery. (USGS 2014).

To address the second objective, the next step will be to scrutinize the collected images to determine the extent of the algal bloom in the reservoir. A basic scale will be developed (e.g. Low-Medium-High) to evaluate the bloom's extent in each image.

3.3. Investigating the Relationship (*RQ3*)

After both land use change and eutrophication events (used interchangeably with "algal blooms") have been determined and identified, the next step will be to investigate an example of how this data can be used in various applications to attempt to determine a causal link between the two components

There are numerous factors involved in the development of algal blooms (Bellinger 2014). In order to provide an example of how to investigate the relationship between land use and algal blooms, one of these factors (precipitation) will be singled out and explored. The objective for this third research question aims at investigating the link between land use and eutrophication through precipitation data. Precipitation events can stimulate the movement of agricultural runoff, comprising of nitrogen and phosphorus from fertilizers, into water bodies (Reichwaldt and Ghadouani 2012; Chorus and Mur 1999; Spatharis *et al.* 2007; Heisler *et al.* 2008; Glandon *et al.* 1981). Thus, the objective will be aimed at investigating this phenomenon by looking at precipitation for the period of study and seeing if satellite-identified algal blooms tend to occur after large events of precipitation. This will be achieved by obtaining precipitation data for the region and graphing it against identified these major eutrophication events to ascertain the relationship, if any, between the two components.

3.4. Deliverables

As discussed in Section 1, one of the primary aims of this research is to develop a foundation upon which further research in the region can be based upon. In order to do this, a number of deliverables will be developed through these steps that will be standalone results from the study and will be able to be used for further research. Some of these will be published online and be made freely available to the public. The deliverables that will be developed will include:

- Detailed land use map of the study area, resulting from land use classification
- List of all available Landsat imagery available for May to October 2008-2012 (+/-2 years of the intended study year) with satellite and cloud cover information
- Visual catalogue of eutrophic algal blooms identified through satellite imagery
- List of eutrophic algal blooms with determined extent

4. Results and Analysis

This section provides the specific steps taken to answer the research question, as well as discuss the results obtained. Like the Methodology chapter in Section 3, each main section addresses one of the research questions.

4.1. Analysis of Land Use and Land Use Changes (*RQ1*)

The first research questions (*RQ1*) aim at determining both the state of land use around the time of documented harmful algal bloom instances by performing land use classification and investigating how, if at all, land use, particularly the amount of agricultural lands, has changed over time. Another main goal of this first section is to develop a land use thematic map of the region, which can be used as a foundation for future research.

4.1.1. Land Use Land Cover Classification

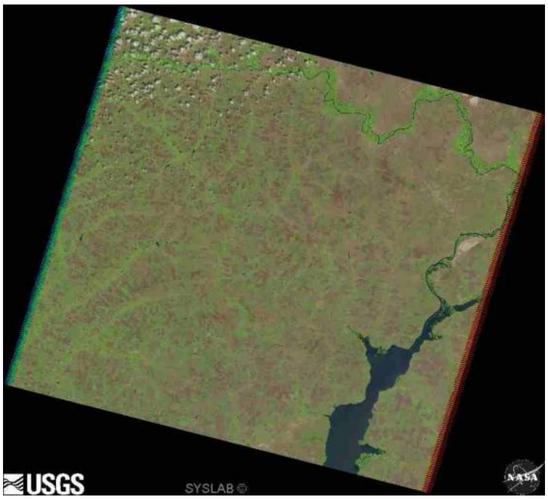
The first steps in addressing *RQ1* are to obtain satellite imagery and perform a land use classification to develop a land use land cover map to determine the extent to which agricultural lands cover the area of study. This technique was learned at IAMO, practiced, and then performed for the study area (Prishchepov 2014). The appropriateness of using this technique to determining land use is discussed in Section 3. But before classification could be done, a number of steps had to be taken to prepare the data.

Selection of Landsat Tiles

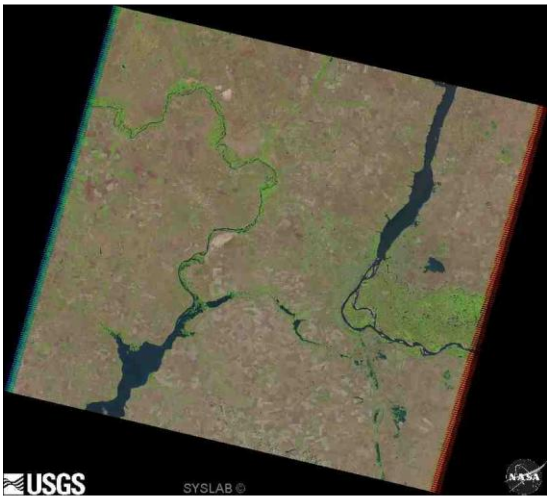
Based on information derived from the literature review on remote sensing in Section 2, the Landsat program has produced the most consistent set of high-quality satellite imagery for the past few decades. As such, the Landsat database was used to obtain satellite imagery footprints of the area surrounding the Tsimlyansk Reservoir. Landsat images were obtained from the U.S. Geological Survey database (glovis.usgs.gov). Images were selected based on the 1) time of year, 2) satellite, and 3) cloud cover. Since the main type of land use in the region is cropland, the important dates for analysis fall within the agricultural season (May to October) and as such, images from only this time period were considered for selection. As discussed in Section 2, the Landsat-7 satellite was damaged in 2003, rendering images from it unusable. Because of this, only images from the Landsat-5 program (Thematic Mapper) considered. And finally, only those images with little or no cloud cover were selected, as clouds can interfere with the proper classification of satellite imagery.

Four tiles were selected, as seen in **Figure 5**, that adequately covered the reservoir and surrounding area for two dates, one at the beginning of the growing season (June-July) and one towards the end of the growing season (August), as shown in **Table 2**. While it would be ideal to have the four tiles on the exact same date, this was not possible due to 1) existence of and download capabilities of the data, because the tiles are in two different satellite scanner paths and thus do not have the same date availability and 2) quality of data, because many images were obscured by clouds. **Appendix Figure 1** shows a catalogue of all Landsat tiles from 2008-2012 (+/- 2 years of the study period) to show the limited availability of suitable images for remote sensing analysis. This list was made available online on the Azov Center website at http://azovcenter.ru/tsimlyansk-landsat, which can be seen in **Appendix Figure 2**. Regarding cloud cover, as seen in **Table 2**, tile 172/027 for 08/15 has a cloud cover of 7%, which is higher than was aimed for. But the clouds were mostly far away from the reservoir and would mostly be cropped out by the buffer zone, which was applied in the next step. As such, this tile was deemed adequate for use in the classification process.

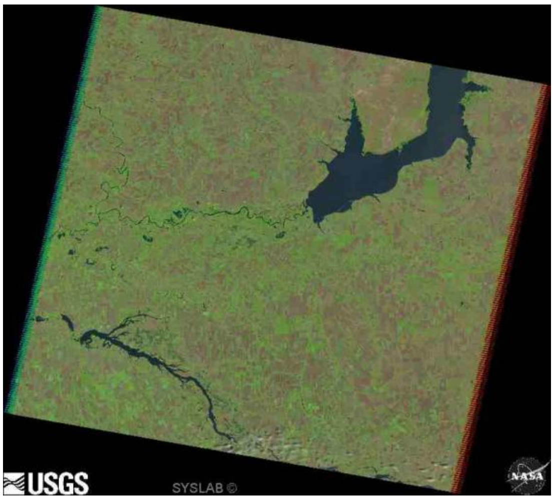
Tile 173/026



Tile 172/026



Tile 173/027



Tile 172/027

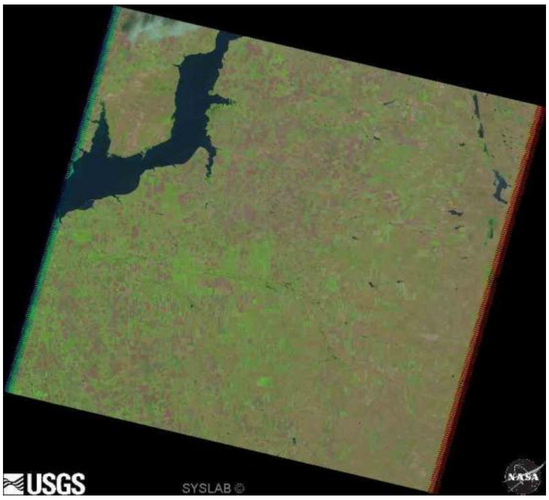


Figure 5. Four Landsat tiles selected for land use classification. (USGS 2014).

Date 1				Date 2			
Path/Row	**Date (2010)**	**Cloud Cover**	**Satellite**	**Path/Row**	**Date (2010)**	**Cloud Cover**	**Satellite**
173/027	06/19	0%	LT5	173/027	08/22	0%	LT5
173/026	06/19	1%	LT5	173/026	08/22	0%	LT5
172/026	07/14	0%	LT5	172/026	08/15	0%	LT5
172/027	06/12	1%	LT5	172/027	08/15	7%	LT5

Table 2. Eight Landsat tiles selected for land use cover classification. Data source: (USGS 2014)

Preparation of Landsat Tiles

The Landsat 5 Thematic Mapper tiles, each of which is 170 km x 185 km in size, contain 7 spectral bands, as detailed in **Table 3**.

Band	Wavelength	Resolution
Band 1	Visible (0.45 – 0.52 μm)	30 m
Band 2	Visible (0.52 – 0.60 μm)	30 m
Band 3	Visible (0.63 – 0.69 μm)	30 m
Band 4	Near-Infrared (0.76 – 0.90 μm)	30 m
Band 5	Near-Infrared (1.55 – 1.75 μm)	30 m
Band 6	Thermal (10.40 – 12.50 μm)	120 m
Band 7	Mid-Infrared (2.08 – 2.35 μm)	30 m

Table 3. Landsat 5 Thematic Mapper band characteristics. Data source: (USGS 2013).

As can be seen in **Table 3**, the Thermal infrared band (Band 6) is the only one with a resolution of 120 m, far less accurate than the 30 m resolution of the other bands. For this reason, Band 6 was not included, and only Bands 1-5 and 7 were used in classification and analysis. This practice can be seen in a number of land use classification studies (Heinl *et al.* 2009; Abd El-Kawy *et al*. 2011). The band-layering combination used for analysis was 4-5-3, a common band combination for Landsat imagery known as one of the “false colour” combinations, which combines two near-infrared and one visible band.

The Landsat tiles, and all later GIS files were projected in the WGS_84 UTM Zone38N geographic coordinate system, which was the automatic coordinate system of the majority of the tiles. This projection was used for all GIS files, except when exporting files to Google Earth, in which files had to be re-projected into WGS_84 to be compatible with the software.

In order to perform the classification, the four tiles were merged into two different mosaics, one for each date (Date 1 and Date 2, the sets seen in **Table 2**). QGIS was used to merge the tiles into one image, complete with all 6 bands being used in the classification. The next step was to clip out the desired area around the reservoir.

Phosphorus from agricultural runoff, one of the main nutrients associated with eutrophic algal blooms, can travel up to 50 miles (approximately 80 kilometres) from an agricultural field to a water body. Nitrogen's potential travel distance, the other main nutrient that causes algal blooms, is much harder to estimate because it is very mobile and easily changes form (American Farmland Trust 2013). Based on the approximation of phosphorus travel potential (and the difficulty of attributing a numeric approximation to nitrogen travel), a buffer zone of 80 km was chosen to surround reservoir. This buffer zone was developed using the ArcMap buffer tool and was used to clip the Landsat mosaics using QGIS to be used in the classification, as seen in **Figure 6**. Because of the importance of obtained detailed land data to study environmental phenomena (Heinl *et al.* 2009), the entire area around the reservoir is of interest. The buffer zone around the reservoir encompasses two oblasts, Rostov and Volgograd, as seen in **Figure 7**.

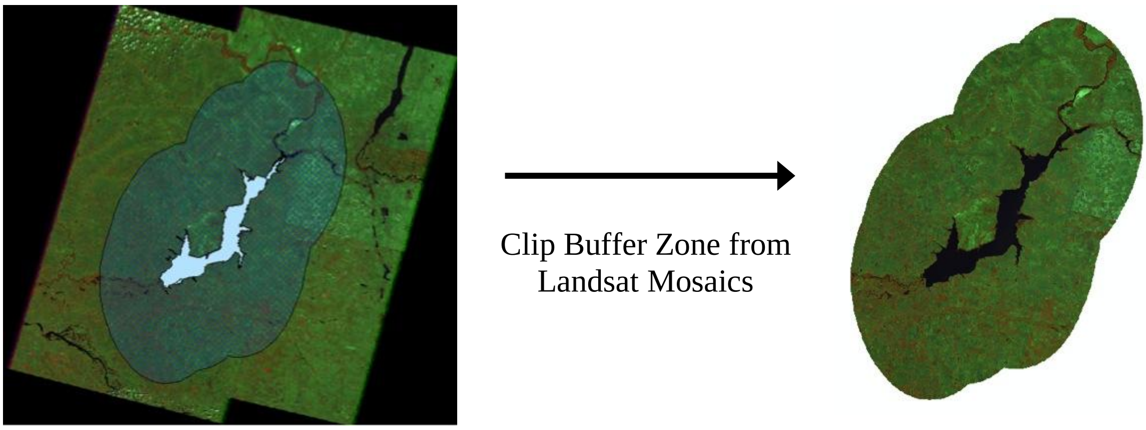


Figure 6. Clipping the 80 km buffer zone, developed in ArcMap, from the Landsat tile mosaics.

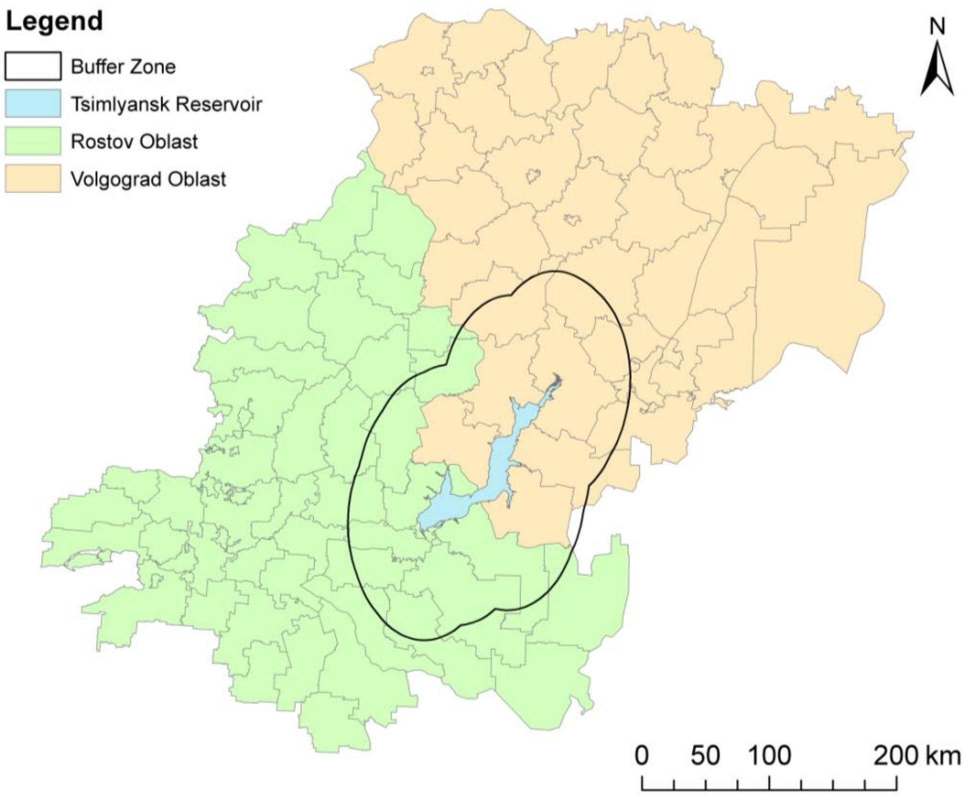


Figure 7. Buffer zone around the reservoir encompassing parts of Rostov and Volgograd oblasts. (Map created by author).

Training

As discussed in Section 3, the first step in the classification process is training. Five predominant land use land cover classes were determined, based on assessment of satellite imagery and discussions with academics whose research includes agricultural land and land use changes in this region (Prishchepov 2014). These five classes are found in **Table 4**.

#	Class	Additional Description
1	Agriculture	Cropland
2	Forests	Forested areas Trees
3	Grasslands	Sparse shrublands Fallow fields
4	Other	Impervious surfaces Barren land Urban areas
5	Water	Water bodies

Table 4. Land use land cover classes for classification.

Next, using high-resolution images from Google Earth, at least 100 training polygons, each containing at least 3 pixels, were manually drawn in each of the five land classes and attributed a number, as seen in **Table 4**. An example of the development of training polygons can be seen in **Figure 8**.

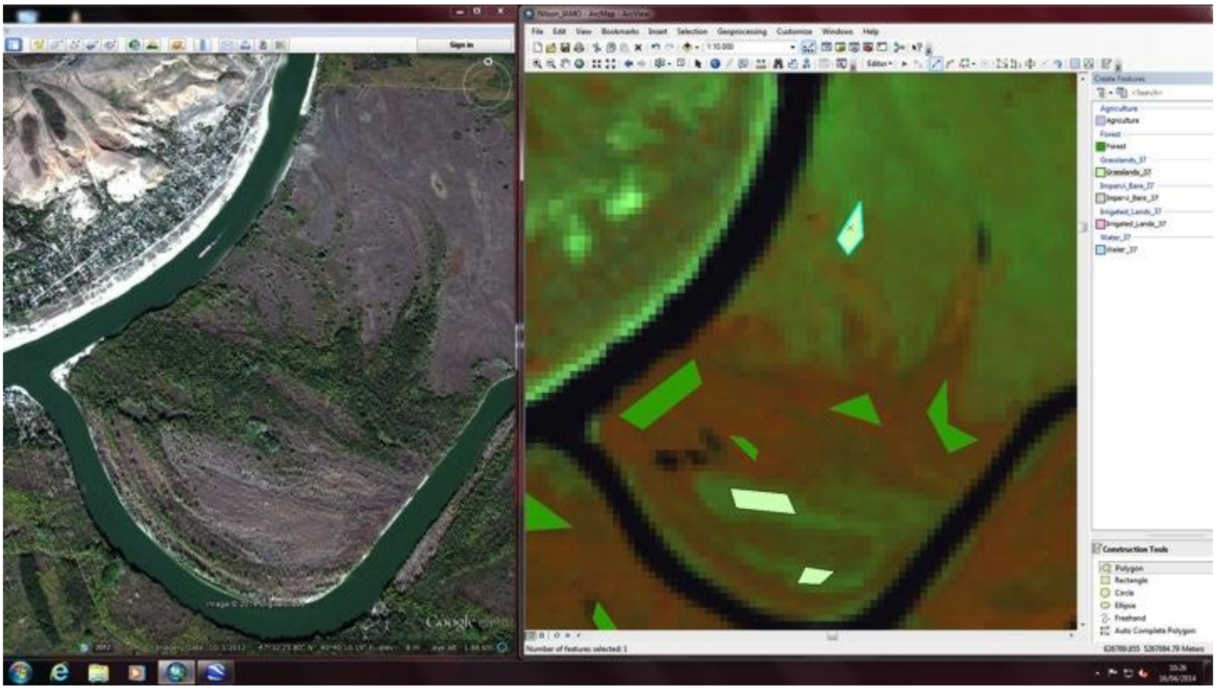


Figure 8. Screenshot taken while developing training polygons using high-resolution images on Google Earth and ArcMap.

According to Chuvieco and Huete (2010), many authors suggest that the number of training pixels per category should at least fall within 10*m* and 100*m*, "*m*" being the number of spectral bands being used in the classification, which for this study was 6. As such, the number of polygons and pixels satisfies this criterion. When developing the training polygons, priority was given to high-resolution images on Google Earth from June-August 2010 to coincide with the precise time of the satellite images, but these were often not available using the Google Earth historical imagery tool. When those were not available, images within +/- 2 years were used, and if those, too, were not available, the standard Google Earth satellite imagery was used, rather than the historical imagery. As will be discussed in the next section, it was determined that land use, particularly agricultural land area, has not changed very much over time. As such, using satellite images that are not from the exact time period under study was deemed adequate. While the trainings were predominantly based on the Google Earth satellite images, it was helpful to compare the two different Landsat tile dates in ArcMap to determine the accurate identification of certain classes, e.g. agriculture. For agricultural fields that are in use, the spectral signature is different in June than it is in August, when, for example, fields are covered in crops and then later harvested, as seen in **Figure 9**. The ability to see these dynamics on the Landsat tiles aided in the proper identification of existing agricultural lands, versus fallow fields.

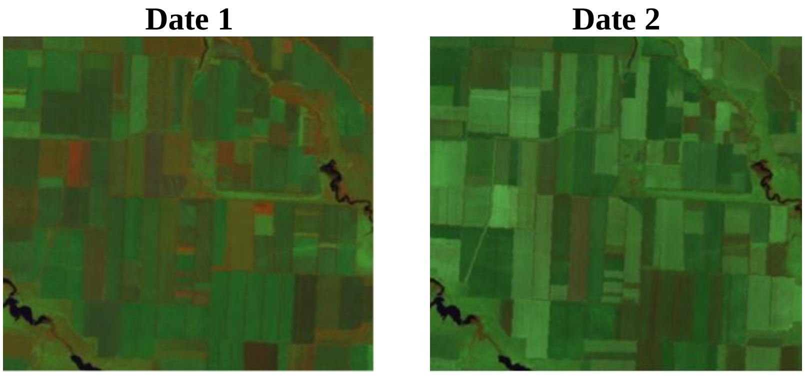


Figure 9. Comparison of spectral signatures of agricultural land in June versus August. (USGS 2014).

Classification

There are a number of classification algorithms, both traditional and advanced, for land use land cover classification (Lu and Weng 2007). These algorithms vary in complexity, accuracy, and computational time and fall into two categories 1) supervised and 2) unsupervised. Supervised classification assumes some existing knowledge of the study area, which the user can utilize to determine the most appropriate land use classes. Unsupervised classification implies no previous knowledge of the area and instead relies on the classification algorithm to determine clusters of homogenous spectral characteristics, which the user will categorize and define later (Chuvieco and Huete 2010). While supervised classification is often preferred for land use classification (Heinl *et al*. 2009), both types have been found to be successful when used either alone or in combination (Rozenstein and Karnieli 2011). The most widely used and well-known supervised algorithm (Chuvieco and Huete 2010; Otukei and Blaschke 2010), is called the maximum likelihood classification (MLC) and is what will be utilized in this study. Maximum likelihood is one of the traditional classification algorithms that is based on statistical probabilities and that relies upon an assumption of normally distributed data, which remote sensing data often satisfies (Chuvieco and Huete 2010).

GRASS GIS was used to perform the classification, but in order to do so, the data had to be prepared in a certain way. The Landsat mosaics were imported into GRASS and grouped together into one file using the GRASS command [i.group]. The resulting file contained 12 layers (2 mosaics, 6 bands each). The training files (5 in total, one for each class) were merged together into one file that noted the numeric value of their land use class, as noted in **Table 4**, and then imported into GRASS and converted from vector file type to the required raster file format. Next the command [i.gensig] was run to develop what GRASS calls "signatures" (their term for "trainings"). The MLC was then run using GRASS [i.maxlik] with the following inputs: 1) Group: combined Landsat mosaics, 2) Subgroup: combined Landsat mosaics, 3) Sigfile: the signatures that had been developed with the training files, 4) Class: the name of the output file, which will contain the results of the MLC. The classification took approximately one hour, which produced a file that could be exported to raster format and then imported into ArcMap for viewing. The classification output, seen in **Figure 10**, exhibited an obvious delineation between the two right-hand and two left-hand tiles, a result of the tiles being from different dates and not generating ample training polygons in these two tiles to highlight the variation in spectral signatures among the tiles and dates for each of the five classes.

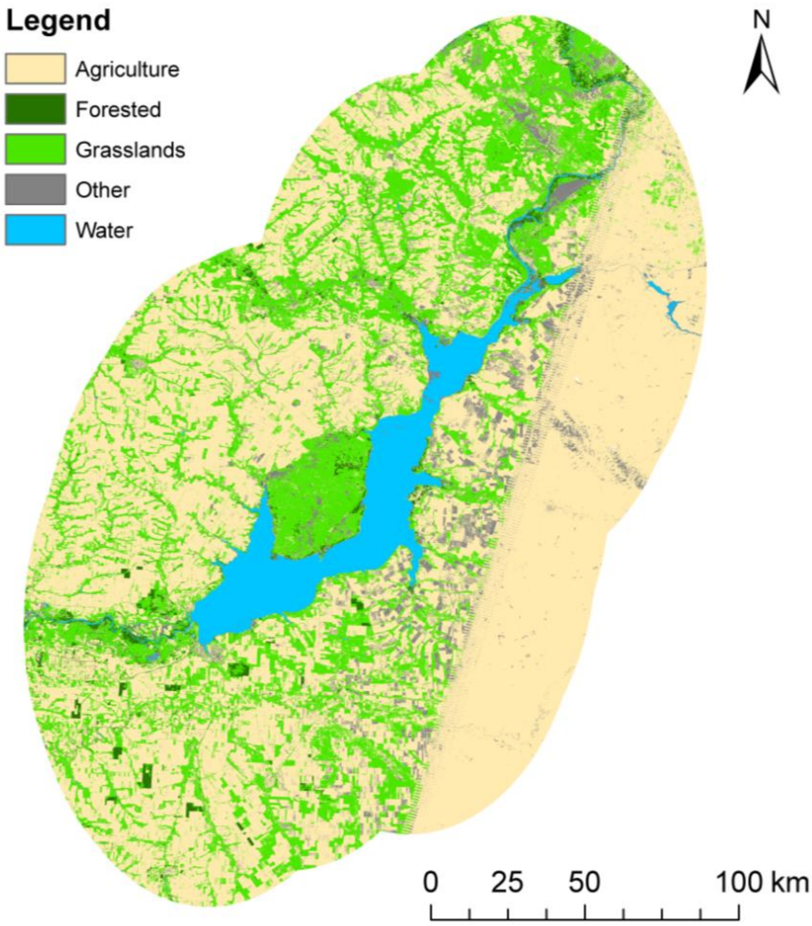


Figure 10. First (and unsuccessful) MLC output viewed in ArcMap. (Map created by author).

As discussed in the previous section, the last step in the classification process typically includes repeat iterations to improve the classification and resulting accuracy, which is done after the validation and accuracy assessment have been completed, which had not yet been done for this research. But since the problem was fairly obvious, it was decided to return to the training development without performing these other two steps first, knowing that the accuracy would be quite low. More polygons were developed, primarily in the left-hand two tiles, for each of the five classes. The total number of polygons and pixels for this second (and final) attempt can be found in **Table 5**. As illustrated in the table, the number of pixels per class is above and beyond the aforementioned requirement of at least 10*m* to 100*m.*

#	Class	Polygons	Pixels
1	Agriculture	215	149,110
2	Forests	129	2,150
3	Grasslands	206	5,482
4	Other	139	1,452
5	Water	183	98,655

Table 5. Number of polygon trainings and pixels developed for the second classification.

After these additional trainings were developed, the MLC was run again using the aforementioned process in GRASS GIS. The classification output from the second attempt can be seen in **Figure 11**.

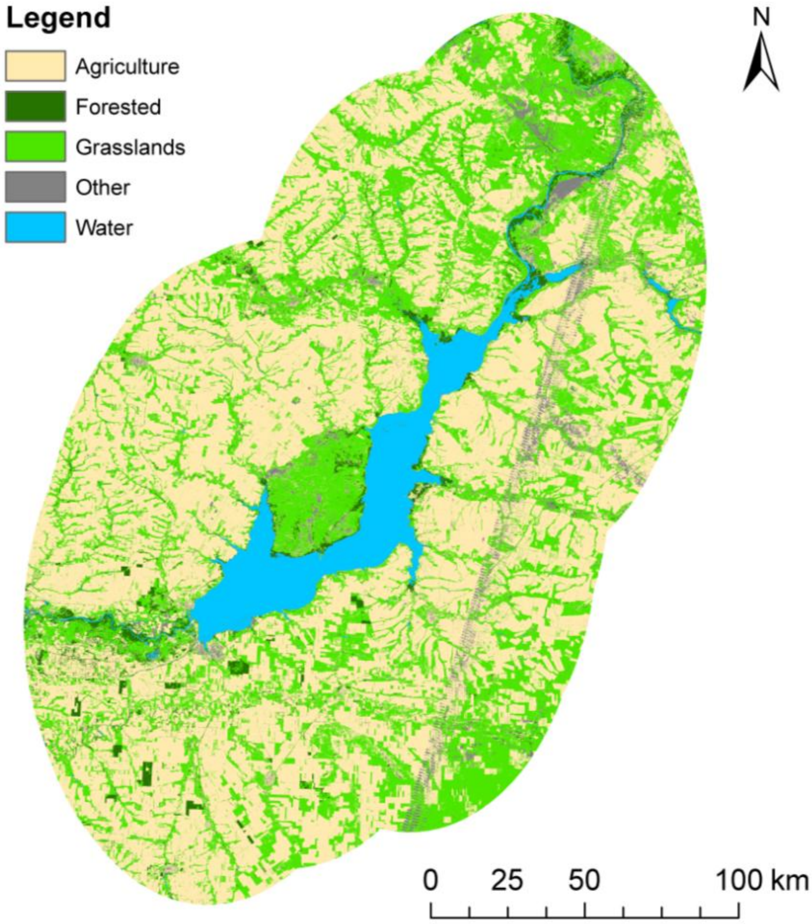


Figure 11. Second (and final) MLC output viewed in ArcMap. (Map created by author).

Unlike the first output, the second MLC output didn't exhibit the sharp delineation between tiles. There is a slight line (in grey, part of the "other" category) visible due to the mosaicking process and the rough edges on the Landsat tiles, but it did not end up impacting the integrity of the classification accuracy, which is discussed in the next section.

Accuracy Assessment

Due to the inherent complexity of classification, it is recommended that an accuracy assessment be performed in order to evaluate the accuracy of the classification output to a higher and more reliable degree than mere visual assessment (Congalton 1991). Accuracy assessment encompasses sampling, validation, and development of accuracy statistics.

Sampling

The two most common types of sampling methods for land use classification accuracy assessment are simple random sampling and stratified random sampling. Stratified random sampling ensures that a minimum number of samples are chosen from each "strata" or, in this case, land use classes. Since there are some classes representing small areas (e.g. the "other" category that includes barren land and impervious surfaces), this method was chosen so these categories would not be underrepresented as they would likely be with simple random sampling (Congalton 1991). According to Congalton (1991), for large areas of land encompassing more than one million acres (approximately 4,000 km^2), which is true of the study area, at least 75 or 100 samples should be chosen per land use class. The number of samples for each land use class can be altered if there are classes of particular interest or importance to the classification objectives (Congalton 1991). In accordance with Congalton (1991), a total of 200 samples were generated for the agriculture class, which is of particular interest to the classification because it will be tied to agricultural statistics and thus should be ensured that the classification is done with a higher rate of accuracy. A total of 400 samples were generated for the four non-agriculture classes, totalling 600 points overall, yielding at least 100 points per class.

The samples were developed by generating random points using GRASS GIS command [r.mask]. The “mask” function was used to select only the agriculture class, for which 200 points were allocated, and then used again to select non-agricultural classes, for which 400 points were allocated. These points were exported in vector file format and imported into ArcMap and then converted into KML file format to be used concurrently in Google Earth. **Figure 12** shows the random points that were generated, blue for the agriculture class, yellow for the non-agricultural classes.

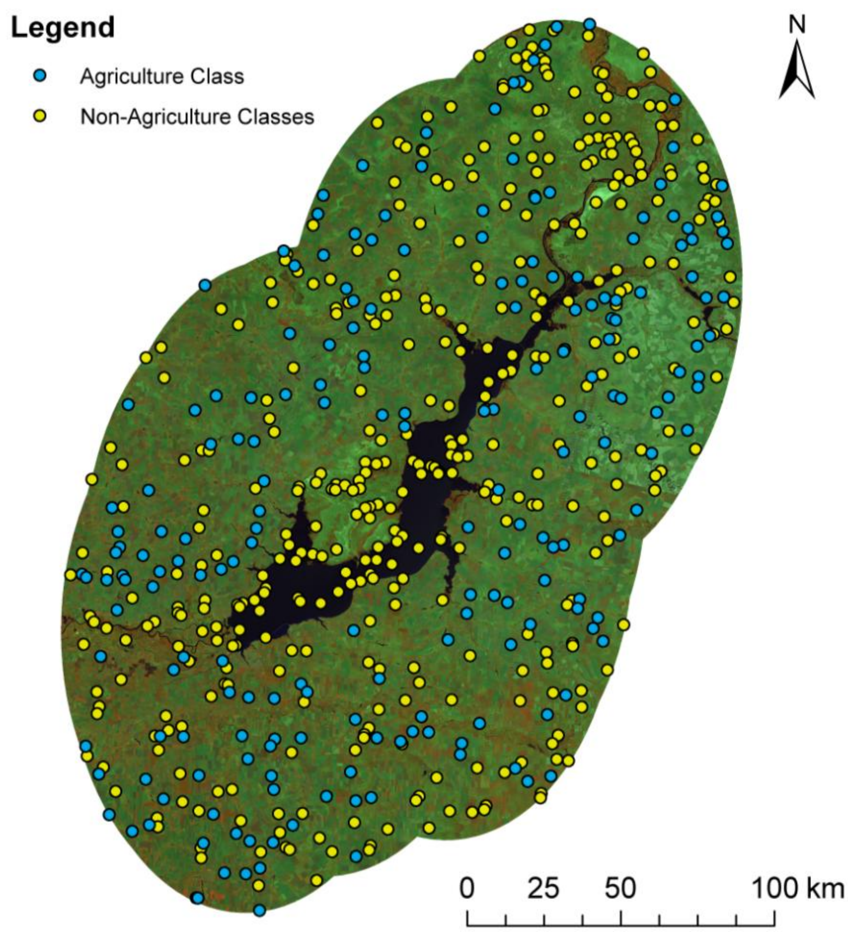


Figure 12. 600 random points used for classification validation. (Map created by author).

Validation

The next step included scrutinizing each individual sample (random point) using high-resolution images on Google Earth and the Landsat satellite images in ArcMap to determine which land use land cover class it belonged to. See **Figure 13** and **Figure 14** for a visual representation of this process.

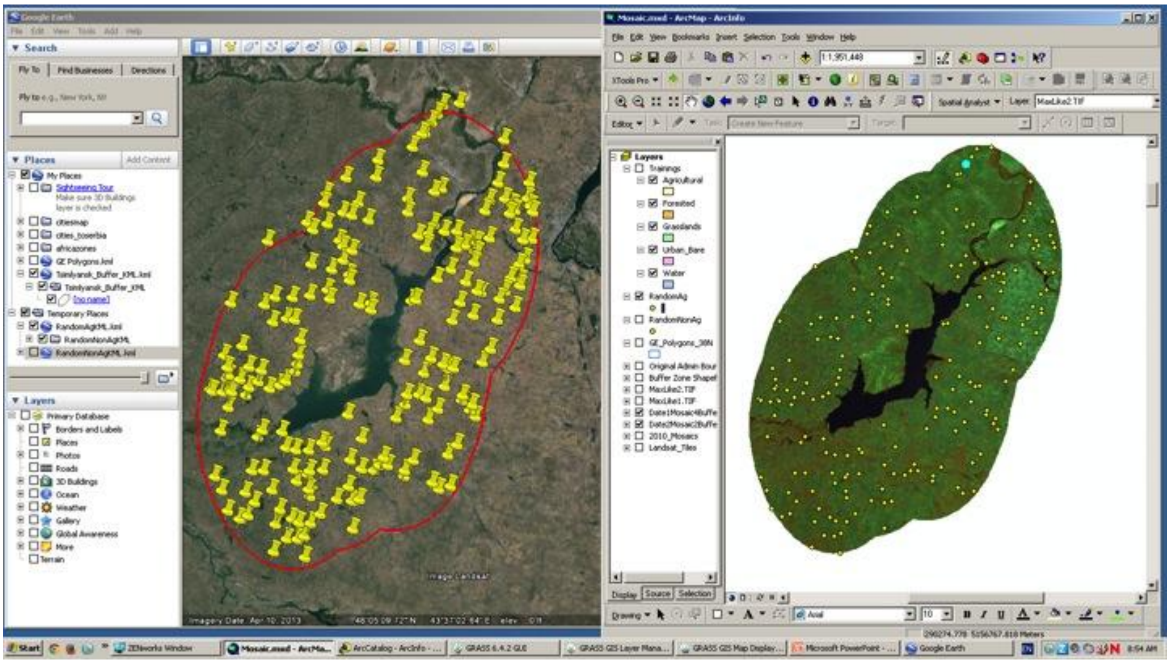


Figure 13. Screenshot taken while conducting random point validation using Google Earth and ArcMap.

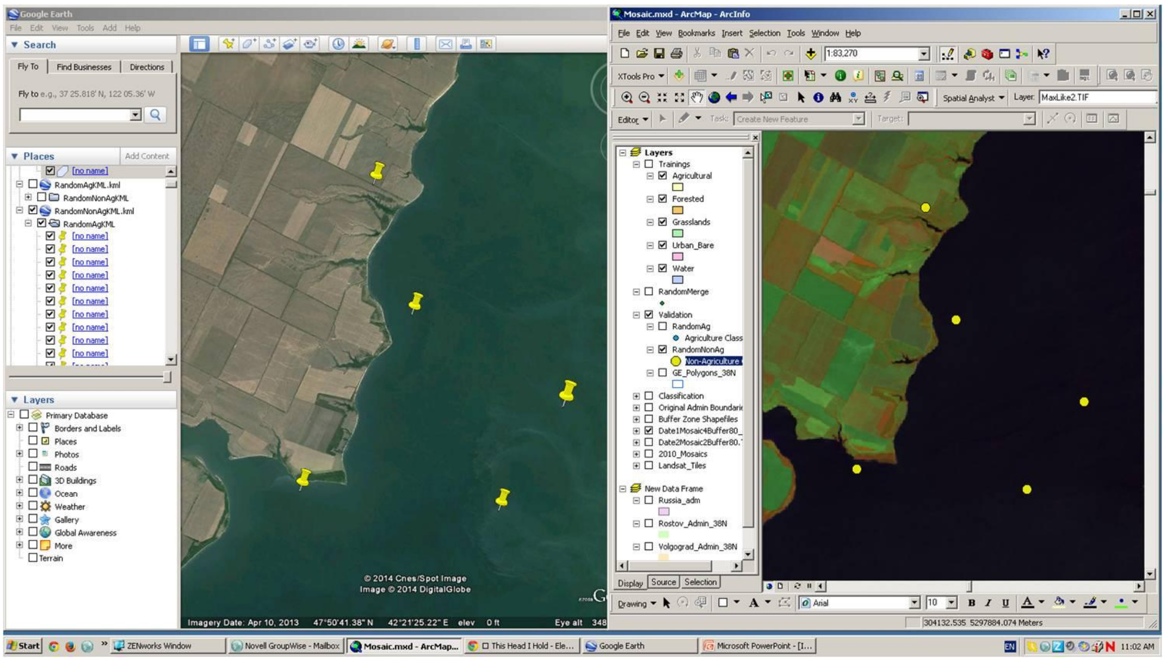


Figure 14. Screenshot taken of a zoomed in representation of random point validation using Google Earth and ArcMap.

For each individual point, the actual land cover class was documented (using the numerical categories in **Table 4**) in the attribute table of the random points GIS shapefile. Points that were either too close to borders to ascertain what the proper land class was were given the value 999. Those that were obscured by minor cloud cover were given 444. Points that appeared close together were measured to ensure they were at least 500 m apart so as not to have samples that were too close to each other. The total number of points per class that were sampled is found in **Table 6**. The validated sample files were merged together with QGIS, excluding the points identified as '444' or '999', for a total of 532 sample points, still greater than the recommended 100 points per class.

Category	Class or Description	Number
1	Agriculture	189
2	Forests	25
3	Grasslands	250
4	Other	11
5	Water	57
444	Obscured by clouds	5
999	Border, cannot confidently determine	63

Table 6. Points per class sampled in the classification process.

Assessment

To determine accuracy statistics for the land use land cover classification, a Kappa Analysis was performed using GRASS GIS command [r.kappa]. This analysis provides overall accuracy statistics, an error matrix, and the Kappa statistic. The use of an error matrix is the most common way to represent accuracy statistics resulting from classification (Congalton 1991; Foody 2002). The output from the accuracy assessment including all of these parameters is shown in **Figure 15**. The desired overall accuracy for land use land cover classification is at least 85% (Thomlinson *et al.* 1999).

	Class 1 (Agriculture)	**Class 2 (Forested)**	**Class 3 (Grasslands)**	**Class 4 (Other)**	**Class 5 (Water)**	**Total**
Class 1	**178**	0	6	0	0	184
Class 2	0	**25**	1	0	0	26
Class 3	10	0	**241**	0	0	251
Class 4	1	0	2	**11**	2	16
Class 5	0	0	0	0	**55**	55
Total	189	25	250	11	57	**532**

	Commission	**Omission**	**Estimated Kappa**
Class 1 (Agriculture)	3.26%	5.82%	0.95
Class 2 (Forested)	3.85%	-	0.96
Class 3 (Grasslands)	3.98%	3.60%	0.92
Class 4 (Other)	31.25%	-	0.68
Class 5 (Water)	-	3.51	1.00

Figure 15. Kappa analysis output: error matrix.

The error matrix in **Figure 15** shows the classification output in rows and validated points in columns. The bolded numbers going diagonally show the number of points the classifier classified correctly for each class. As an example, in the first row, the classifier correctly classified 178 points in the agriculture class, but it also classified 6 points as agriculture that were actually in the grasslands class. These data are summarized in the commission (errors of inclusion) and omission statistics (errors of exclusion) in **Figure 15** (Congalton 1991). For Class 1 (Agriculture), the commission error is 6 / 184 = 3.26%. There were 6 points that were incorrectly *included* in the agricultural class, but that were actually grasslands. And the omission error for Class 1 is 11 / 189 = 5.82%. There were 10 points the classifier thought were grasslands and 1 point the classifier thought was in the “other” class that were actually agriculture, so these points were incorrectly *excluded*. The commission error for Class 4 (Other) is higher than the others, but this class represents a very small portion of the study area and did not greatly impact the overall accuracy for the classification.

The overall accuracy was 95.86%, calculated by the total correct observations (510) divided by the total observations (532). The Kappa statistic was 0.94, also indicating the suitability of the classification. The Kappa statistic is a well-known and utilized parameter in accuracy assessment of land use classification (Otukei and Blaschke 2010; Heinl *et al.* 2009; Abd El-Kawy *et al.* 2011; Rozenstein and Karnieli 2011). It takes into consideration pixels that have been properly classified due to random chance rather than proper classification (Chuvieco and Huete 2010; Foody 2002) and is a metric of the accuracy and suitability of the classification output. A value of 1 is perfect, so the obtained value of 0.94 is very good.

Result of Classification

Because the desired level of accuracy was exceeded for the classification, no repeat iterations were deemed necessary. To calculate proportional land use class statistics, raster statistics were calculated using the "Build Raster Attribute Table" tool in ArcMap. Within the study area, the classification found the following proportions for each land class: 57.0% Agriculture, 3.1% Forested, 31.3% Grasslands, 2.8% Other, and 5.7% Water. The next step was to transform the classification output into a thematic land use map, which is described in the next subsection.

4.1.2. Development of a Land Use Thematic Map

Since the land use classification accuracy was found to be adequate, this information was used to generate a final thematic map showing land use in the study area using ArcGIS. The map was originally created using the 80 km buffer zone around the entire reservoir. If the map were to be used in actual runoff modelling, a modified buffer zone can easily be applied, as was done as an example in the final map. When used in runoff modelling, there is a low likelihood that runoff from below the reservoir would make its way up to it. This does remain a possibility, due to the constant back-and-forth movement of water at the base of the reservoir from transportation and shipping, but its effects are not likely significant. As such, a modified buffer zone was applied to the final map, which can be seen in **Figure 21**.

4.1.3. Determination of Agricultural Land Use Change

The last step in addressing *RQ1* is to examine how land use has changed in the region in recent years. Since the land use of interest is agricultural land (cropland), statistics were obtained from the Russian Federal Service of State Statistics providing the total area of croplands from 1995 to 2009 (statistics from 2010 were not available) in the Rostov and Volgograd oblasts, which can be seen in **Appendix Figure 3** (ROSSTAT 2010).This data was compared to the total land area of each region (National Census 2014) to determine the percentage of agricultural lands within each oblast for the period, as seen in **Figure 16**.

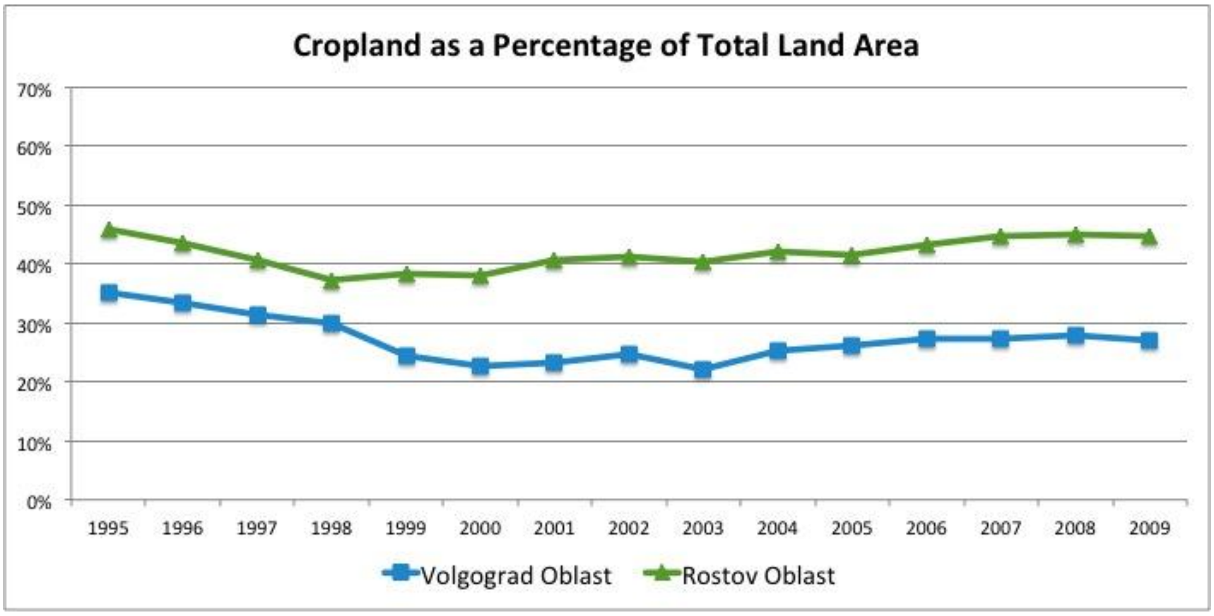


Figure 16. Cropland as a percentage of total land area, 1995 to 2009. Data source: (ROSSTAT 2010)

As seen in **Figure 16**, the proportion of cropland in both Rostov and Volgograd oblasts has stayed relatively constant since 1995. It must be noted that these statistics are at the oblast level, and are thus representing a larger area than the area under study (80 km around the reservoir). But because there has not been much change overall and because the land use classification determined agricultural lands constituted approximately 57.0% of the total study area, this data is assumed to be representative of the study area.

Another indication of the use of agricultural lands is through crop yield data. Crop yield statistics were obtained for a number of area crops, also from the Russian Federal Service of State Statistics, at the oblast level, for the period between 1995 to 2009 (ROSSTAT 2010). During this time, grain and forage crops have made up a substantial amount (ranging from 70-80%) of the sown area in these two regions, as seen in **Figure 17**. Because of the dominance of grain and forage crops in the area, yields from these crops were investigated.

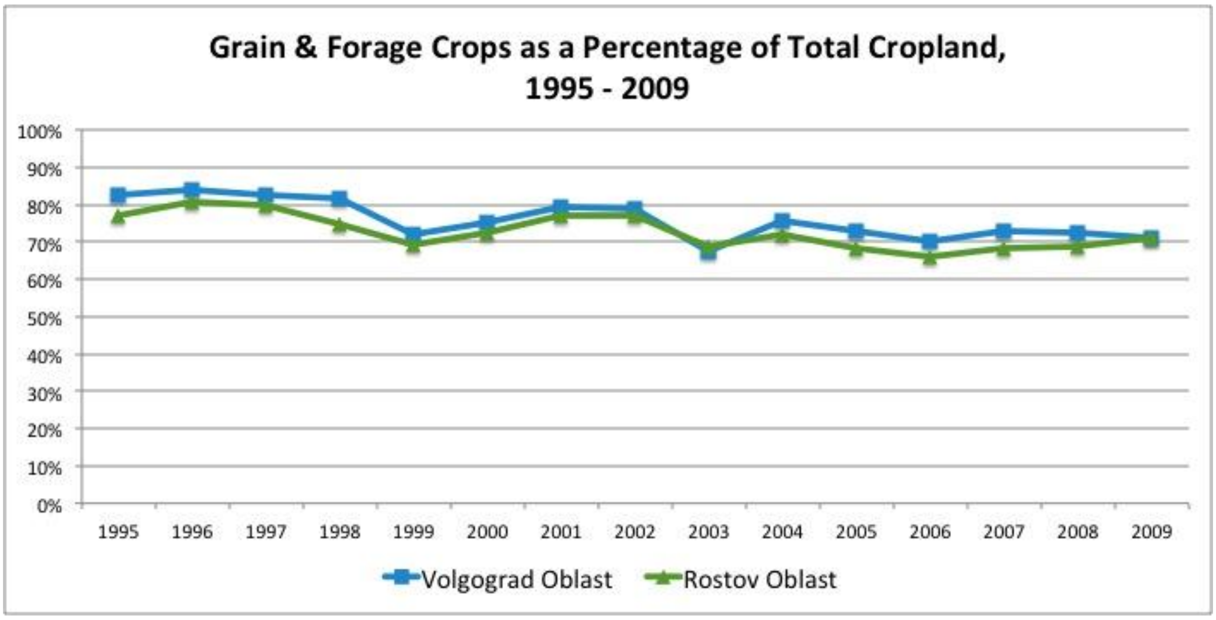


Figure 17. Grain and forage crops as the predominant crops in the region. Data source: (ROSSTAT 2010)

Crop yield data was obtained at the oblast level for 9 grain and forage crops: annual grass hay, barley, grain, oats, perennial grass hay, spring wheat, winter wheat, and sugar beets. Crop yields for the first 8 crop types are shown in **Figure 18** for Volgograd and **Figure 19** for Rostov. Sugar beets were graphed separately in **Figure 20** because the yield is measured in quintals per hectare, which is a value of mass. Sugar beets have a higher mass than other grain and forage crops, e.g. winter wheat, and are more easily viewed with a different vertical axis.

While there is apparent fluctuation of the crop yields for the period and an overall increase in a few of the crops' yields (e.g. grain and winter wheat), some of the crop yields remained relatively constant for the period. Crop yields can fluctuate on a yearly basis based on the climatic and meteorological conditions, as well as on the application of and timing of fertilizers. In order to make a conclusion on the crop yields and their potential effect on agricultural land use, more information, e.g. fertilizer application statistics, would need to be obtained for the entire region, which was not available at the time of research.

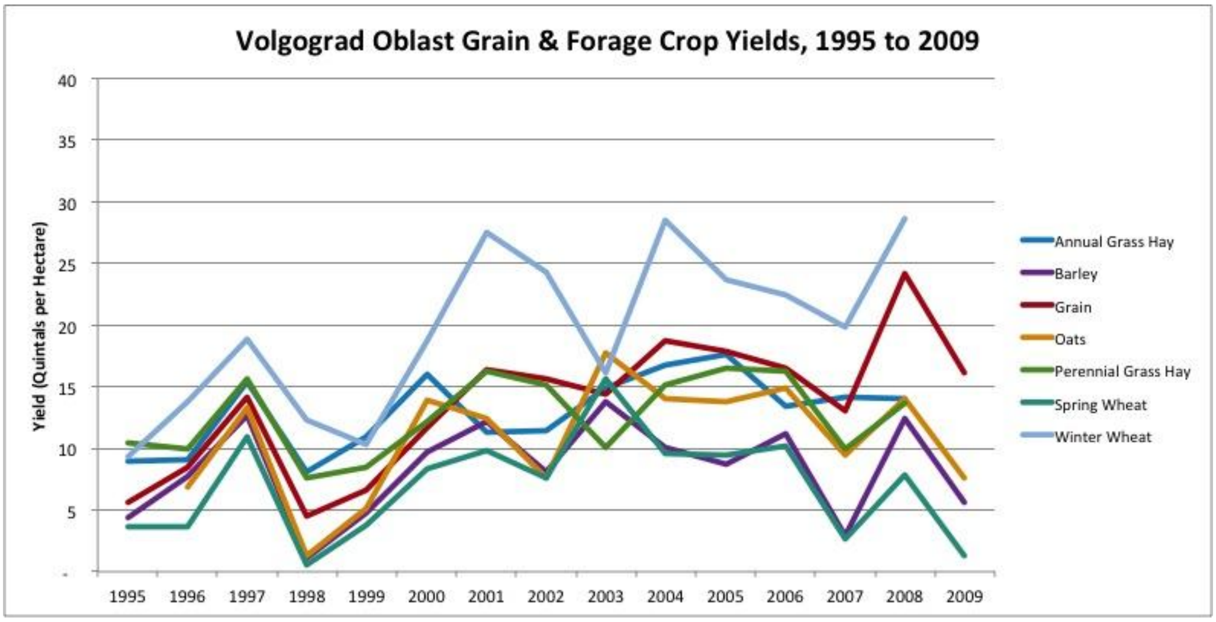


Figure 18. Volgograd grain and forage crop yields (excluding sugar beets) from 1995 to 2009. Data source: (ROSSTAT 2010)

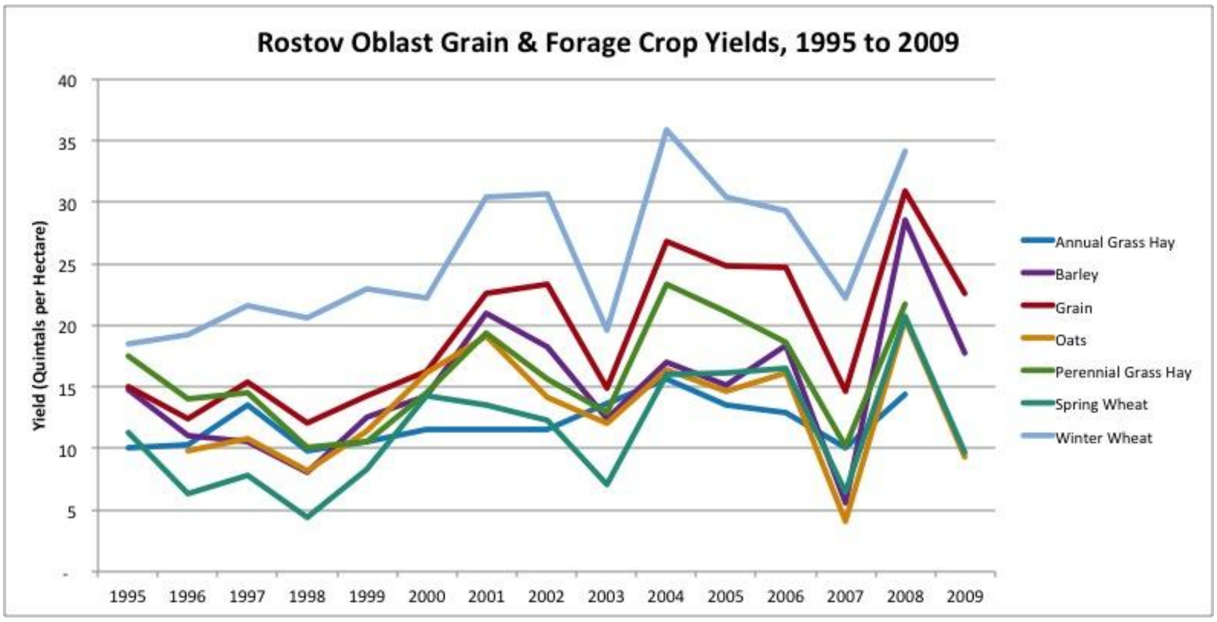


Figure 19. Rostov grain and forage crop yields (excluding sugar beets) from 1995 to 2009. Data source: (ROSSTAT 2010)

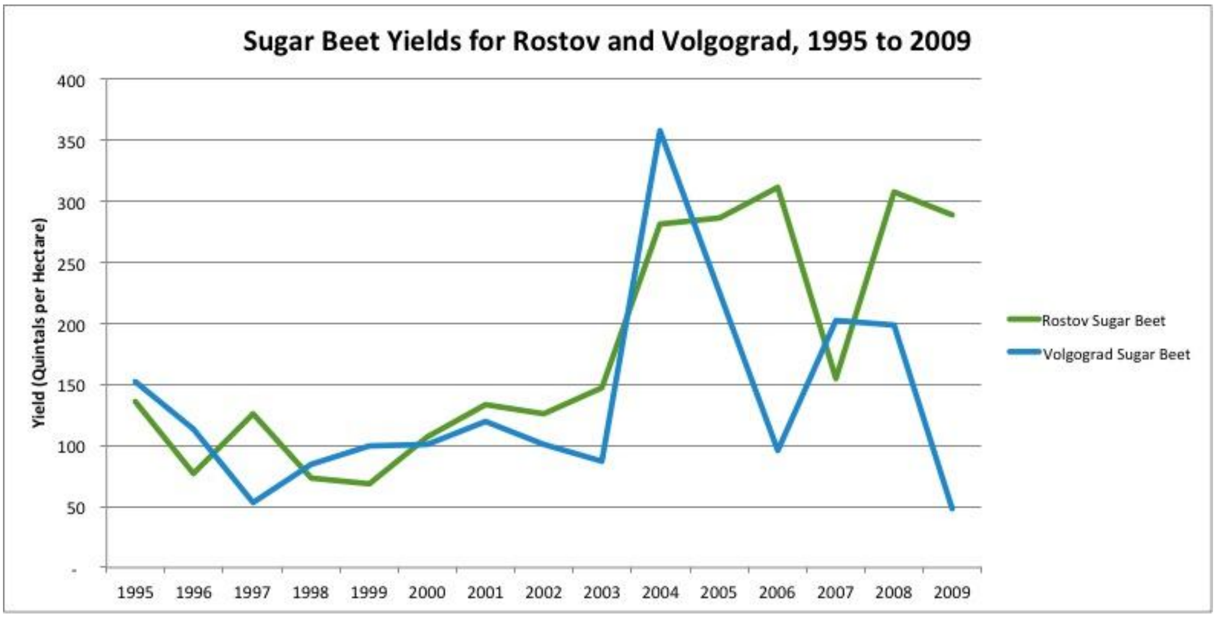


Figure 20. Sugar beet yields for both oblasts from 1995 to 2009. Data source: (ROSSTAT 2010)

4.1.4. Summarizing Work Conducted for *RQ1*

The aforementioned work and analysis has answered the first research question and has produced a valuable deliverable, which can be used for future research. A land use classification was performed for the study area, finding 57.0% of the region to be comprised of agricultural lands. A thematic land use map has been developed (**Figure 21**), which provides a basis for future land use studies and can be used as a base for future studies of land use change in the region. It was also determined that the proportion of agricultural lands has not changed much over the period of study.

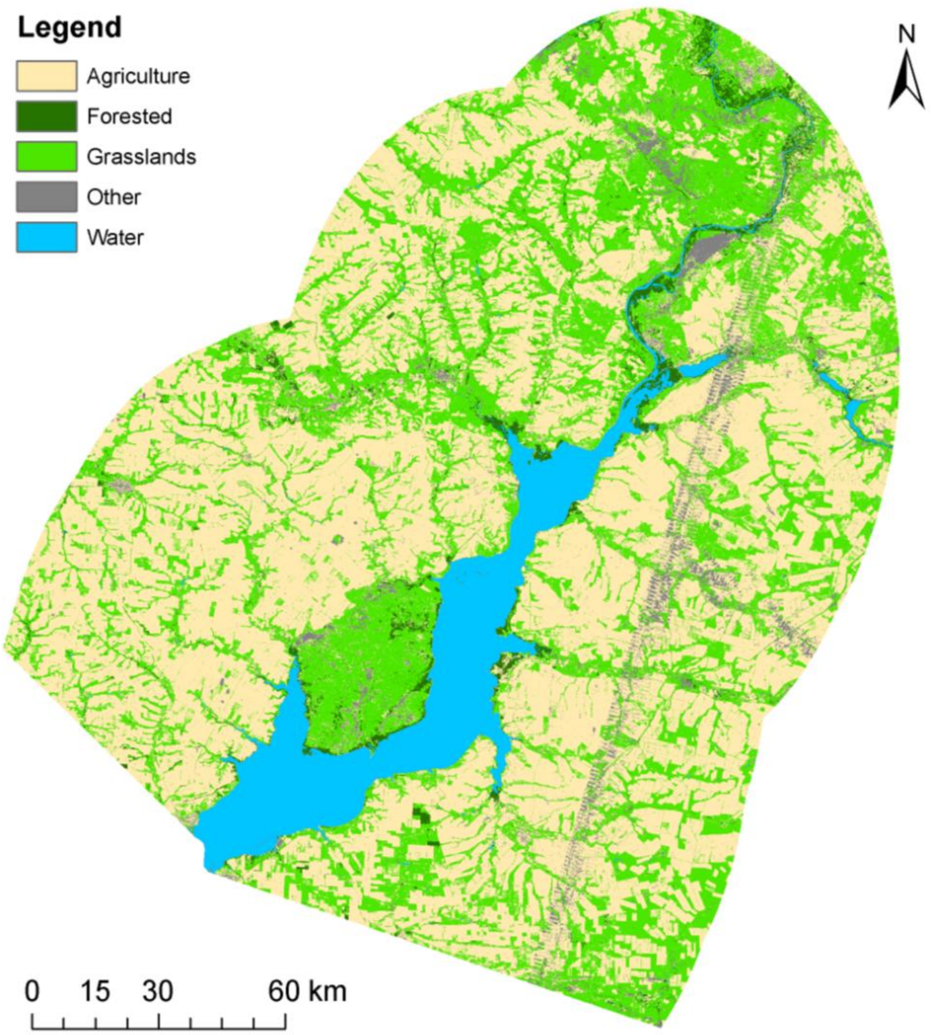


Figure 21. Final land use map. (Map created by author).

4.2. Analysis of Eutrophic Algal Blooms (*RQ2*)

The second research question aims at determining when algal bloom events have occurred and to what extent they have occurred in the past 15 years. Another goal is to develop a list and a visual catalogue of all eutrophic algal blooms that have been identified through satellite imagery and publish these findings online.

4.2.1. Identification of Eutrophication Events

The first step in answering the second research question is to identify instances of algal blooms in the reservoir. As discussed before, because of the quality and consistency of the

Landsat program, the U.S. Geological Survey database will again be used to obtain satellite imagery. As was noted in Section 3, algal blooms are easy to identify on satellite images and thus this method of browsing the available satellite images in the Landsat database was deemed sufficient. Three of the four tiles, Path/Row 173/027, 173/026, and 172/027 as seen in **Figure 5**, were used for this part of the research, as tile 172/026 covered a only small portion of the reservoir in comparison to the other three. More than one tile was used because tiles often have images from different dates, so using more than one tile increases the number of dates available for analysis.

Each individual satellite image for the three tiles from May to October between 1990 and 2013 was studied on the USGS database website (www.glovis.usgs.gov) at 240 m resolution to identify algal blooms. Since the goal of this research is to determine agricultural-related causes, other months in the year that fell outside of the agricultural season were excluded. Each image that demonstrated an algal bloom event (large or small) was downloaded and recorded. This catalogue of images and their corresponding dates can be found in **Appendix Figure 4** and has been published online at the Azov Center website at http://azovcenter.ru/tsimlyansk-algal, as can be seen in **Appendix Figure 5**.

Unlike the land use classification application of the Landsat tiles, factors like cloud cover, satellite type, and quality were not of concern for this part of the study, as the tiles were not used in software applications, only for visual examination. If eutrophication could easily be identified through clouds obscuring the image, the tile was still used. Tiles from the Landsat 7 mission (post 2003 scanner malfunction) were also included, as eutrophic algal blooms were still easily identifiable beyond the missing scan lines.

The availability and ability to download Landsat images was also mentioned in Section 3. This, too, was not a concern for this part of the research. The land use classification required a special specific file type, called the “Level 1 Product”, which contains all 7 spectral bands. These comprehensive files are often not available for download. But for every image that can be seen on the USGS database, a simple preview image can be downloaded, called the “LandsatLook ‘Natural Color’ Image”. These images were sufficient for the algal bloom existence and extent analysis. A total of 82 images showing algal blooms were collected. Images from the same date but on different tiles were not repeated and the tile exhibiting the larger extent of the bloom was selected.

4.2.2. Determination of the Extent of Identified Algal Blooms

Next, each image was scrutinized to determine the extent of the algal bloom in the reservoir. For each image, the bloom concentration was deemed “Minor”, “Moderate”, or “Extensive” based on the appearance of the bloom. The size of the algal bloom in the reservoir was deemed “Small”, “Medium”, or “Large”. After determining these two qualitative parameters, the extent was determined to be “Low”, “Medium” or “High”, based on the criteria in **Table 7**, with a corresponding numerical level, which will be used in the next section.

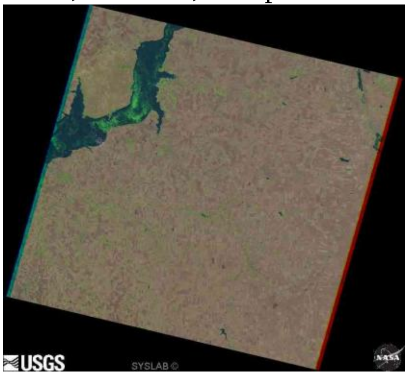
Determined Extent	Bloom Concentration	Bloom Size
High (Level 3)	Extensive	Large
Medium (Level 2)	Moderate	Medium or Large
Low (Level 1)	Small	Small or Medium

Table 7. Algal bloom extent criteria.

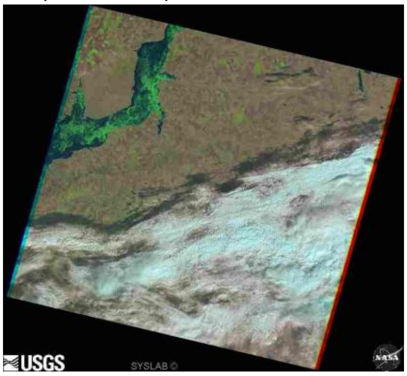
While this process could have been done in a more quantifiable way, e.g. drawing a polygon around the area of the reservoir in ArcGIS and calculating the area or proportion to the reservoir, the size of the bloom is only one factor. Concentration is another major factor. Having a scale based purely on size would not be representative of the actual state of the bloom, as a large bloom with low concentration could show to be of a higher extent than a medium-sized bloom with a very high concentration. As such, these factors were taken into consideration when making a qualitative assessment of the extent of the bloom.

A total of 17 dates were determined to have a “High” (Level 3) algal bloom extent. These 17 images can be seen below in **Table 8**. A “Low” (Level 1) algal bloom was identified on 42 dates, and “Medium” (Level 2) was identified on 23 dates. The full table of all identified algal blooms is at **Appendix Figure 4**, which was also published online at http:// http://azovcenter.ru/tsimlyansk-algal.

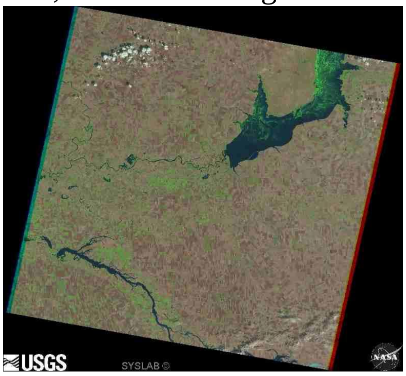
#3, 172/027, 9 Sept. 1990



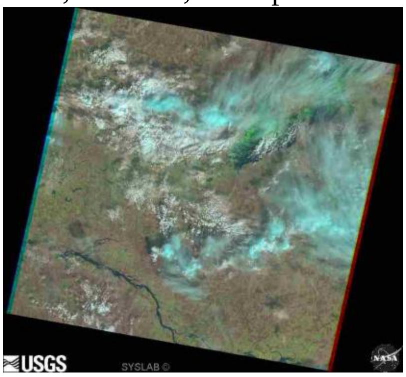
#5, 172/027, 11 October 1990



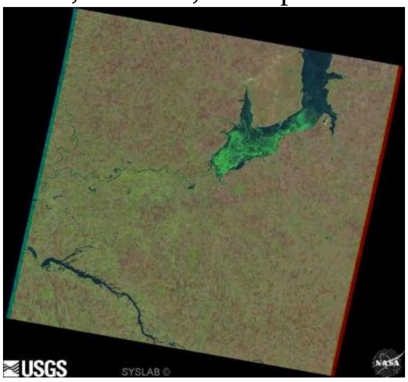
#6, 173/027 18 August 1991



#7, 173/027, 19 Sept. 1991

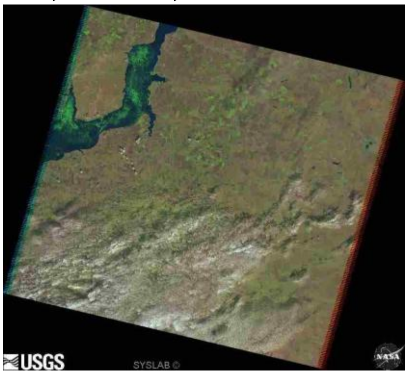


#18, 173/027, 19 Sept. 1997

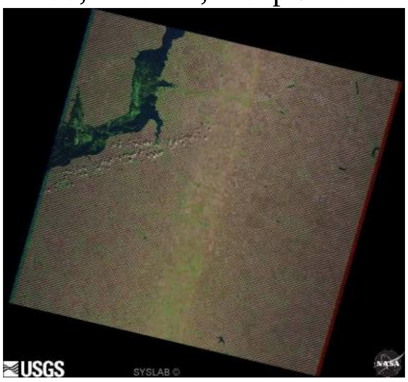


#29, 173/027, 20 Sept. 2003

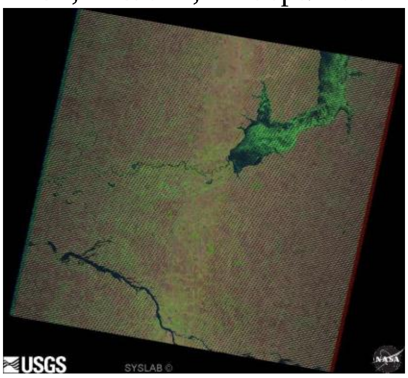
#30, 172/027, 15 October 2003



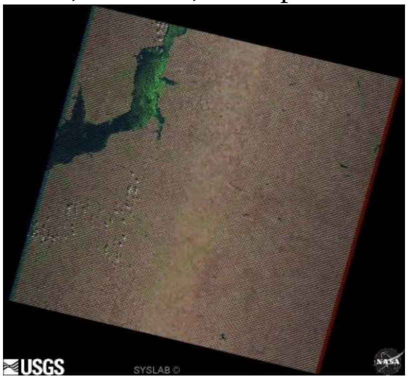
#33, 172/027, 7 Sept. 2004



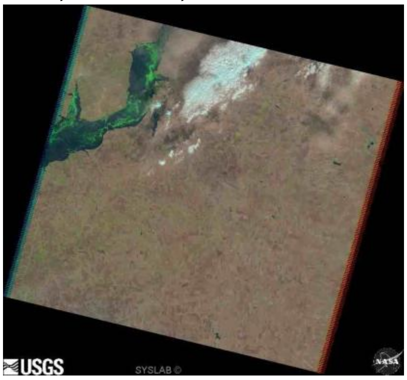
#34, 173/027, 14 Sept. 2004



#40, 172/027, 13 Sept. 2006

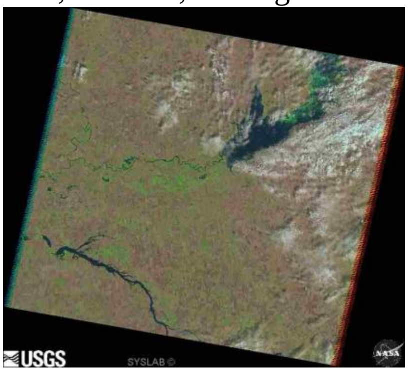


#42, 172/027, 7 October 2006

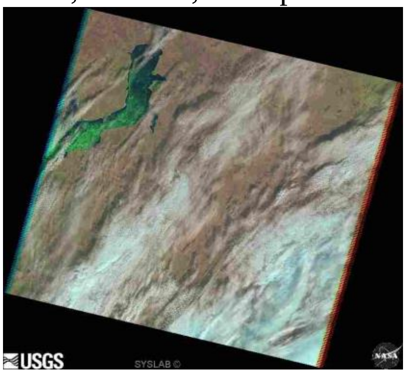


#49, 172/027, 2 Sept. 2008

#54, 173/027, 19 August 2009



#56, 172/027, 29 Sept. 2009



#69, 173/027, 12 Sept. 2012

#74, 173/027, 27 June 2013

#81, 173/027, 1 October 2013

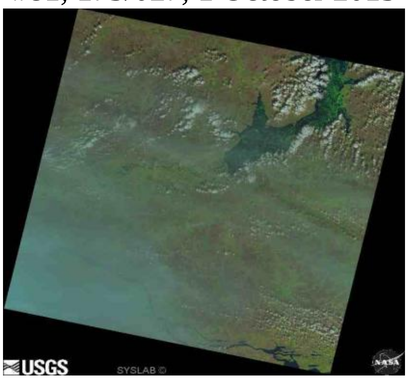


Table 8.Satellite-identified algal blooms with a "High" bloom extent.

The temporal distribution of identified algal blooms from the satellite images is found by month in **Table 9**. Based on the blooms identified through the satellite images, most algal blooms occur within August and September. This is consistent with literature, discussed in Section 2, which says that a large bloom often occurs in late summer. In Section 1 of this study, a number of environmental events (e.g. fish kills) were mentioned resulting from algal blooms in recent years (2007-2001). As has been shown through this research, these algal blooms are not a recent phenomenon. They have been occurring on an almost yearly basis (from what can be ascertained through the available satellite images) in varying degrees since at least 1990.

Month	Number of Images	Percent of Total
June	4	4.9%
July	14	17.1%
August	22	26.8%
September	26	31.7%
October	16	19.5%

Table 9. Temporal distribution (by month) of identified algal blooms.

After these blooms were identified, other data sources were explored for identifying additional algal bloom events, including NASA's Ocean Color portal (oceancolor.gsfc.nasa.gov). Using the Level 3 Browser, every date in which a "High" algal bloom occurred was searched for using the Aqua MODIS Chlorophyll concentration option to see if the two sources would match, which would mean that this source could be used as another tool to identify additional algal blooms. But only 2 of the 17 dates (7 September 2004 and 29 September 2009) showed any sign of chlorophyll, presumably because the very coarse resolution, as seen in **Figure 22**. The Tsimlyansk Reservoir can be seen in the middle of the image between the Black Sea and Caspian Sea and a very small amount of red can be identified within the reservoir indicating a high concentration of chlorophyll-a, an indicator of cyanobacteria (Tebbs, Remedios, and Harper 2013), which is noted as one of the main types of algae associated with algal blooms in the reservoir in Section 2. Due to the apparent superiority of using the Landsat database to identify algal blooms because of the better resolution, this source was not used to search for other algal bloom events. No other data source provided adequate identification of blooms and as such, the data obtained from the Landsat database were relied upon for study.

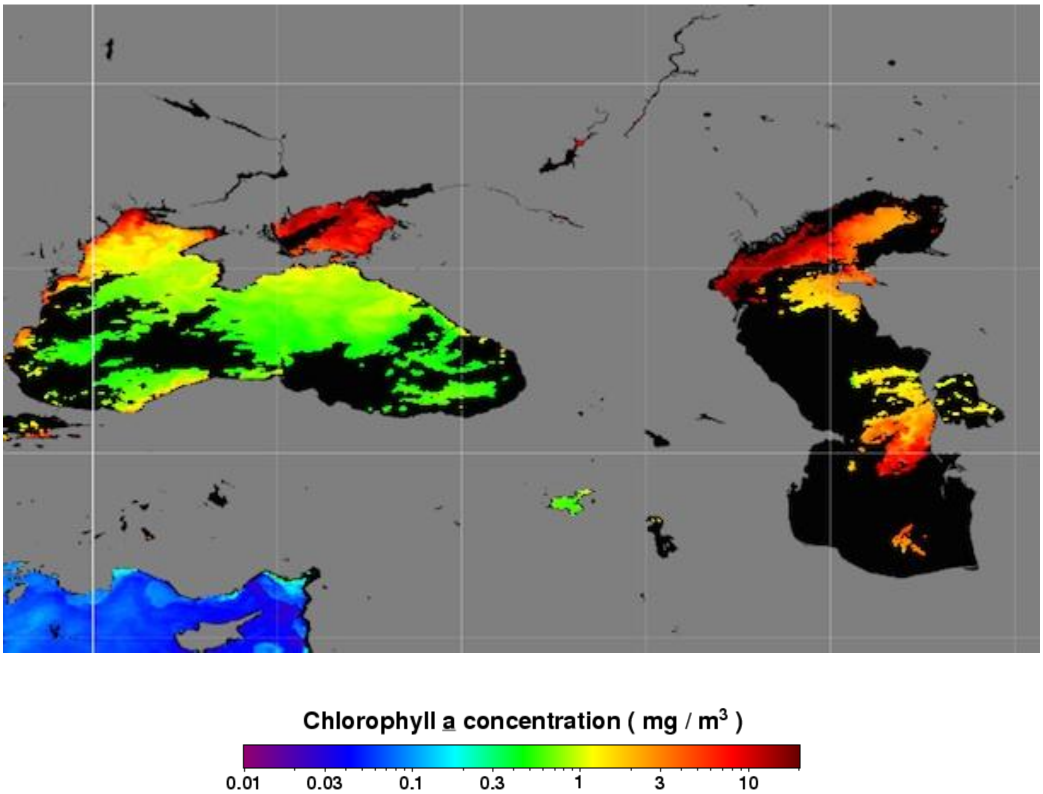


Figure 22. Screenshot from the NASA Ocean Color Level 3 Browser. Image from: (NASA 2014)

4.2.3. Summarizing Work Conducted for *RQ2*

The second research question (*RQ2)* was fulfilled by the aforementioned research. A total of 82 algal bloom events were identified through the use of satellite imagery, including 17 events whose extent was deemed “High” (Level 3). From the information gathered, it is clear that algal blooms of varying degrees have been occurring on an almost yearly basis since 1990 and are not a recent phenomenon.

Pursuant to the research question, a catalogue of all the algal bloom events found in the USGS database was developed, including an assessment of the extent of the bloom. The catalogue of images and their corresponding dates can be found in **Appendix Figure 4** and the list of algal bloom events with the determination of the bloom extent can be found in **Appendix Figure 6**. The next step, which appears in the following section, will be to see if there is a relationship between land use and these eutrophication events.

4.3. Finding Relationships (*RQ3*)

Now that the first two research questions relating to land use and algal bloom events have been addressed and concrete deliverables have been developed, the next step is to explore an example how this data can be used to begin to understand the relationship between land use and eutrophication in the reservoir. The two components will be investigated through the use of precipitation data, one of the factors involved in the development of algal blooms, to see if a relationship can be identified.

4.3.1. Investigation into Precipitation-Induced Algal Blooms

The objective aims to investigate the relationship between land use and algal blooms through precipitation. Precipitation events can stimulate the movement of agricultural runoff, including nitrogen- and phosphorus-based fertilizers, into water bodies (Reichwaldt and Ghadouani 2012; Chorus and Mur 1999; Spatharis *et al.* 2007; Heisler *et al.* 2008; Glandon *et al*. 1981).

To investigate this in the Tsimlyansk Reservoir, precipitation data for the region surrounding the reservoir was obtained from the Giovanni web portal, which was discussed in Section 2. The Meteorological Portal, TRMM Online Visualization and Analysis System (TOVAS) was used to obtain daily rainfall estimates for the area: West 41.438, North 49.975, South 46.375, and East 44.306, ensuring full enclosure of the reservoir and buffer zone, as seen in **Figure 23**.

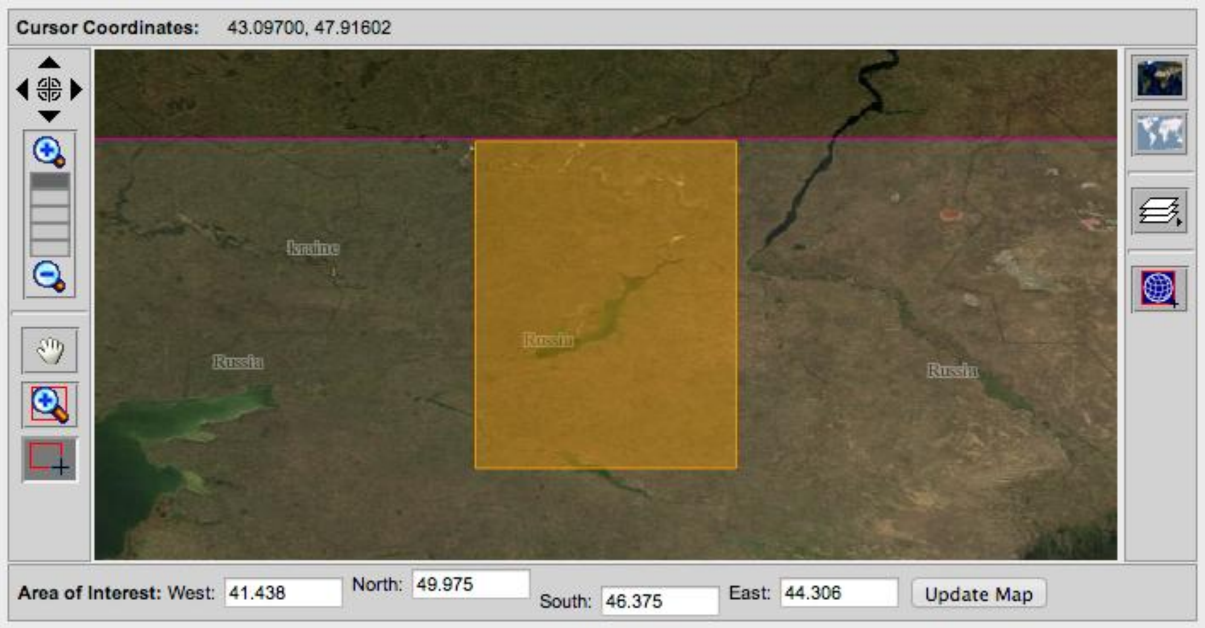


Figure 23. Screenshot showing the geographical extent of Giovanni precipitation data. Image from: (NASA 2013a)

Daily rainfall data was obtained for every year available on the Giovanni portal (1998 to 2013, slightly different than the time frame for land use and eutrophication research, but still covering a 15 year period) for the period of May to October, to match the time period for the identification of algal blooms. Using Microsoft Excel, a graph of precipitation for the period was generated for each year. The algal bloom event data developed in the previous section was added to each precipitation graph on a second vertical axis. As with the scale that had been developed, "High" instances are indicated by a 3, "Medium" by a 2, and "Low" by a 1. While the specific vertical placement of the algal bloom events on the graph is arbitrary, it clearly identifies when the satellite-identified bloom occurred and of what magnitude it was.

For certain years, there appears to be a clear relationship between precipitation and algal bloom events, as seen in **Figure 24**. In 2003, the three largest rainfall events occurred on 11 August (15.586 mm), 4 September (12.959 mm), and 11 October (19.007 mm). Similarly, one medium and two large algal blooms were identified through the satellite images, each occurring a shortly after each rainfall event on 28 August, 20 September, and 15 October, respectively, indicating a relationship.

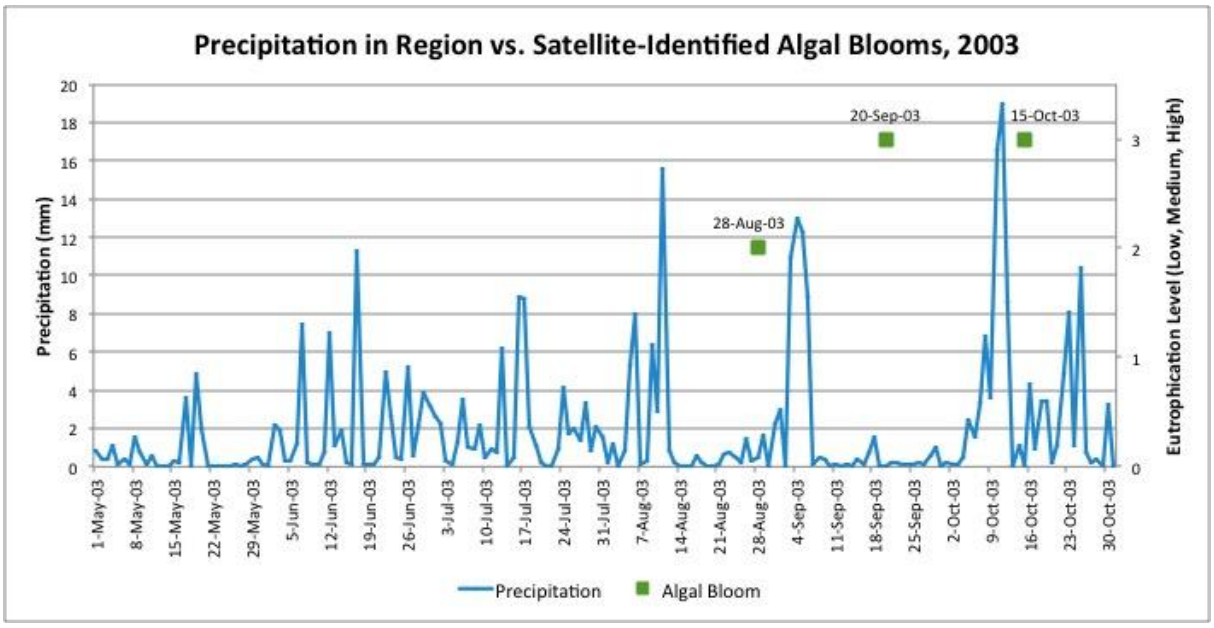


Figure 24. Precipitation vs. algal blooms for 2003. Data source: (NASA 2013a; USGS 2014)

A number of other years show similar patterns, e.g. 2000 and 2001 seen in **Figure 25** and **Figure 26**, respectively. Two algal blooms were identified in 2000, both occurring shortly after episodes of rain occurring a multiple days within a short period of time. The three algal blooms that were identified in 2001 all occurred amidst periods of rain as well.

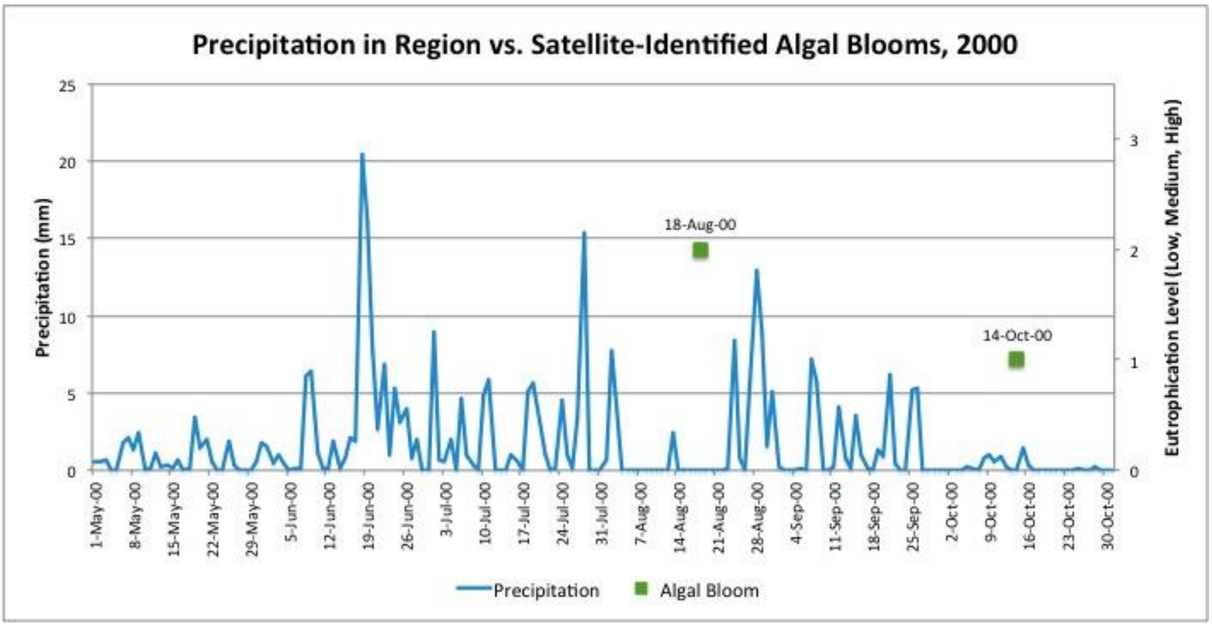


Figure 25. Precipitation vs. algal blooms for 2000. Data source: (NASA 2013a; USGS 2014)

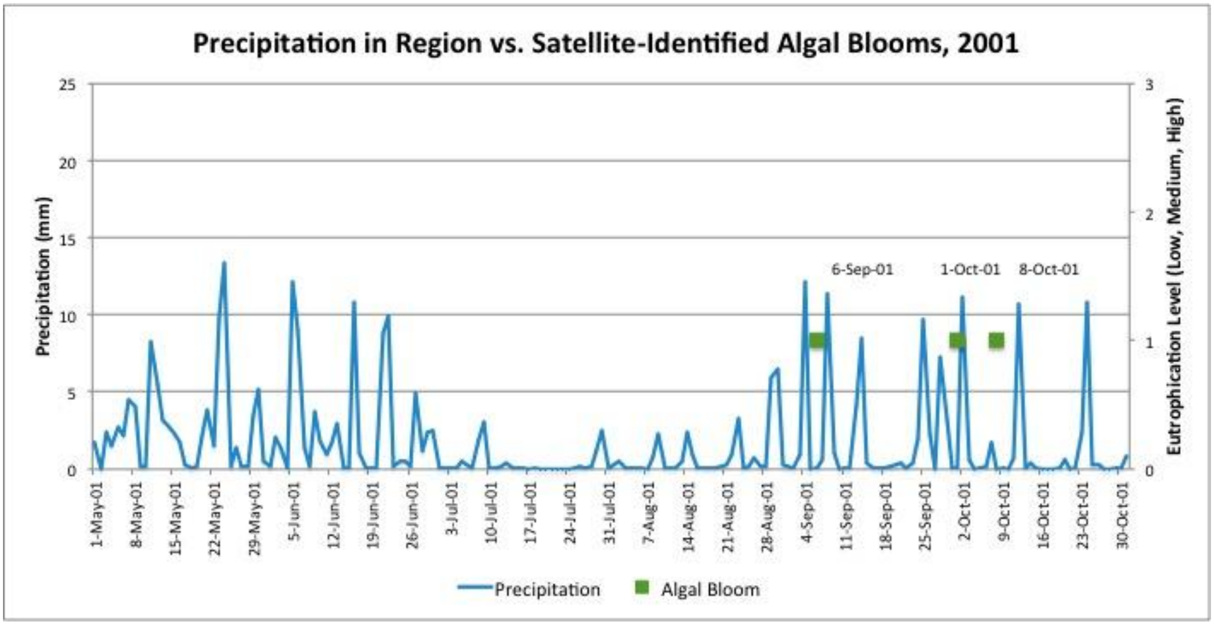


Figure 26. Precipitation vs. algal blooms for 2001. Data source: (NASA 2013a; USGS 2014)

There does appear to be a relationship between precipitation and algal blooms based on these images, but in other years studied, the relationship wasn't as clear. An example of this is in 2012, when a number of algal bloom events occurred, some of them deemed "High" and "Medium", yet precipitation remained relatively low over the time period. This graphs is seen in **Figure 27**. All of the graphs used for analysis, from 1998 to 2013 can be found in **Appendix Figure 7**.

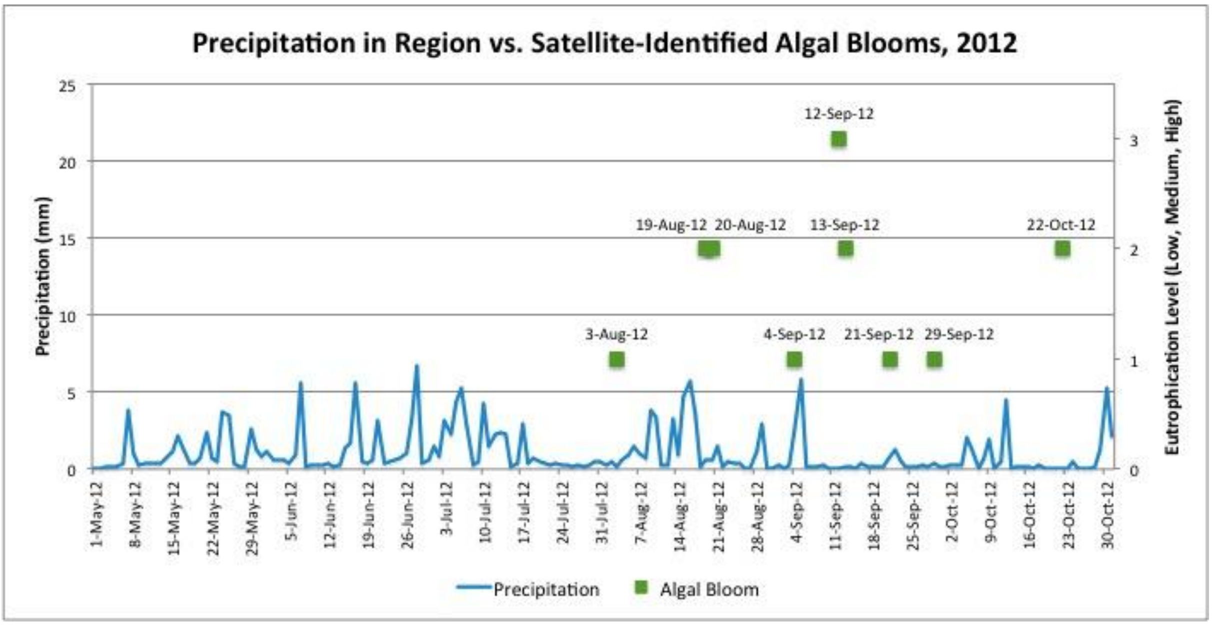


Figure 27. Precipitation vs. algal blooms for 2012. Data source: (NASA 2013a; USGS 2014)

4.3.2. Summarizing Work Conducted for *RQ3*

The aforementioned work and analysis has addressed the objective of *RQ3*. An example of how the developed land use and eutrophication data can be utilized was investigated. Through the lens of precipitation, it was determined that there is a potential relationship between the two components, although more work can be done to further investigate each event and identify more events to solidify the presumed relationship between the two.

But the applicability of the developed land use and eutrophication data is clear. Using these two remote sensing- and GIS-derived components, other variables (e.g. precipitation data) can be added to study potential causal relationships between these two elements.

5. Discussion

5.1. Research Results and Limitations

A primary aim of this study was to conduct the preliminary groundwork for future research and to generate a set of deliverables that can be used and expanded upon in the future. In addition, another main goal was to make use of remote sensing and GIS technologies as well as to explore and utilize the vast amount of data available through data portals. These overall aims were pursued through the lens of three research questions, targeted at investigating potential agricultural-related causes of eutrophication in the Tsimlyansk Reservoir. The following section will discuss the results of the work conducted for each of these research questions as well as their limitations.

5.1.1. Land Use Classification

Regarding the first research question, the land use classification that was performed was determined to have an overall accuracy of 95.86%, deeming it a suitably accurate representation of land cover in the area surrounding the reservoir in 2010. The land use map resulting from this process can be used as a foundation for further research in both land and water applications, similar to how it was used in this study to investigate the relationship between land use and eutrophication through precipitation.

While the desired classification accuracy was achieved (and exceeded), there are some factors to take into consideration when relying upon digitally classified data. Although the use of digital classification of remote sensing images to develop land use thematic maps is very common, there are a number of constraints and limitations associated with it. The most notable limitation is due to the inherent subjectivity involved throughout the entire process: 1) interpreting both high-resolution images and Landsat satellite imagery, 2) developing the training areas, 3) validating the random sampling points, and 4) interpreting the accuracy statistics. Human subjectivity and human error play a role in this process, which inevitably impact the true accuracy of the classification output and resulting thematic map. To overcome this, additional sources of information are often used in land classification studies, including actual ground-truth data acquisition, which is physically visiting the study area to ascertain the proper land class at specific points. But this, too, involves some degree of subjectivity on the part of the individual conducting the ground-truthing (Prishchepov 2014). Because of feasibility issues, physical ground-truthing was not conducted for this study and classification instead relied upon the interpretation of high-resolution images and Landsat satellite images as reference data. Taking this into consideration, the land use classification developed still provides a sound basis for future research in the area.

5.1.2. Land Use Change

The statistics obtained to determine how agricultural land has changed over the past 15 years were at the oblast level. These statistics represent an area larger than the buffer zone for which the land use classification was developed, based on the approximate potential travel distance of phosphorus in agricultural runoff. Obtaining statistics for the particular rayons (the next smallest administrative level) that fall within the buffer zone would yield more accurate results regarding the actual changes in agricultural land in the immediate vicinity around the reservoir. But since the results showed that the proportion of agricultural land has remained relatively stable over the time period studied, these results were assumed to be representative of the smaller area.

5.1.3. Land Use Map

The final map developed in Section 4.1 (**Figure 21**) used a modified buffer zone for the purposes of taking into consideration the low likelihood of runoff from below the reservoir travelling upwards to the reservoir. Depending on the intended use of the classified land use map (e.g. for uses in modelling), other approaches could be taken to modify this buffer zone, e.g. based on a drainage basin for the reservoir or based on a digital elevation model of the area.

5.1.4. Identification of Algal Blooms

A total of 82 algal blooms were identified through Landsat satellite imagery from 1990-2013. Having identified these bloom occurrences, additional work could be done to examine each individual event to attempt to identify the underlying cause or set of factors.

While the identification of algal blooms through satellite imagery was achieved, the images (and corresponding dates) identified do not represent all of the algal blooms that occurred in the time period, due to the limited temporal availability of Landsat imagery. Only blooms that occurred on 1) dates for which images were taken and 2) images in which an algal bloom could still be identified through atmospheric interference were identified. Years in which there were an absence of images does not necessarily indicate an absence of bloom activity. To address this, more remote sensing data sources could be investigated to find additional dates showing algal blooms. Additionally, other sources of information, like additional news articles, could be investigated to make the sample more representative of actuality. But this aside, the identified algal blooms do present a viable set of information that can be used as a basis for further research.

5.1.5. Comparing Land Use and Algal Blooms Through Precipitation

A relationship between precipitation and algal blooms was indeed identified and is very evident in a few of the years under study (e.g. 2000, 2001, and 2003). But as the set of satellite imagery used to identify these blooms is not representative of all the algal blooms that have occurred during the study period, more information would have to be obtained to conclude on a causal link between the two.

5.2. Pathways for Further Research

The work done for this research has set a foundation for future research to be able to be conducted in the region around the reservoir. More factors can be investigated and combined with the existing findings to strengthen the existence of potential causal relationships (e.g. between precipitation and algal blooms, as was explored through this research) and to identify new relationships. Future research could include 1) investigating the role air temperature plays in the development of algal blooms; 2) obtaining data on the specific time, amount, and composition of fertilizer applications (ideally on a field-by-field basis); 3) combining both of these factors with the developed precipitation data to see what combination of factors causes blooms to occur (e.g. a few days of hot temperatures around the time of a fertilizer application, followed by a large precipitation event). Combining these and other environmental factors with the results obtained through this research could lead to further discoveries about the underlying causes of algal blooms and get closer to finding ways to mitigate the effects of future occurrences. In addition, further research could involve finding new sources of satellite imagery to identify additional algal blooms or finding and applying new ICTs.

Overall, the research conducted for this study provides a fundamental basis for future work to be done in the region and provides an example of how data portals, remote sensing and GIS can be used to apply to environmental issues. There are a number of pathways for future research that would involve combining new factors with the results already obtained to gain further understanding of the underlying causes of eutrophication in the Tsimlyansk Reservoir and get closer to identifying ways to mitigate the effects of harmful algal blooms, thereby addressing one of the facets of water security in the region.

6. Conclusion

The overall goals of this research were to conduct the preliminary groundwork and develop deliverables (e.g. catalogue of algal blooms) for future research in the region; make use of the immense amount of data that is currently underutilized; and provide an example of how remote sensing and GIS technologies can be applied in a practical and useful manner.

These general goals were addressed through the use of three research questions aimed at investigating potential agricultural-related causes of eutrophication in the Tsimlyansk Reservoir, an issue that has been causing problems and threatening water security in the region in recent years:

- *RQ1: What was the state of land use around the Tsimlyansk Reservoir around the time of reported harmful algal blooms? Has it changed much over the past 15 years?*
- *RQ2: When and to what extent have algal blooms occurred in the Tsimlyansk Reservoir in the past 15 years?*
- *RQ3: How can this data be used to investigate the relationship between land use and eutrophication in the Tsimlyansk Reservoir?*

To address the first research question, a land use classification was performed using remote sensing and GIS data and technologies, which yielded a detailed functional land use map of the study area in 2010. The map that was developed can be used as a basis for future research in the region and can easily be modified based on its intended function. It was determined that the proportion of agricultural land use in the region has remained relatively stable over the past 15 years, therefore pointing to other more complex factors as potential sources of eutrophication in the reservoir.

The second research question was answered by obtaining and evaluating satellite imagery exhibiting algal blooms in the reservoir. A catalogue of this information was developed and made publicly available at http://azovcenter.ru/tsimlyansk-algal for interested stakeholders.

As identified through satellite imagery, algal blooms of varying extents (low, medium, and high) have occurred on an almost yearly basis since 1990 and are not a new phenomenon.

The third research question aimed to provide an example of how the data obtained and developed through the use of data portals and remote sensing and GIS technologies can be used to identify relationships between the two components. Land use and eutrophication were investigated through the lens of precipitation, ultimately discovering a relationship between the two. More work can be done to gather more information about each algal bloom identified and to identify a larger sample to solidify the presumed relationship between the two elements.

The three research questions were answered and the goal of developing the fundamental groundwork for future research was achieved. Furthermore, data has been obtained and made accessible to be a valuable and time-saving resource for interested stakeholders wanting to continue research of land use and eutrophication in the region. These deliverables are already accessible and can be found at www.azovcenter.ru/tsimlyansk-algal and www.azovcenter.ru/tsimlyansk-landsat. And lastly, this research set out to make use of the continually expanding set of available ICTs and vast amount of data freely available through data portals and apply these to a practical environmental problem. This aim was achieved by sorting through and collecting data from remote sensing data portals and utilizing this data in conjunction with multiple remote sensing and GIS techniques in a novel way.

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Appendices

Appendix Figure 1. Landsat image catalogue: May to October 2008-2010. Data Source: (USGS 2014)
*Selected for land use classification
Note: cloud cover of "0%/no" means the database incorrectly indicated 0% cloud cover

Path/Row	Year	Month	Date	Cloud	Satellite
Landsat Tile 173/027					
173/027	2008	5	4	14%	LE7+L1T
173/027	2008	5	20	52%	LE7+L1T
173/027	2008	6	5	18%	LE7+L1T
173/027	2008	6	21	14%	LE7+L1T
173/027	2008	7	7	71%	LE7+L1T
173/027	2008	7	23	1%	LE7+L1T
173/027	2008	8	8	0%	LE7+L1T
173/027	2008	8	24	0%	LE7+L1T
173/027	2008	9	9	0%	LE7+L1T
173/027	2008	10	27	0%	LE7+L1T
173/027	2009	5	7	34%	LE7+L1T
173/027	2009	5	23	5%	LE7+L1T
173/027	2009	6	8	0%	LE7+L1T
173/027	2009	6	16	11%	LT5
173/027	2009	6	24	0%	LE7+L1T
173/027	2009	7	2	0%	LT5
173/027	2009	7	18	43%	LT5
173/027	2009	7	26	1%	LE7+L1T
173/027	2009	8	3	2%	LT5
173/027	2009	8	19	11%	LT5
173/027	2009	8	27	23%	LE7+L1T
173/027	2009	9	4	80%	LT5
173/027	2009	9	20	58%	LT5
173/027	2010	5	26	74%	LE7+L1T
173/027	2010	6	11	0%	LE7+L1T
173/027*	2010	6	19	0%	LT5
173/027	2010	7	5	7%	LT5
173/027	2010	7	13	29%	LE7+L1T
173/027	2010	7	21	36%	LT5
173/027	2010	7	29	0%	LE7+L1T
173/027	2010	8	6	0%	LT5
173/027*	2010	8	22	0%	LT5
173/027	2010	8	30	0%	LE7+L1T
173/027	2010	9	7	40%	LT5

Path/Row	Year	Month	Date	Cloud	Satellite
173/027	2010	9	23	10%	LT5
173/027	2011	6	6	1%	LT5
173/027	2011	6	14	56%	LE7+L1T
173/027	2011	6	22	22%	LT5
173/027	2011	6	30	57%	LE7+L1T
173/027	2011	7	8	37%	LT5
173/027	2011	7	16	9%	LE7+L1T
173/027	2011	7	24	39%	LT5
173/027	2011	8	1	9%	LE7+L1T
173/027	2011	8	9	0%	LT5
173/027	2011	8	17	6%	LE7+L1T
173/027	2011	8	25	45%	LT5
173/027	2011	9	2	6%	LE7+L1T
173/027	2011	9	10	23%	LT5
173/027	2011	9	18	0%	LE7+L1T
173/027	2011	9	26	28%	LT5
173/027	2011	10	4	81%	LE7+L1G
173/027	2012	5	15	69%	LE7+L1T
173/027	2012	5	31	53%	LE7+L1T
173/027	2012	6	16	93%	LE7+L1T
173/027	2012	7	2	54%	LE7+L1T
173/027	2012	7	10	-1%	LM5
173/027	2012	7	18	5%	LE7+L1T
173/027	2012	7	26	-1%	LM5
173/027	2012	8	3	0%/no	LE7+L1T
173/027	2012	8	11	-1%	LM5
173/027	2012	8	19	27%	LE7+L1G
173/027	2012	8	27	-1%	LM5
173/027	2012	9	4	0%	LE7+L1T
173/027	2012	9	12	-1%	LM5
173/027	2012	9	20	1	LE7+L1T
173/027	2012	10	6	28%	LE7+L1T
173/027	2012	10	22	33%	LE7+L1T
173/027	2012	10	30	0%/no	LM5
Landsat Tile 173/026					
173/026	2008	5	4	0%	LE7+L1T
173/026	2008	5	20	44%	LE7+L1T
173/026	2008	6	5	55%	LE7+L1T
173/026	2008	6	21	68%	LE7+L1T
173/026	2008	7	7	91%	LE7+L1T
173/026	2008	7	23	2%	LE7+L1T
173/026	2008	8	8	12%	LE7+L1T
173/026	2008	8	24	0%	LE7+L1T
173/026	2008	9	9	0%	LE7+L1T

Path/Row	Year	Month	Date	Cloud	Satellite
173/026	2008	10	27	0%	LE7+L1T
173/026	2009	5	7	39%	LE7+L1T
173/026	2009	5	23	10%	LE7+L1T
173/026	2009	6	8	0%	LE7+L1T
173/026	2009	6	16	16%	LT5
173/026	2009	6	24	17%	LE7+L1T
173/026	2009	7	2	0%	LT5
173/026	2009	7	18	55%	LT5
173/026	2009	7	26	0%	LE7+L1T
173/026	2009	8	3	35%	LT5
173/026	2009	8	11	36%	LE7+L1T
173/026	2009	8	19	16%	LT5
173/026	2009	8	27	28%	LE7+L1T
173/026	2009	9	4	77%	LT5
173/026	2009	9	20	9%	LT5
173/026	2009	10	14	4%	LE7-SLC
173/026	2010	5	10	13%	LE7+L1T
173/026	2010	5	26	70%	LE7+L1T
173/026	2010	6	3	15%	LT5
173/026	2010	6	11	0%	LE7+L1T
173/026*	2010	6	19	1%	LT5
173/026	2010	7	5	66%	LT5
173/026	2010	7	13	68%	LE7+L1T
173/026	2010	7	21	32%	LT5
173/026	2010	7	29	0%	LE7+L1T
173/026	2010	8	6	0%	LT5
173/026*	2010	8	22	0%	LT5
173/026	2010	8	30	2%	LE7+L1T
173/026	2010	9	7	0%/no	LT5
173/026	2010	9	23	15%	LT5
173/026	2011	5	29	0%	LE7+L1T
173/026	2011	6	6	1%	LT5
173/026	2011	6	14	88%	LE7+L1T
173/026	2011	6	30	69%	LE7+L1T
173/026	2011	7	8	3%	LT5
173/026	2011	7	16	8%	LE7+L1T
173/026	2011	7	24	4%	LT5
173/026	2011	8	1	23%	LE7+L1T
173/026	2011	8	9	0%	LT5
173/026	2011	8	17	8%	LE7+L1T
173/026	2011	8	25	0%	LT5
173/026	2011	9	2	19%	LE7+L1T
173/026	2011	9	10	33%	LT5
173/026	2011	9	18	15%	LE7+L1T

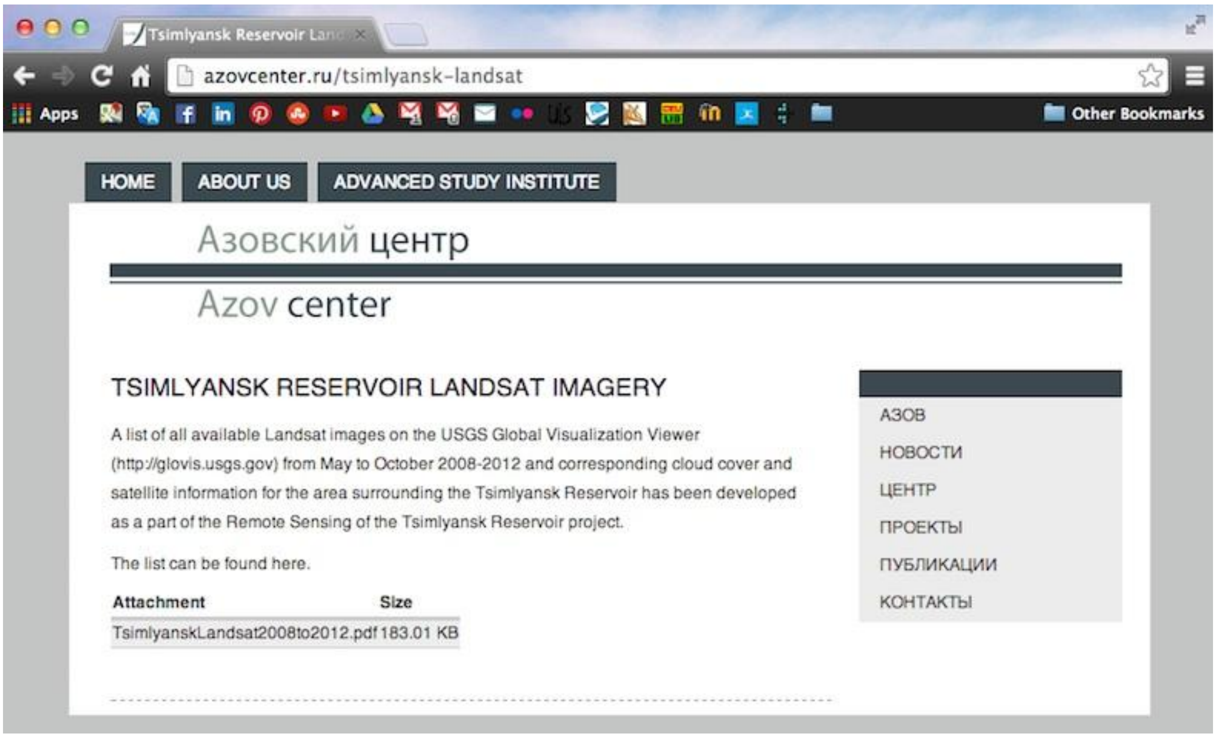
Path/Row	Year	Month	Date	Cloud	Satellite
173/026	2011	9	26	47%	LT5
173/026	2011	10	4	61%	LE7+L1T
173/026	2012	5	15	58%	LE7+L1T
173/026	2012	5	31	85%	LE7+L1T
173/026	2012	6	16	29%	LE7+L1T
173/026	2012	7	2	19%	LE7+L1T
173/026	2012	7	10	0%	LM5
173/026	2012	7	18	9%	LE7+L1T
173/026	2012	7	26	-1%	LM5
173/026	2012	8	3	30%	LE7+L1T
173/026	2012	8	11	-1%	LM5
173/026	2012	8	19	39%	LE7+L1G
173/026	2012	8	27	-1%	LM5
173/026	2012	10	6	68%	LE7+L1T
173/026	2012	10	22	0%	LE7+L1T
173/026	2012	10	30	0%/no	LM5
Landsat Tile 172/026					
172/026	2008	6	30	56%	LE7+L1G
172/026	2008	7	16	4%	LE7+L1T
172/026	2008	8	17	32%	LE7+L1T
172/026	2008	9	2	0%	LE7+L1T
172/026	2008	9	18	32%	LE7+L1T
172/026	2008	10	4	0%	LE7+L1T
172/026	2009	6	1	0%	LE7+L1T
172/026	2009	6	17	29%	LE7+L1T
172/026	2009	6	25	1%	LT5
172/026	2009	7	11	2%	LT5
172/026	2009	7	19	0%	LE7+L1T
172/026	2009	7	27	75%	LT5
172/026	2009	8	4	7%	LE7+L1T
172/026	2009	8	12	68%	LT5
172/026	2009	9	13	39%	LT5
172/026	2009	9	21	0%	LE7+L1T
172/026	2009	9	29	1%	LT5
172/026	2009	10	15	73%	LT5
172/026	2010	5	3	12%	LE7+L1T
172/026	2010	6	4	7%	LE7+L1T
172/026	2010	6	12	27%	LT5
172/026	2010	6	20	0%	LE7+L1T
172/026	2010	6	28	86%	LT5
172/026*	2010	7	14	0%	LT5
172/026	2010	7	30	7%	LT5
172/026*	2010	8	15	0%	LT5
172/026	2010	8	31	16%	LT5

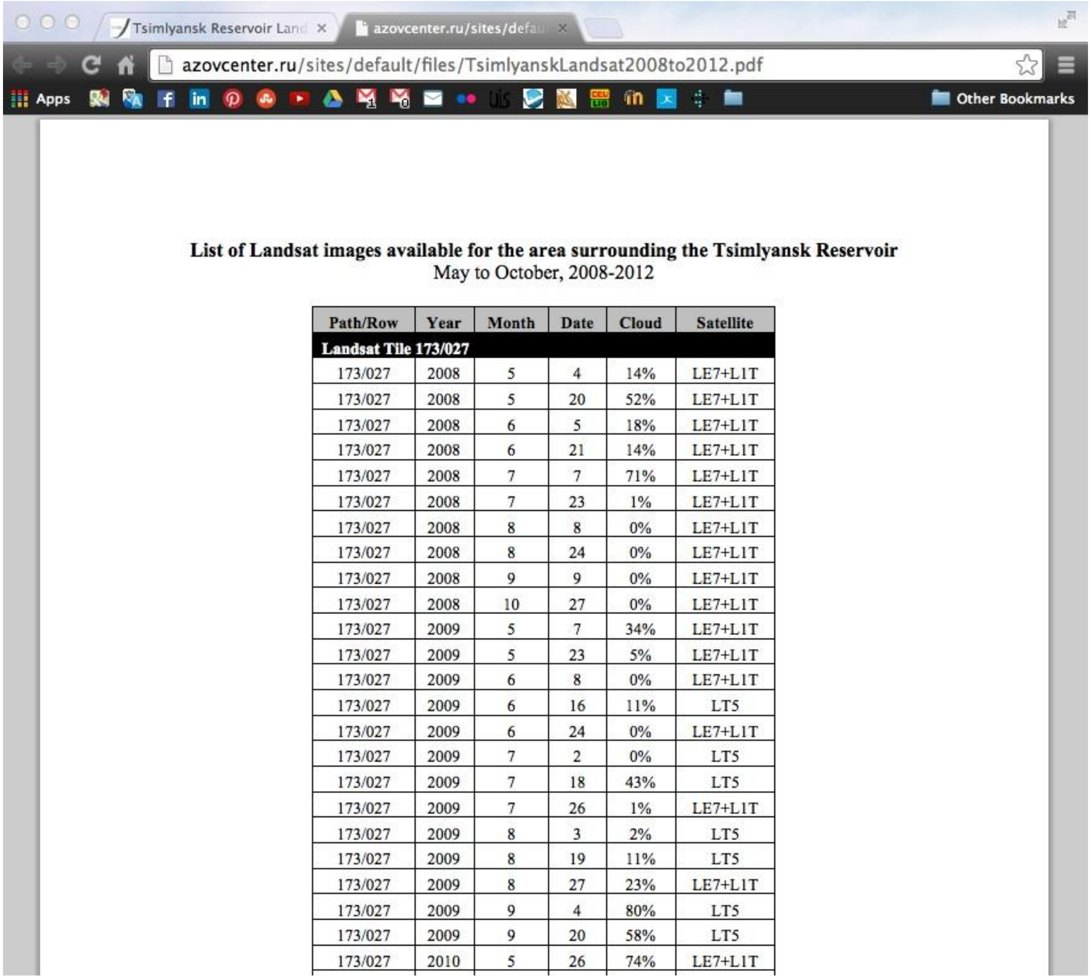
Path/Row	Year	Month	Date	Cloud	Satellite
172/026	2010	9	16	13%	LT5
172/026	2010	10	26	3%	LE7+L1T
172/026	2011	6	7	30%	LE7+L1T
172/026	2011	6	15	27%	LT5
172/026	2011	7	1	90%	LT5
172/026	2011	7	9	13%	LE7+L1T
172/026	2011	7	17	11%	LT5
172/026	2011	7	25	28%	LE7+L1T
172/026	2011	8	2	0%	LT5
172/026	2011	8	10	0%	LE7+L1T
172/026	2011	8	18	21%	LT5
172/026	2011	8	26	0%	LE7+L1T
172/026	2011	9	3	13%	LT5
172/026	2011	9	11	32%	LE7+L1T
172/026	2011	9	19	13%	LT5
172/026	2011	9	27	79%	LE7+L1T
172/026	2011	10	29	98%	LE7+L1G
172/026	2012	5	8	60%	LE7+L1T
172/026	2012	5	24	85%	LE7+L1T
172/026	2012	6	9	4%	LE7+L1T
172/026	2012	6	25	59%	LE7+L1T
172/026	2012	7	11	88%	LE7+L1G
172/026	2012	7	27	2%	LE7+L1T
172/026	2012	8	4	-1%	LM5
172/026	2012	8	12	34%	LE7+L1T
172/026	2012	8	20	-1%	LM5
172/026	2012	8	28	0%	LE7+L1T
172/026	2012	9	5	-1%	LM5
172/026	2012	9	13	0%	LE7+L1T
172/026	2012	9	21	-1%	LM5
172/026	2012	9	29	2%	LE7+L1T
172/026	2012	10	15	75%	LE7+L1T
172/026	2012	10	23	-1%	LM5
172/026	2012	10	31	32%	LE7+L1T
Landsat Tile 172/027					
172/027	2008	6	14	55%	LE7+L1T
172/027	2008	6	30	39%	LE7+L1T
172/027	2008	7	16	4%	LE7+L1T
172/027	2008	8	17	90%	LE7+L1T
172/027	2008	9	2	2%	LE7+L1T
172/027	2008	9	18	6%	LE7+L1T
172/027	2008	10	4	17%	LE7+L1T
172/027	2009	5	16	40%	LE7+L1T
172/027	2009	6	1	0%	LE7+L1T

Path/Row	Year	Month	Date	Cloud	Satellite
172/027	2009	6	25	0%	LT5
172/027	2009	7	3	1%	LE7+L1T
172/027	2009	7	11	8%	LT5
172/027	2009	7	19	30%	LE7+L1T
172/027	2009	7	27	48%	LT5
172/027	2009	8	4	2%	LE7+L1T
172/027	2009	8	12	99%	LT5
172/027	2009	9	13	7%	LT5
172/027	2009	9	21	9%	LE7+L1T
172/027	2009	9	29	43%	LT5
172/027	2009	10	23	52%	LE7-SLC
172/027	2010	5	3	45%	LE7+L1T
172/027	2010	6	4	3%	LE7+L1T
172/027*	2010	6	12	1%	LT5
172/027	2010	6	20	0%no	LE7+L1T
172/027	2010	6	28	31%	LT5
172/027	2010	7	14	31%	LT5
172/027	2010	7	30	0%	LT5
172/027	2010	8	7	0%	LE7+L1T
172/027*	2010	8	15	7%	LT5
172/027	2010	8	23	0%	LE7+L1T
172/027	2010	8	31	11%	LT5
172/027	2010	9	16	63%	LT5
172/027	2010	10	26	1%	LE7+L1T
172/027	2011	6	7	31%	LE7+L1T
172/027	2011	6	15	35%	LT5
172/027	2011	6	23	34%	LE7+L1T
172/027	2011	7	1	35%	LT5
172/027	2011	7	9	5%	LE7+L1T
172/027	2011	7	17	14%	LT5
172/027	2011	7	25	80%	LE7+L1T
172/027	2011	8	2	1%	LT5
172/027	2011	8	10	0%	LE7+L1T
172/027	2011	8	18	43%	LT5
172/027	2011	8	26	0%	LE7+L1T
172/027	2011	9	11	62%	LE7-L1G
172/027	2011	9	19	0%	LT5
172/027	2011	9	27	18%	LE7+L1T
172/027	2011	10	29	100%	LE7+L1G
172/027	2012	5	8	79%	LE7+L1T
172/027	2012	5	24	99%	LE7-L1G
172/027	2012	6	9	16%	LE7+L1T
172/027	2012	6	25	16%	LE7+L1T
172/027	2012	7	11	92%	LE7-L1G

Path/Row	Year	Month	Date	Cloud	Satellite
172/027	2012	7	27	0%	LE7+L1T
172/027	2012	8	4	-1%	LM5
172/027	2012	8	12	35%	LE7+L1T
172/027	2012	8	20	-1%	LM5
172/027	2012	8	28	3%	LE7+L1T
172/027	2012	9	5	-1%	LM5
172/027	2012	9	13	0%	LE7+L1T
172/027	2012	9	21	-1%	LM5
172/027	2012	9	29	0%	LE7+L1T
172/027	2012	10	15	53%	LE7+L1T
172/027	2012	10	23	1%	LM5
172/027	2012	10	31	1%	LE7+L1T

Appendix Figure 2. Screenshots of www.azovcenter.ru showing published Landsat imagery list





List of Landsat images available for the area surrounding the Tsimlyansk Reservoir
May to October, 2008-2012

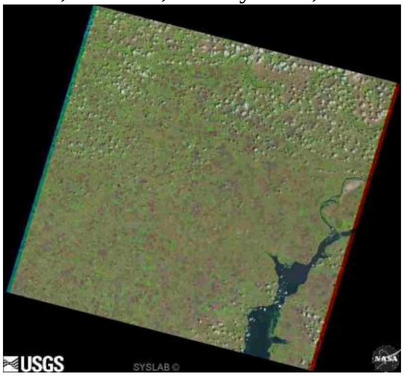
Path/Row	Year	Month	Date	Cloud	Satellite
Landsat Tile 173/027					
173/027	2008	5	4	14%	LE7+L1T
173/027	2008	5	20	52%	LE7+L1T
173/027	2008	6	5	18%	LE7+L1T
173/027	2008	6	21	14%	LE7+L1T
173/027	2008	7	7	71%	LE7+L1T
173/027	2008	7	23	1%	LE7+L1T
173/027	2008	8	8	0%	LE7+L1T
173/027	2008	8	24	0%	LE7+L1T
173/027	2008	9	9	0%	LE7+L1T
173/027	2008	10	27	0%	LE7+L1T
173/027	2009	5	7	34%	LE7+L1T
173/027	2009	5	23	5%	LE7+L1T
173/027	2009	6	8	0%	LE7+L1T
173/027	2009	6	16	11%	LT5
173/027	2009	6	24	0%	LE7+L1T
173/027	2009	7	2	0%	LT5
173/027	2009	7	18	43%	LT5
173/027	2009	7	26	1%	LE7+L1T
173/027	2009	8	3	2%	LT5
173/027	2009	8	19	11%	LT5
173/027	2009	8	27	23%	LE7+L1T
173/027	2009	9	4	80%	LT5
173/027	2009	9	20	58%	LT5
173/027	2010	5	26	74%	LE7+L1T

Appendix Figure 3. Total cropland (in thousands of hectares) in Rostov and Volgograd oblasts. Data Source: (ROSSTAT 2010)

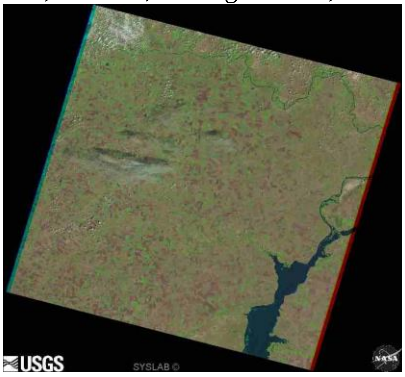
	Rostov	Volgograd
1995	4,621.7	3,992.1
1996	4,389.4	3,796.4
1997	4,110.8	3,582.3
1998	3,760.3	3,403.0
1999	3,872.8	2,779.2
2000	3,847.9	2,599.2
2001	4,086.7	2,637.3
2002	4,149.5	2,816.5
2003	4,063.7	2,522.0
2004	4,240.7	2,881.3
2005	4,180.1	2,979.3
2006	4,351.6	3,102.3
2007	4,519.9	3,110.7
2008	4,552.2	3,164.1
2009	4,499.4	3,075.0

Appendix Figure 4. Algal bloom events seen in Landsat images. Data Source: (USGS 2014)

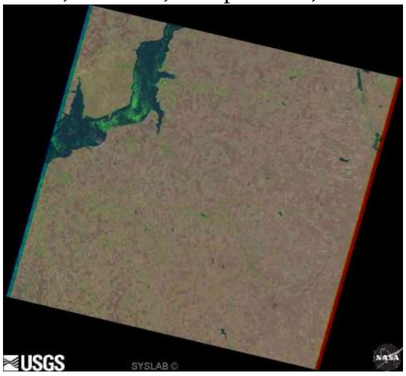
#1, 173/026, 14 July 1990, L1



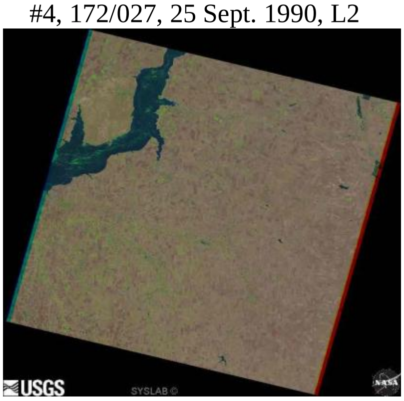
#2, 173/026, 15 August 1990, L1



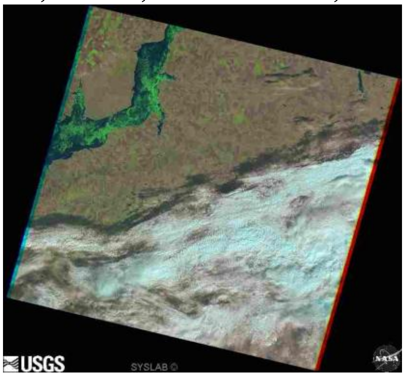
#3, 172/027, 9 Sept. 1990, L3



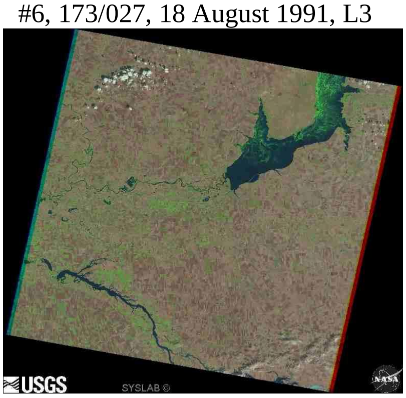
#4, 172/027, 25 Sept. 1990, L2



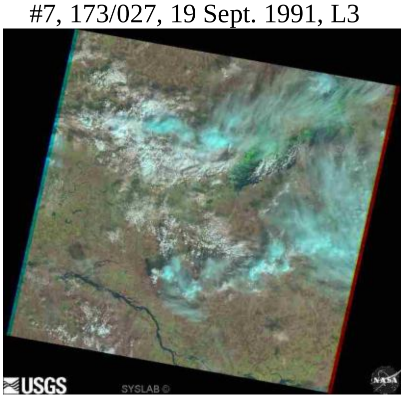
#5, 172/027, 11 October 1990, L3



#6, 173/027, 18 August 1991, L3



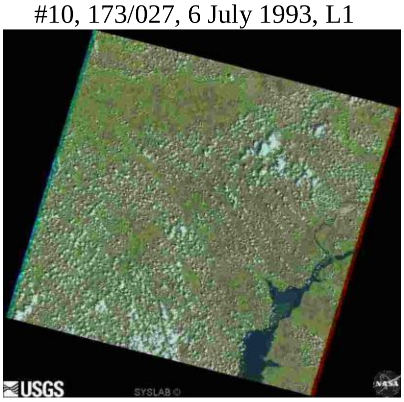
#7, 173/027, 19 Sept. 1991, L3



#8, 173/027, 5 October 1991, L1

#9, 173/027, 21 October 1991, L1

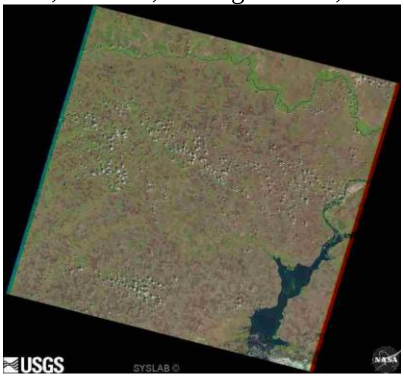
#10, 173/027, 6 July 1993, L1



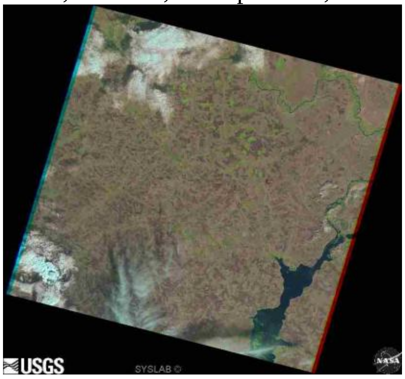
#11, 173/027, 24 Sept. 1993, L2

#12, 173/027, 10 October 1993, L2

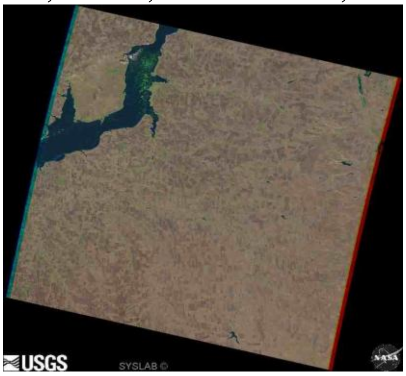
#13, 173/026, 26 August 1994, L1



#14, 173/026, 27 Sept. 1994, L2

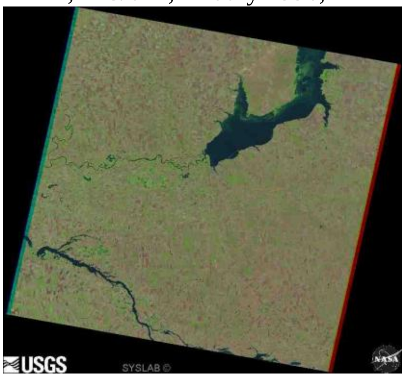


#15, 172/027, 22 October 1994, L2

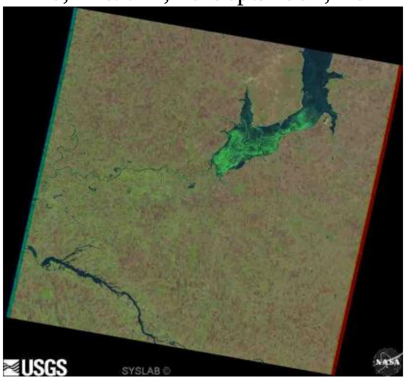


#16, 173/027, 29 August 1995, L2

#17, 173/027, 14 July 1996, L2

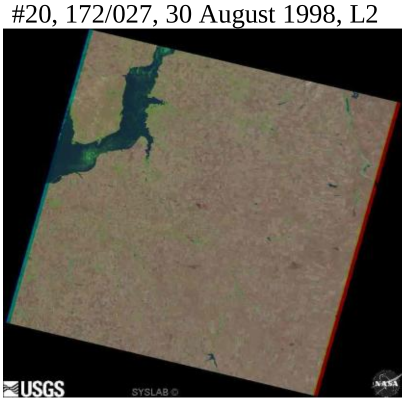


#18, 173/027, 19 Sept. 1997, L3

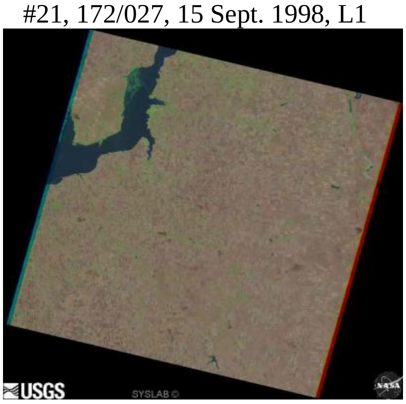


#19, 173/026, 20 July 1998, L2

#20, 172/027, 30 August 1998, L2

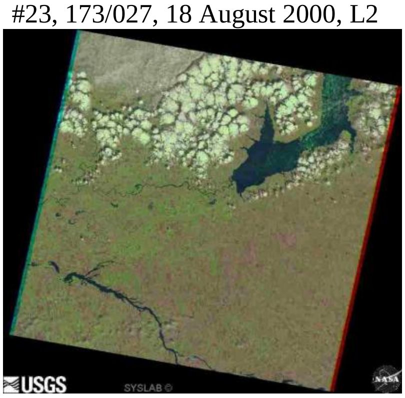


#21, 172/027, 15 Sept. 1998, L1

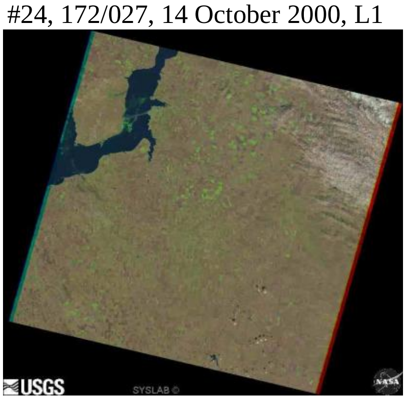


#22, 173/026, 3 October 1999, L2

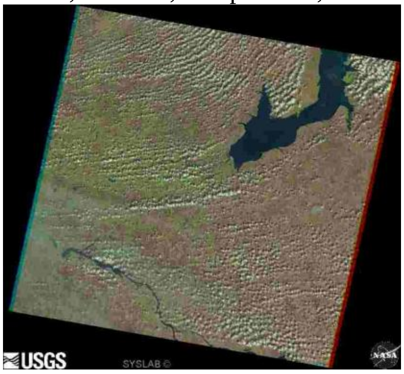
#23, 173/027, 18 August 2000, L2



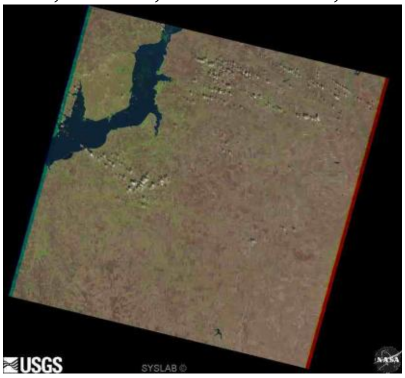
#24, 172/027, 14 October 2000, L1



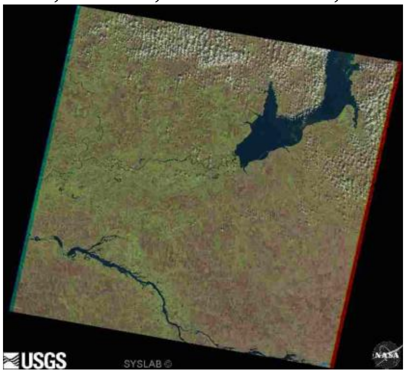
#25, 173/027, 6 Sept. 2001, L1



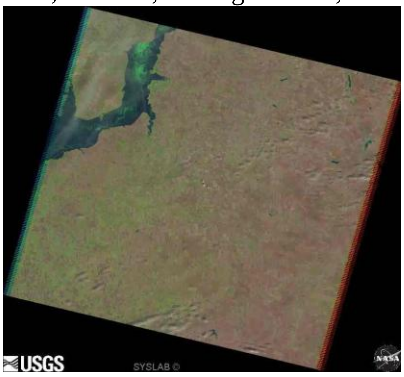
#26, 172/027, 1 October 2001, L1



#27, 173/027, 8 October 2001, L1

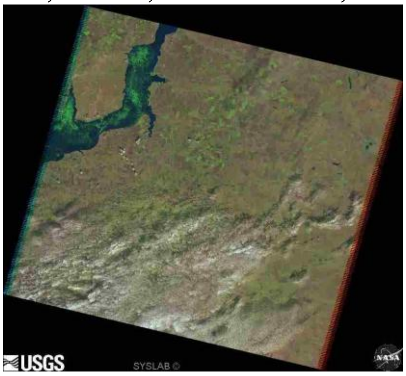


#28, 172/027, 28 August 2003, L2



#29, 173/027, 20 Sept. 2003, L3

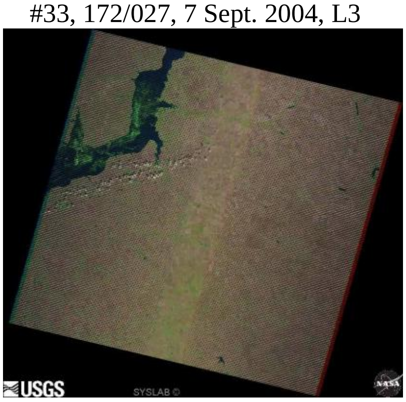
#30, 172/027, 15 October 2003, L3



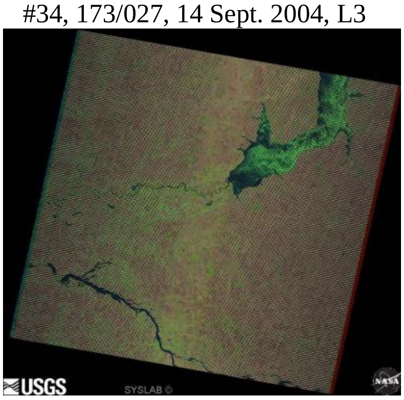
#31, 172/027, 5 July 2004, L2

#32, 173/027, 29 August 2004, L1

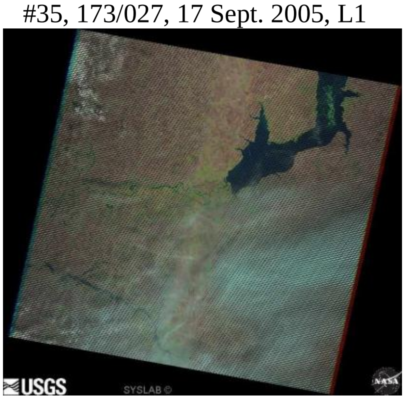
#33, 172/027, 7 Sept. 2004, L3



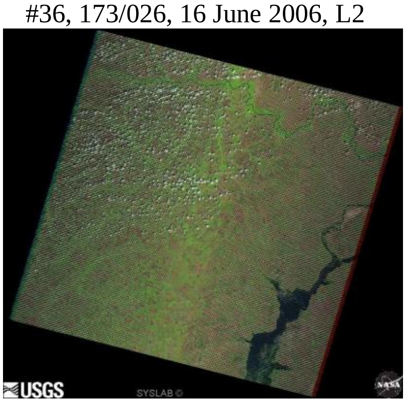
#34, 173/027, 14 Sept. 2004, L3



#35, 173/027, 17 Sept. 2005, L1



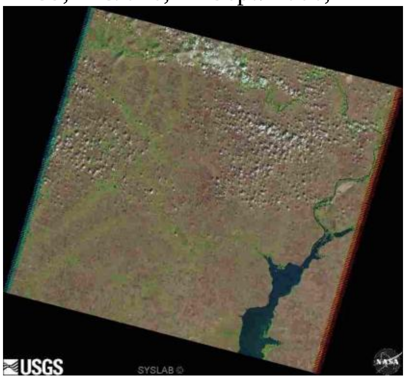
#36, 173/026, 16 June 2006, L2



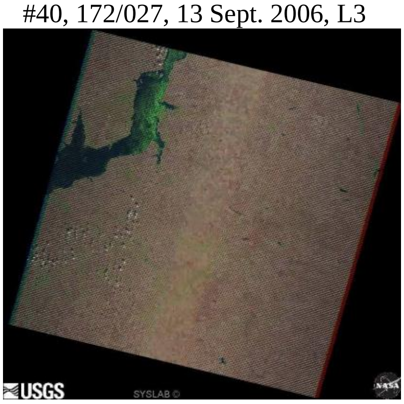
#37, 173/027, 11 August 2006, L2

#38, 173/027, 19 August 2006, L1

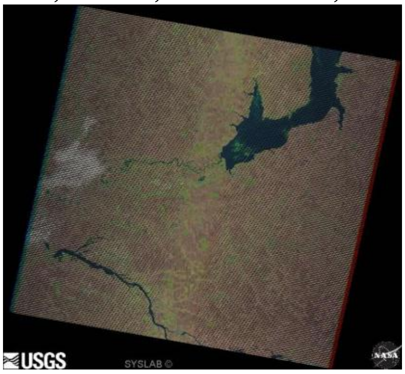
#39, 173/026, 12 Sept. 2006, L1



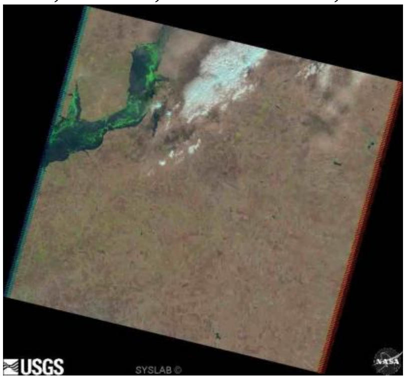
#40, 172/027, 13 Sept. 2006, L3



#41, 173/027, 6 October 2006, L1

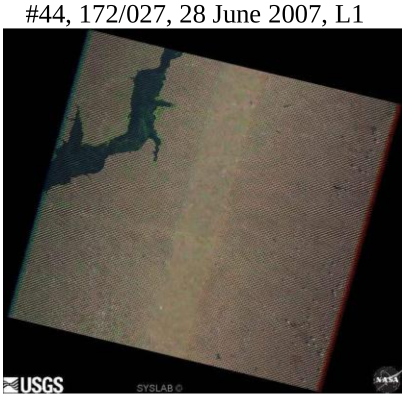


#42, 172/027, 7 October 2006, L3



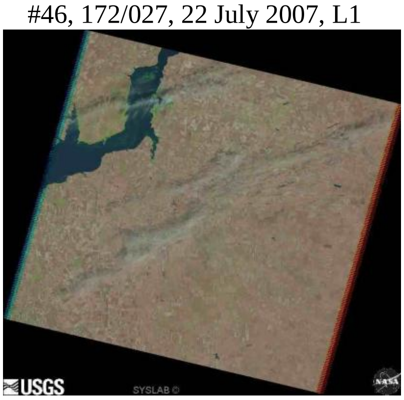
#43, 173/027, 14 October 2006, L1

#44, 172/027, 28 June 2007, L1

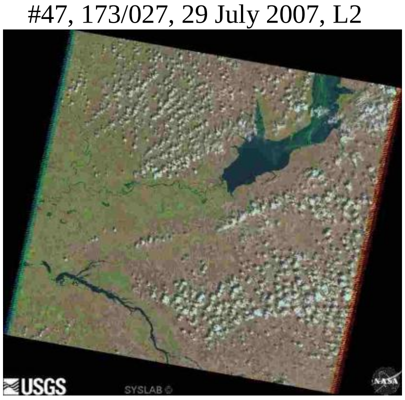


#45, 173/027, 13 July 2007, L1

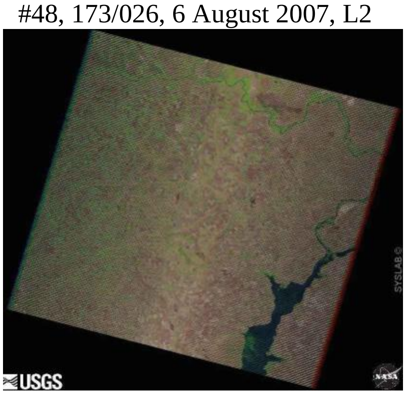
#46, 172/027, 22 July 2007, L1



#47, 173/027, 29 July 2007, L2

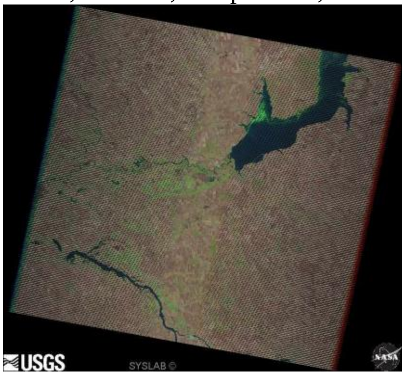


#48, 173/026, 6 August 2007, L2

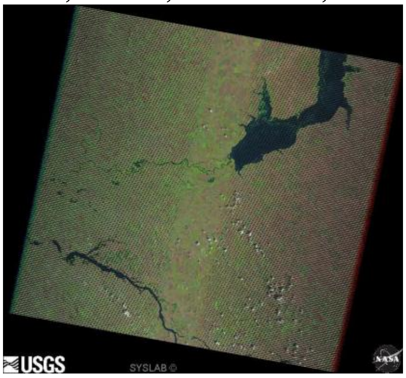


#49, 172/027, 2 Sept. 2008, L3

#50, 173/027, 9 Sept. 2008, L1



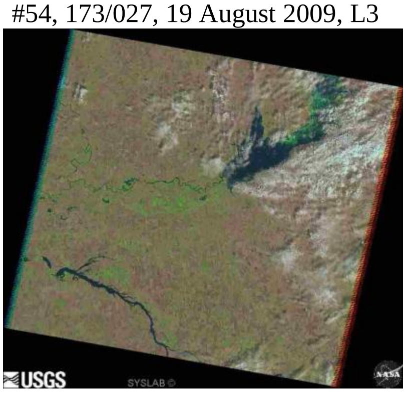
#51, 173/027, 24 June 2009, L1



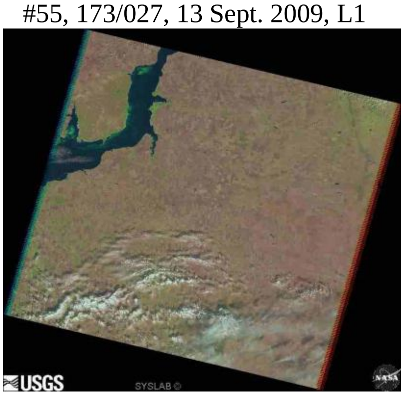
#52, 173/026, 26 July 2009, L1

#53, 173/027, 3 August 2009, L1

#54, 173/027, 19 August 2009, L3



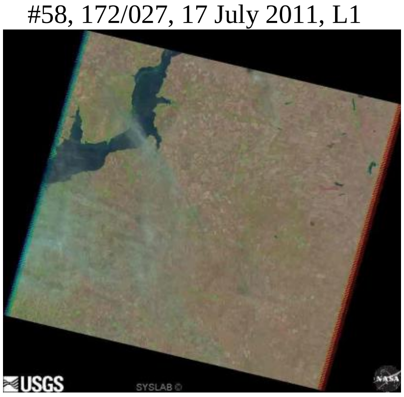
#55, 173/027, 13 Sept. 2009, L1



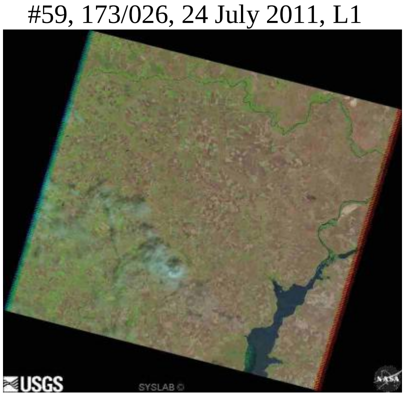
#56, 172/027, 29 Sept. 2009, L3

#57, 172/027, 30 July 2010, L1

#58, 172/027, 17 July 2011, L1



#59, 173/026, 24 July 2011, L1

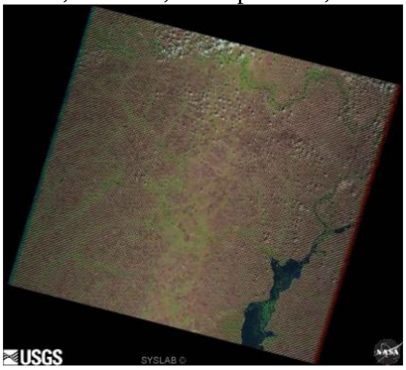


#60, 173/027, 17 August 2011, L1

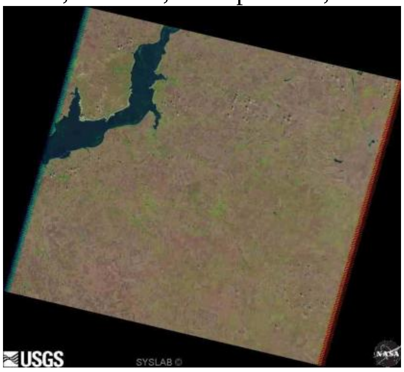
#61, 172/027, 26 August 2011, L1

#62, 173/027, 2 Sept. 2011, L1

#63, 173/026, 18 Sept. 2011, L2

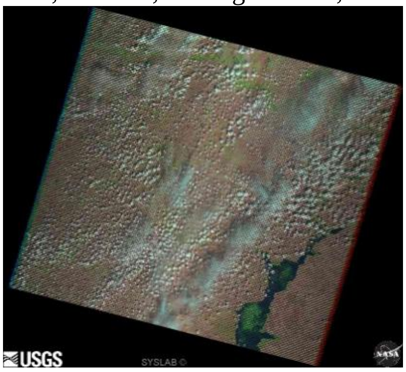


#64, 172/027, 19 Sept. 2011, L1

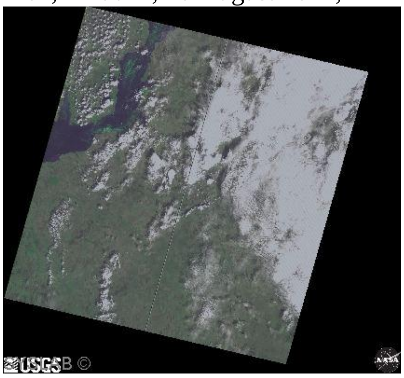


#65, 173/027, 3 August 2012, L1

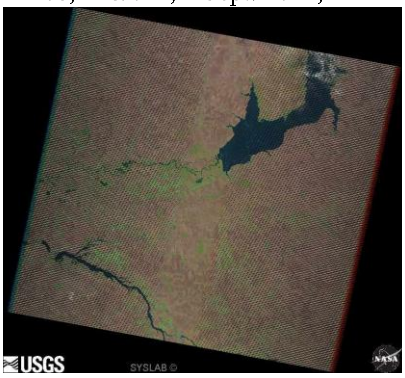
#66, 173/026, 19 August 2012, L2



#67, 172/027, 20 August 2012, L2

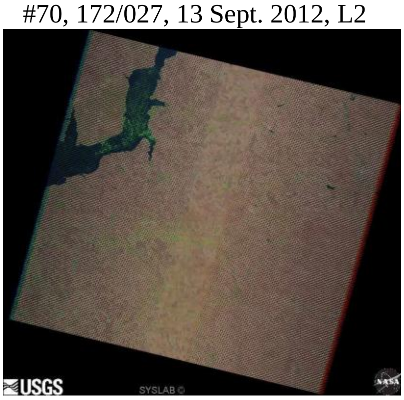


#68, 173/027, 4 Sept. 2012, L1

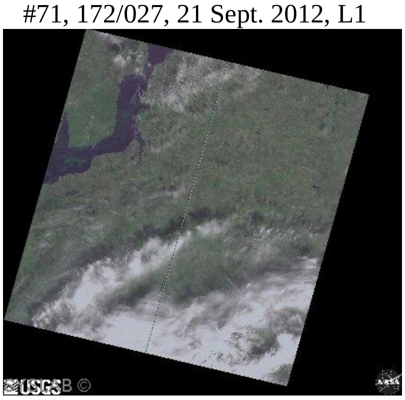


#69, 173/027, 12 Sept. 2012, L3

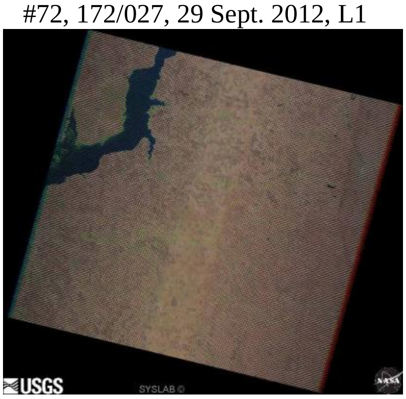
#70, 172/027, 13 Sept. 2012, L2



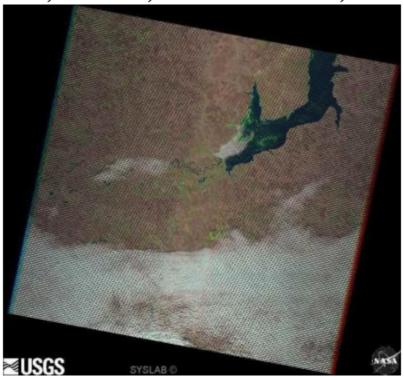
#71, 172/027, 21 Sept. 2012, L1



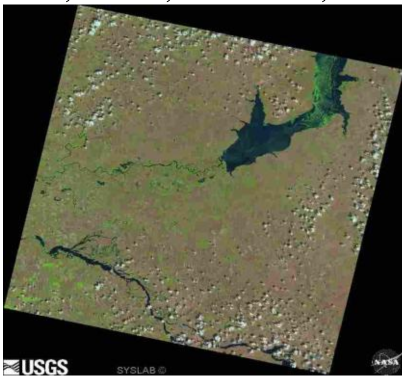
#72, 172/027, 29 Sept. 2012, L1



#73, 173/027, 22 October 2012, L2



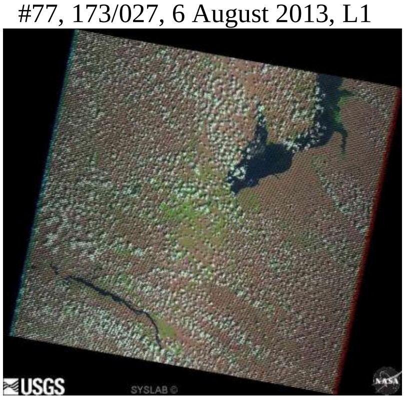
#74, 173/027, 27 June 2013, L3



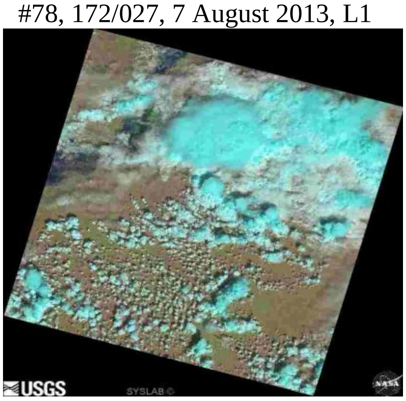
#75, 172/027, 6 July 2013, L1

#76, 173/026, 13 July 2013, L1

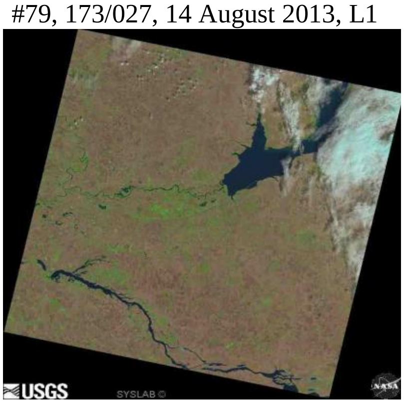
#77, 173/027, 6 August 2013, L1



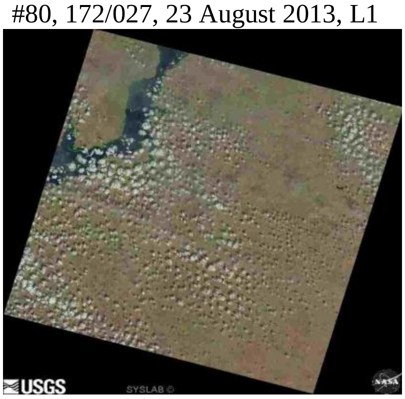
#78, 172/027, 7 August 2013, L1



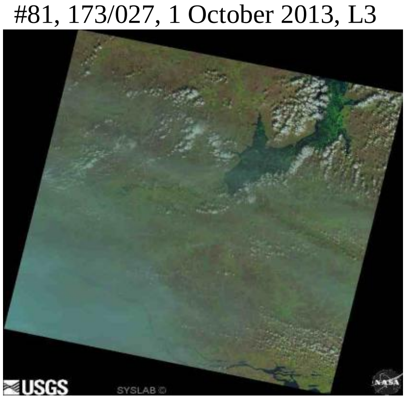
#79, 173/027, 14 August 2013, L1



#80, 172/027, 23 August 2013, L1

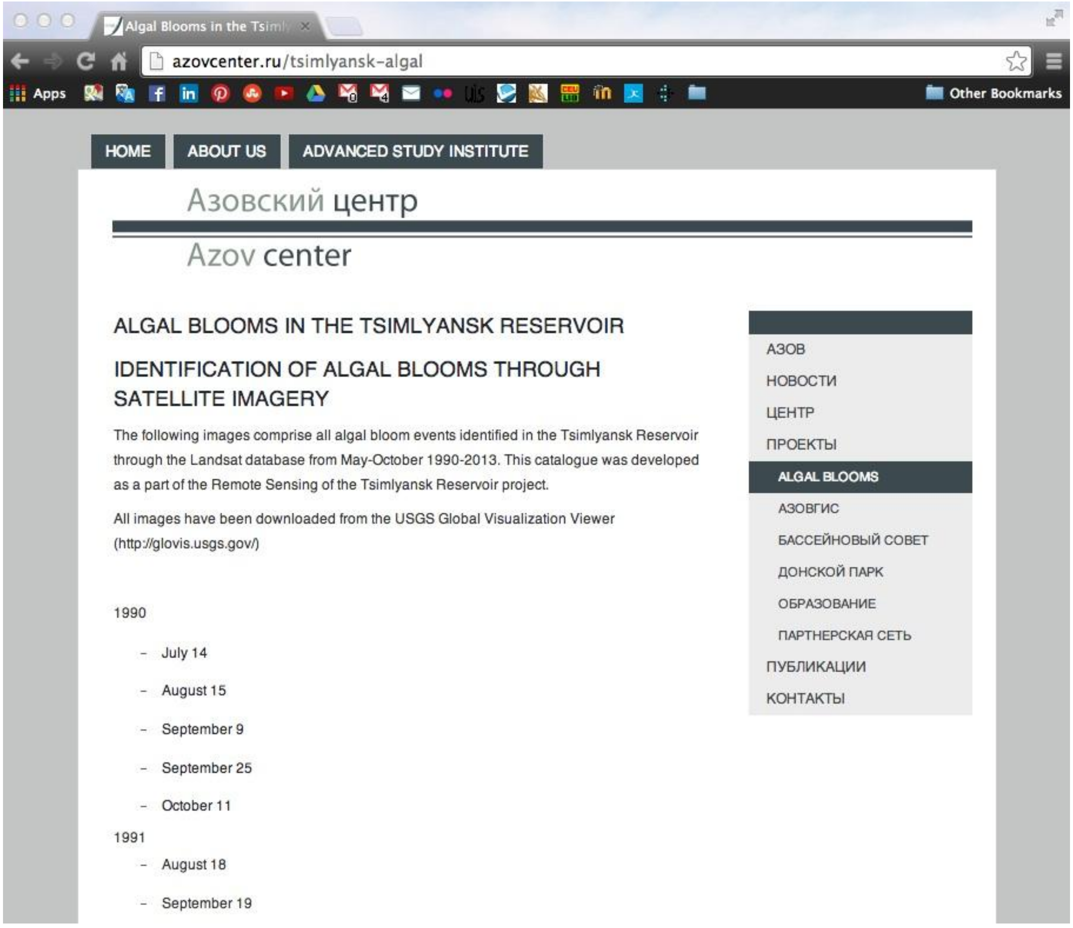


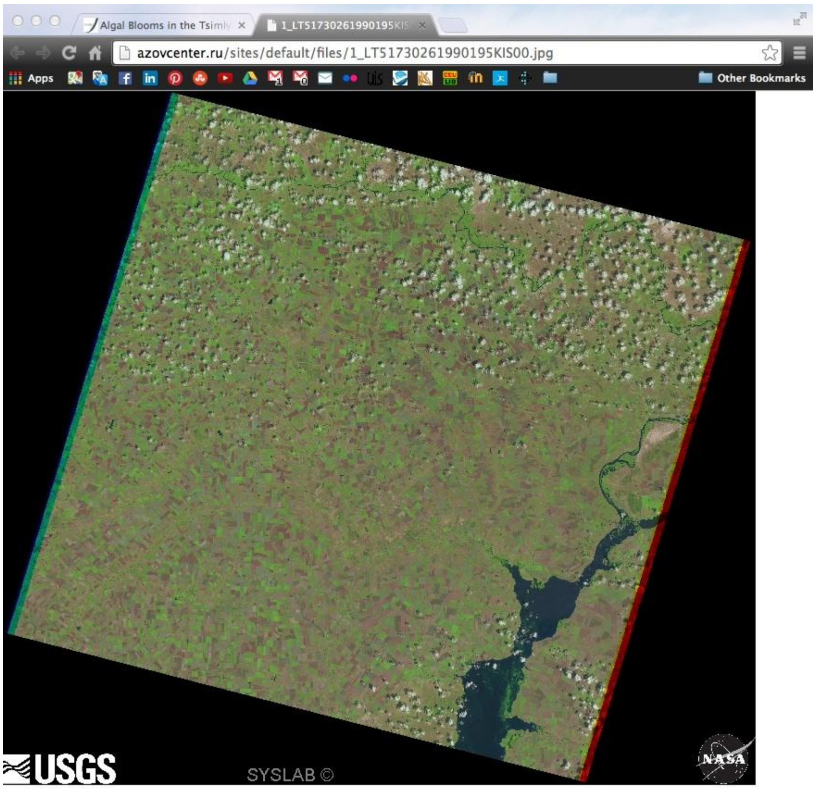
#81, 173/027, 1 October 2013, L3



#82, 172/027, 10 October 2013, L2

Appendix Figure 5. Screenshots of www.azovcenter.ru showing published algal bloom images identified through satellite imagery.



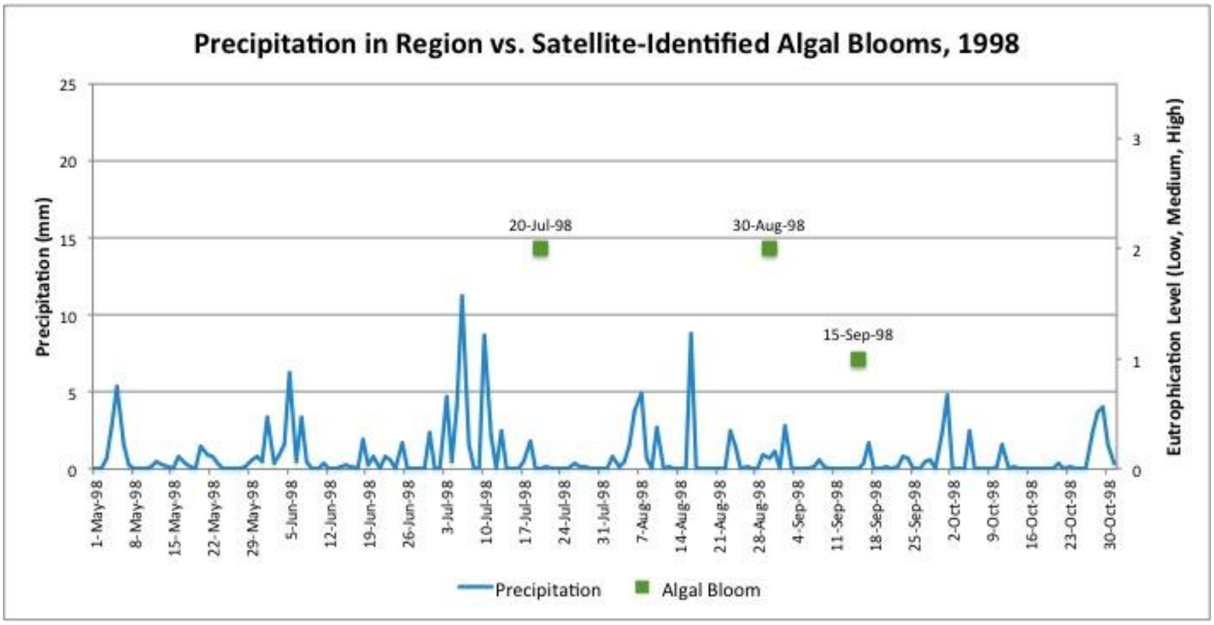


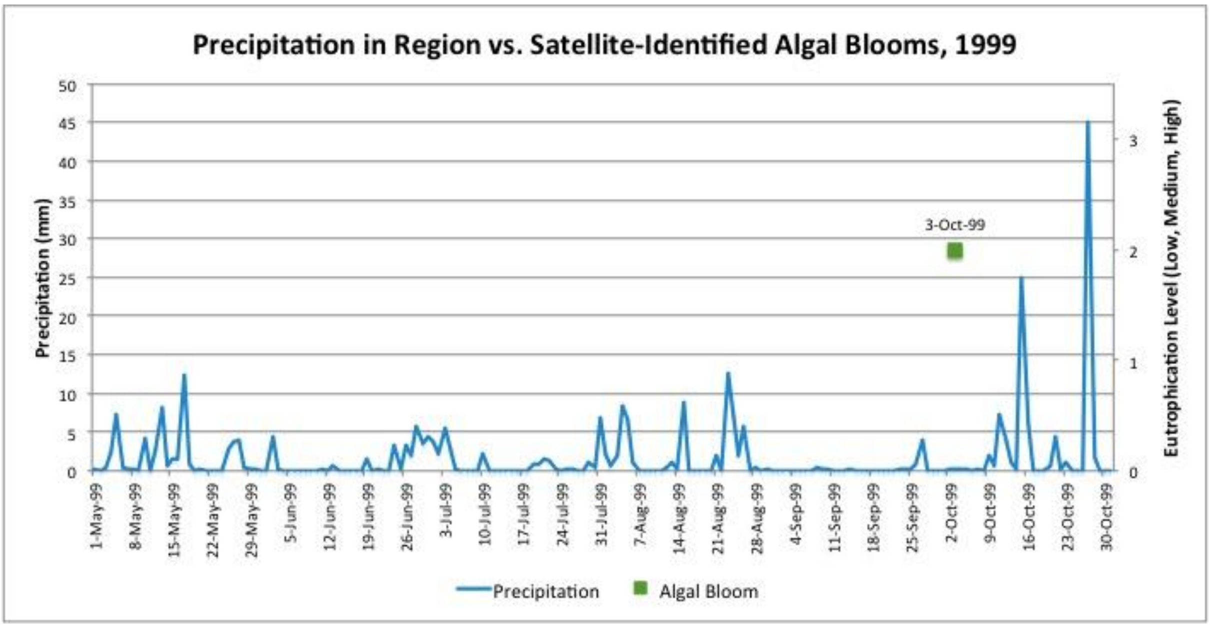
Appendix Figure 6. Determination of algal bloom extent.

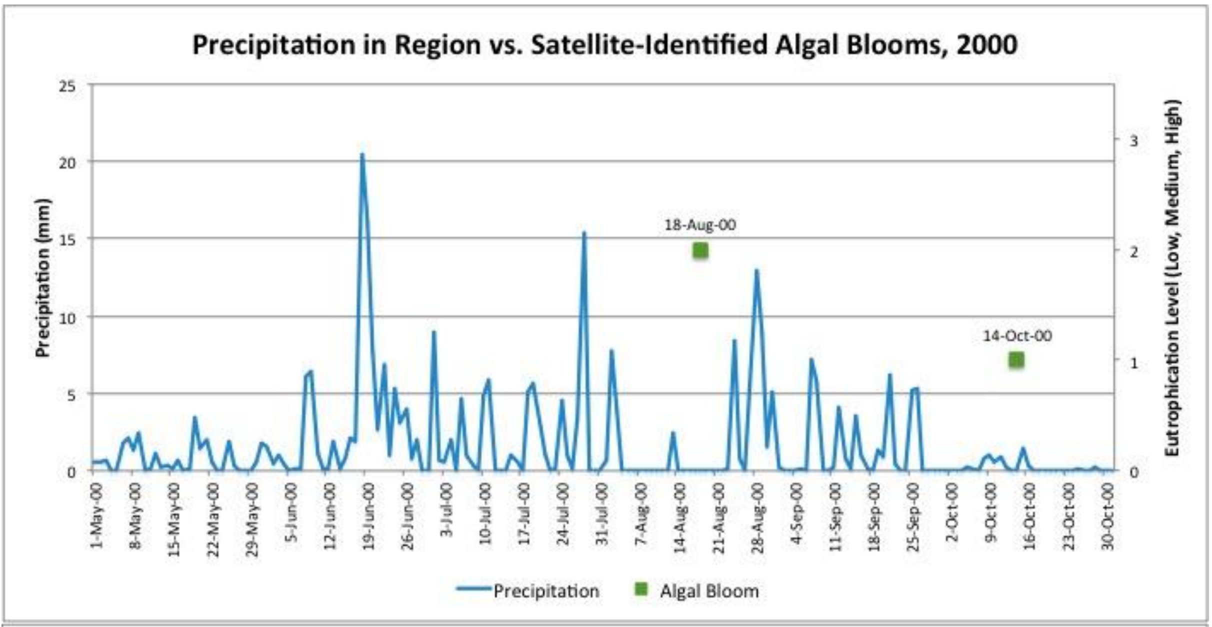
#	Tile	Date	Month	Satellite	Bloom Level	Amount of Reservoir	Level
1	173_026	14-Jul-90	July	LT5	Minor	Small section	1
2	173_026	15-Aug-90	August	LT5	Minor	Small section	1
3	172_027	9-Sep-90	September	LT5	Extensive	Large section	3
4	172_027	25-Sep-90	September	LT5	Moderate	Large section	2
5	172_027	11-Oct-90	October	LT5	Extensive	Large section	3
6	173_027	18-Aug-91	August	LT5	Extensive	Large section	3
7	173_027	19-Sep-91	September	LT5	Extensive	Large section	3
8	173_027	5-Oct-91	October	LT5	Minor	Small section	1
9	173_027	21-Oct-91	October	LT5	Minor	Medium section	1
10	173_026	6-Jul-93	July	LT5	Minor	Small section	1
11	173_027	24-Sep-93	September	LT5	Moderate	Large section	2
12	173_027	10-Oct-93	October	LT5	Moderate	Medium section	2
13	173_026	26-Aug-94	August	LT5	Minor	Small section	1
14	173_026	27-Sep-94	September	LT5	Moderate	Medium section	2
15	172_027	22-Oct-94	October	LT5	Moderate	Medium section	2
16	173_027	29-Aug-95	August	LT5	Moderate	Large section	2
17	173_027	14-Jul-96	July	LT5	Moderate	Medium section	2
18	173_027	19-Sep-97	September	LT5	Extensive	Large section	3
19	173_026	20-Jul-98	July	LT5	Moderate	Large section	2
20	172_027	30-Aug-98	August	LT5	Moderate	Medium section	2
21	172_027	15-Sep-98	September	LT5	Minor	Small section	1
22	173_026	3-Oct-99	October	LE7	Moderate	Medium section	2
23	173_027	18-Aug-00	August	LE7	Moderate	Large section	2
24	172_027	14-Oct-00	October	LE7	Minor	Small section	1
25	173_027	6-Sep-01	September	LE7	Minor	Medium section	1
26	172_027	1-Oct-01	October	LE7	Minor	Small section	1
27	173_027	8-Oct-01	October	LE7	Minor	Small section	1
28	172_027	28-Aug-03	August	LT5	Moderate	Large section	2
29	173_027	20-Sep-03	September	LT5	Extensive	Large section	3
30	172_027	15-Oct-03	October	LT5	Extensive	Large section	3
31	172_027	5-Jul-04	July	LE7	Moderate	Medium section	2
32	173_027	29-Aug-04	August	LE7	Minor	Medium section	1
33	172_027	7-Sep-04	September	LE7	Extensive	Large section	3
34	173_027	14-Sep-04	September	LE7	Extensive	Large section	3
35	173_027	17-Sep-05	September	LE7	Minor	Medium section	1
36	173_026	16-Jun-06	June	LE7	Moderate	Medium section	2
37	173_027	11-Aug-06	August	LT5	Moderate	Medium section	2
38	173_027	19-Aug-06	August	LE7	Minor	Small section	1
39	173_026	12-Sep-06	September	LT5	Minor	Small section	1
40	172_027	13-Sep-06	September	LE7	Extensive	Large section	3
41	173_027	6-Oct-06	October	LE7	Minor	Small section	1
42	172_027	7-Oct-06	October	LT5	Extensive	Large section	3
43	173_027	14-Oct-06	October	LT5	Minor	Small section	1
44	172_027	28-Jun-07	June	LE7	Minor	Medium section	1
45	173_027	13-Jul-07	July	LT5	Minor	Small section	1

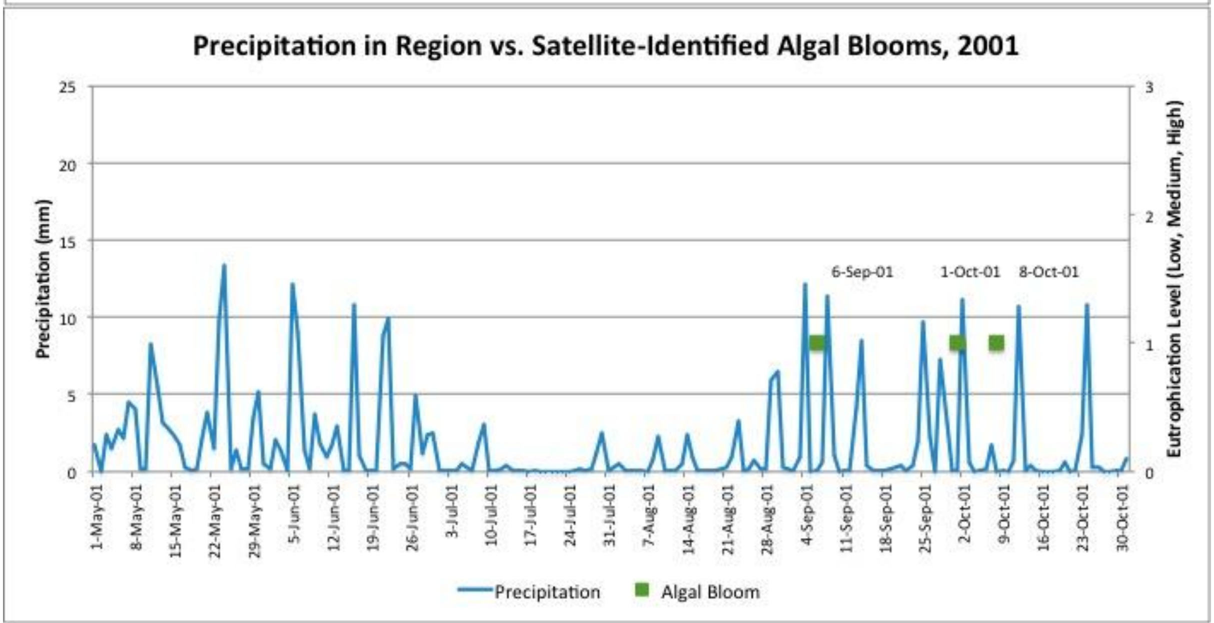
#	Tile	Date	Month	Satellite	Bloom Level	Amount of Reservoir	Level
46	172_027	22-Jul-07	July	LT5	Minor	Small section	1
47	173_027	29-Jul-07	July	LT5	Moderate	Medium section	2
48	173_026	6-Aug-07	August	LE7	Moderate	Medium section	2
49	172_027	2-Sep-08	September	LE7	Extensive	Large section	3
50	173_027	9-Sep-08	September	LE7	Minor	Medium section	1
51	173_027	24-Jun-09	June	LE7	Minor	Medium section	1
52	173_026	26-Jul-09	July	LE7	Minor	Medium section	1
53	173_027	3-Aug-09	August	LT5	Minor	Small section	1
54	173_027	19-Aug-09	August	LT5	Extensive	Large section	3
55	172_027	13-Sep-09	September	LT5	Minor	Medium section	1
56	172_027	29-Sep-09	September	LT5	Extensive	Large section	3
57	172_027	30-Jul-10	July	LT5	Minor	Small section	1
58	172_027	17-Jul-11	July	LT5	Minor	Small section	1
59	173_026	24-Jul-11	July	LT5	Minor	Small section	1
60	173_027	17-Aug-11	August	LE7	Minor	Medium section	1
61	172_027	26-Aug-11	August	LE7	Minor	Small section	1
62	173_027	2-Sep-11	September	LE7	Minor	Small section	1
63	173_026	18-Sep-11	September	LE7	Moderate	Medium section	2
64	172_027	19-Sep-11	September	LT5	Minor	Medium section	1
65	173_027	3-Aug-12	August	LE7	Minor	Medium section	1
66	173_026	19-Aug-12	August	LE7	Moderate	Medium section	2
67	172_027	20-Aug-12	August	LM5	Moderate	Medium section	2
68	173_027	4-Sep-12	September	LE7	Minor	Small section	1
69	173_027	12-Sep-12	September	LM5	Extensive	Large section	3
70	172_027	13-Sep-12	September	LE7	Moderate	Large section	2
71	172_027	21-Sep-12	September	LM5	Minor	Medium section	1
72	172_027	29-Sep-12	September	LE7	Minor	Small section	1
73	173_027	22-Oct-12	October	LE7	Moderate	Medium section	2
74	173_027	27-Jun-13	June	LC8	Extensive	Large section	3
75	172_027	6-Jul-13	July	LC8	Minor	Small section	1
76	173_026	13-Jul-13	July	LC8	Minor	Small section	1
77	173_027	6-Aug-13	August	LE7	Minor	Small section	1
78	172_027	7-Aug-13	August	LC8	Minor	Small section	1
79	173_027	14-Aug-13	August	LC8	Minor	Small section	1
80	172_027	23-Aug-13	August	LC8	Minor	Small section	1
81	173_027	1-Oct-13	October	LC8	Extensive	Large section	3
82	172_027	10-Oct-13	October	LC8	Moderate	Medium section	2

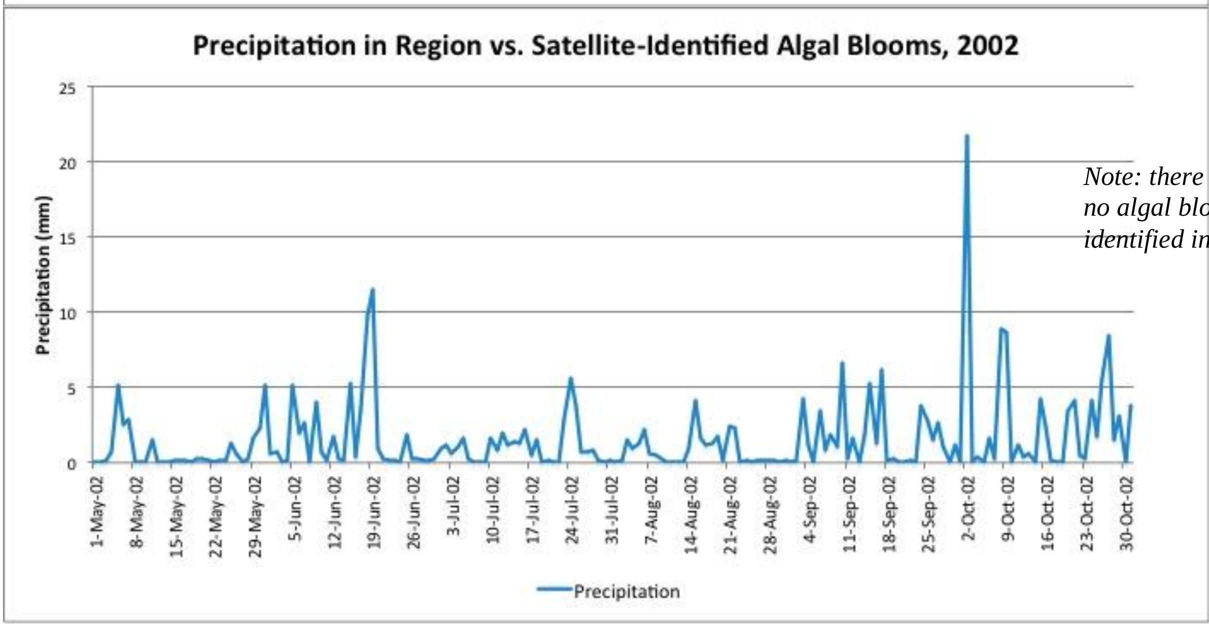
Appendix Figure 7. Precipitation vs. algal bloom graphs, 1998-2013. Data Source: (USGS 2014; NASA 2013a)



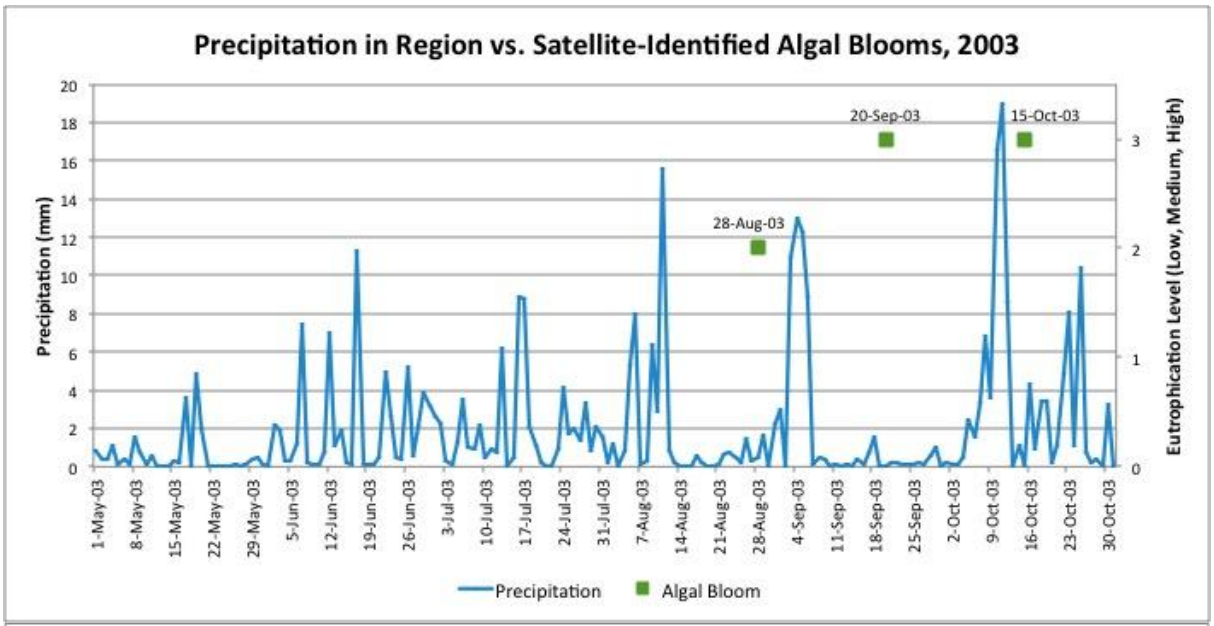




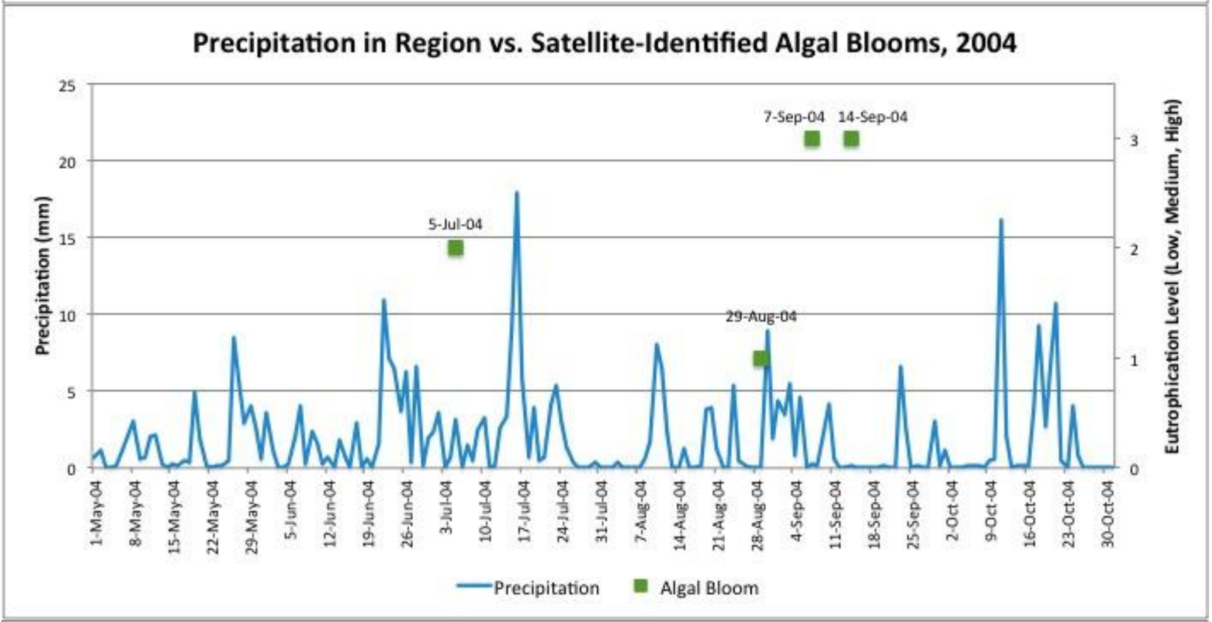




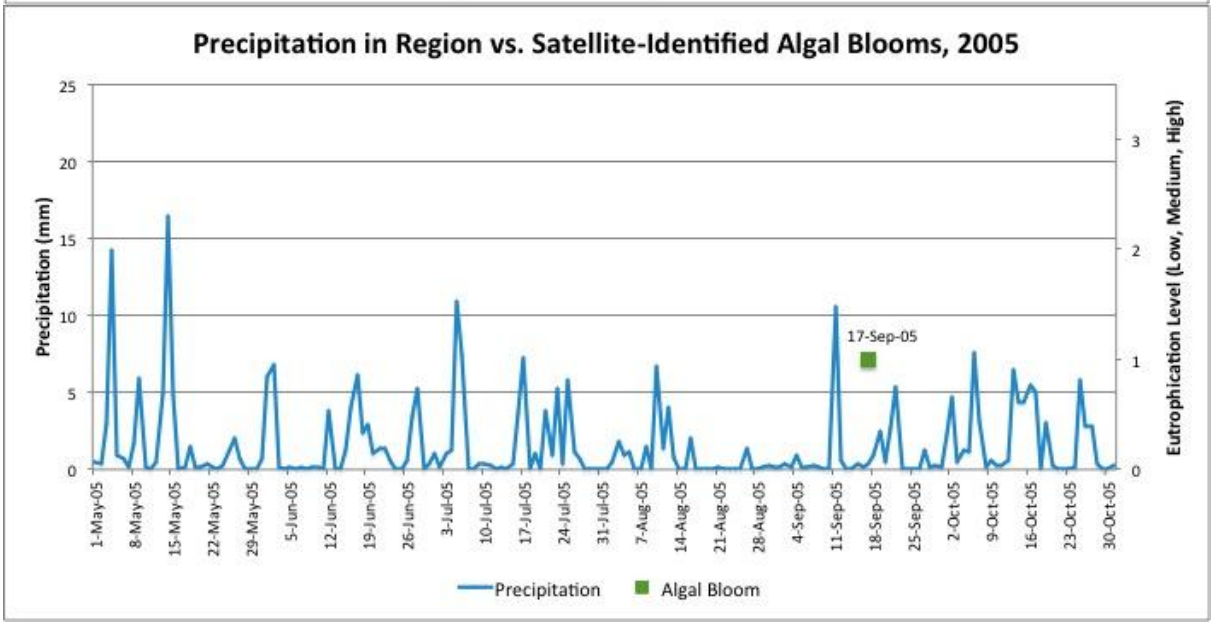
Note: there were no algal blooms identified in 2002.



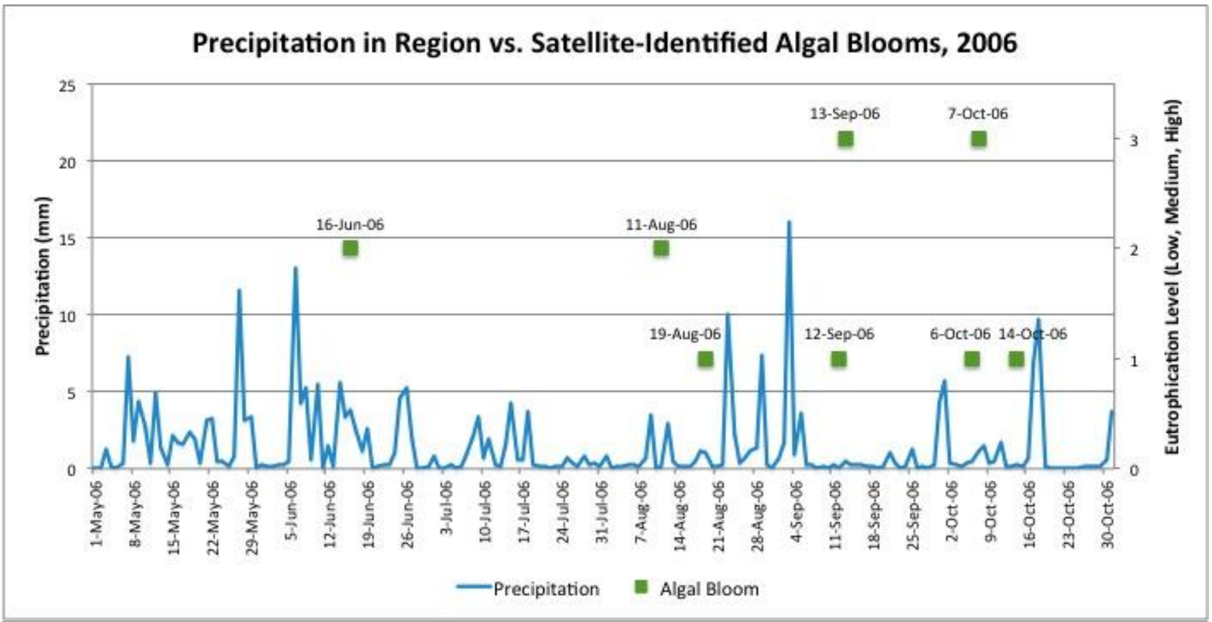
Precipitation in Region vs. Satellite-Identified Algal Blooms, 2003
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
28-Aug-03
20-Sep-03
15-Oct-03
Precipitation
Algal Bloom

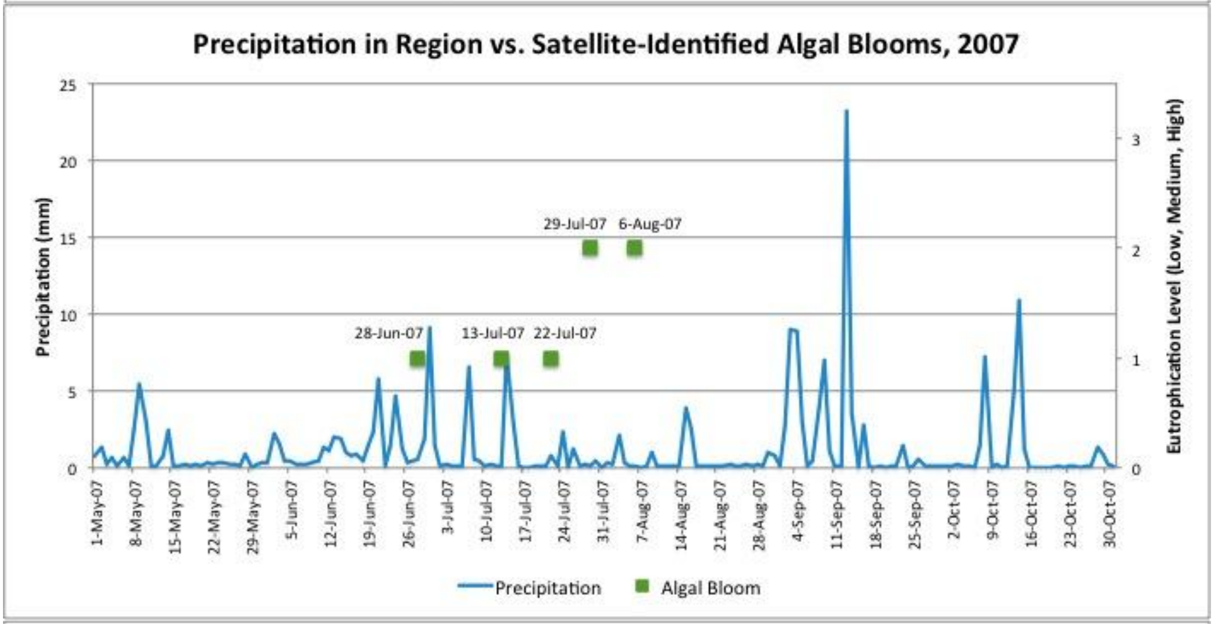


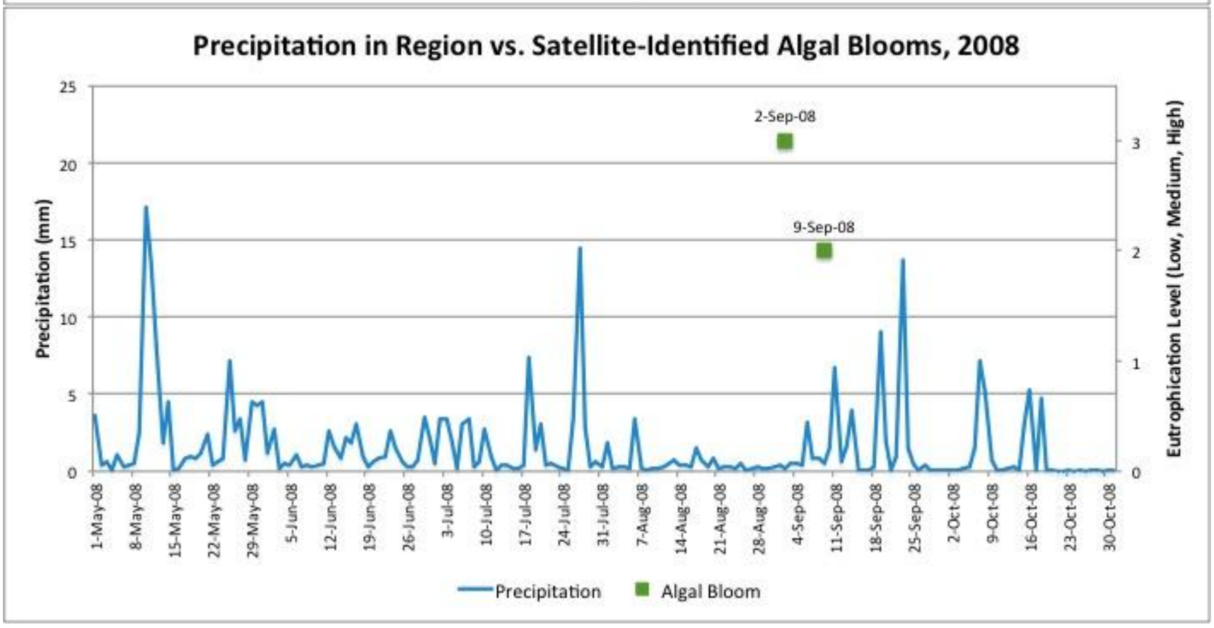
Precipitation in Region vs. Satellite-Identified Algal Blooms, 2004
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
5-Jul-04
29-Aug-04
7-Sep-04
14-Sep-04
Precipitation
Algal Bloom

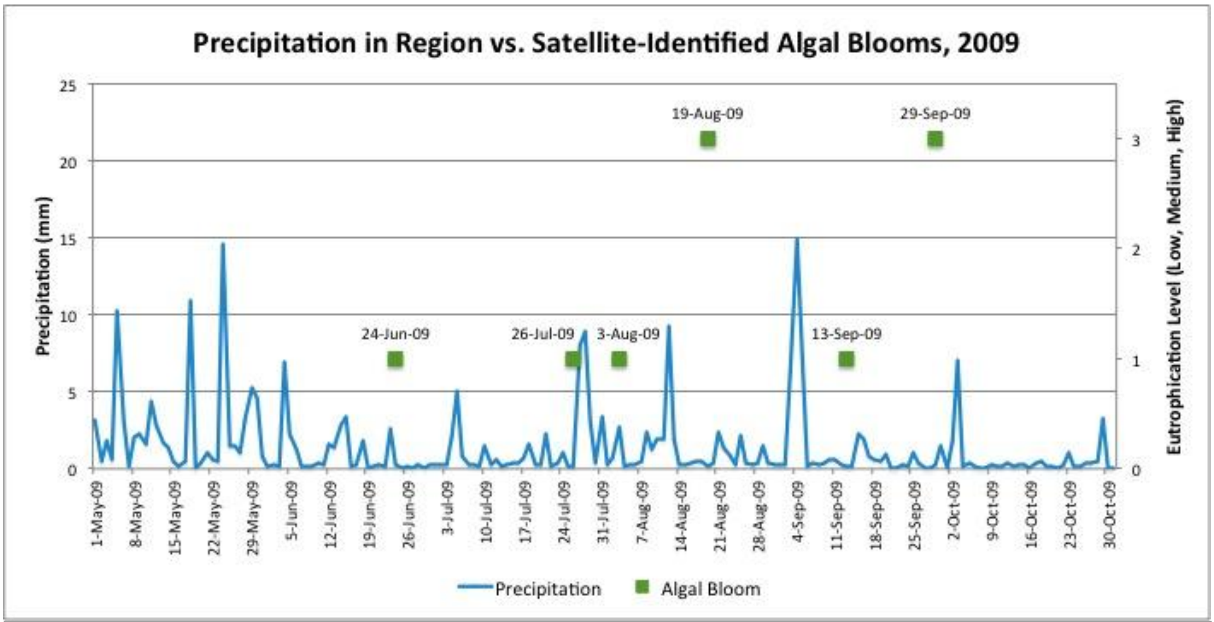


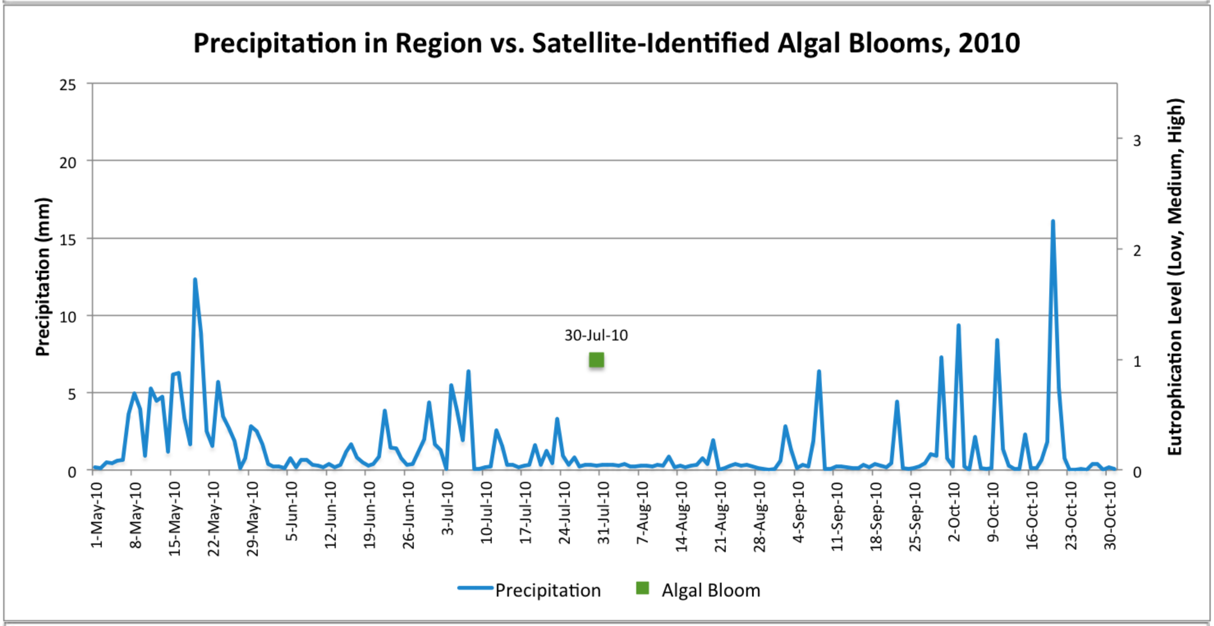
Precipitation in Region vs. Satellite-Identified Algal Blooms, 2005
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
17-Sep-05
Precipitation
Algal Bloom

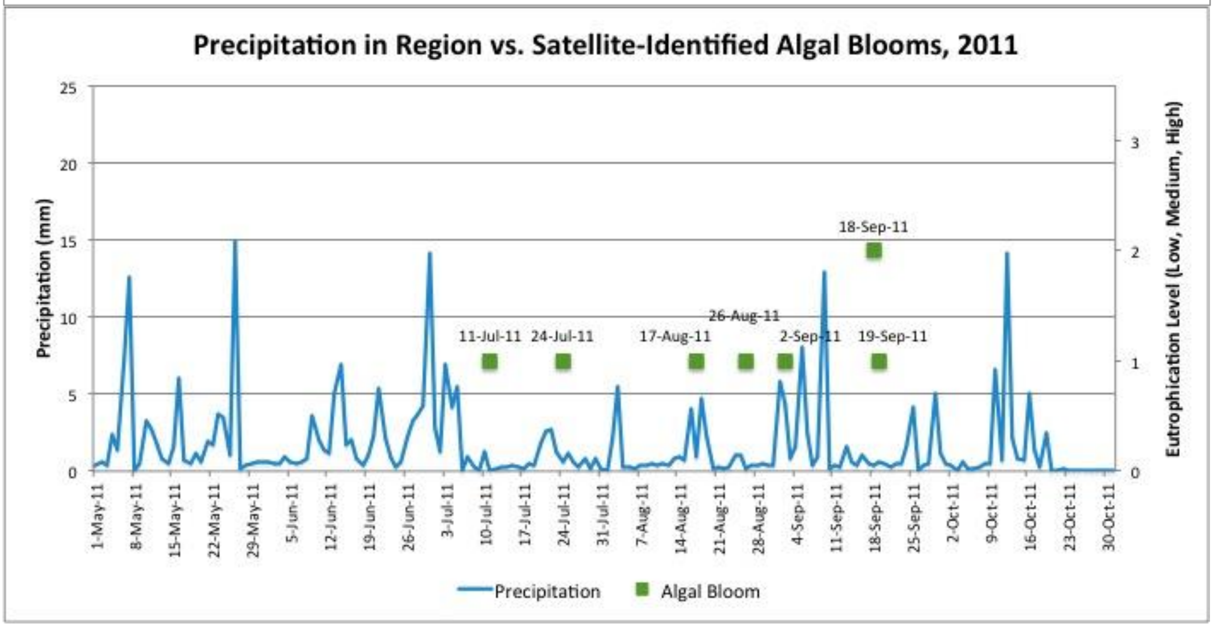

Precipitation in Region vs. Satellite-Identified Algal Blooms, 2006
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
13-Sep-06
7-Oct-06
16-Jun-06
11-Aug-06
19-Aug-06
12-Sep-06
6-Oct-06
14-Oct-06
Precipitation
Algal Bloom

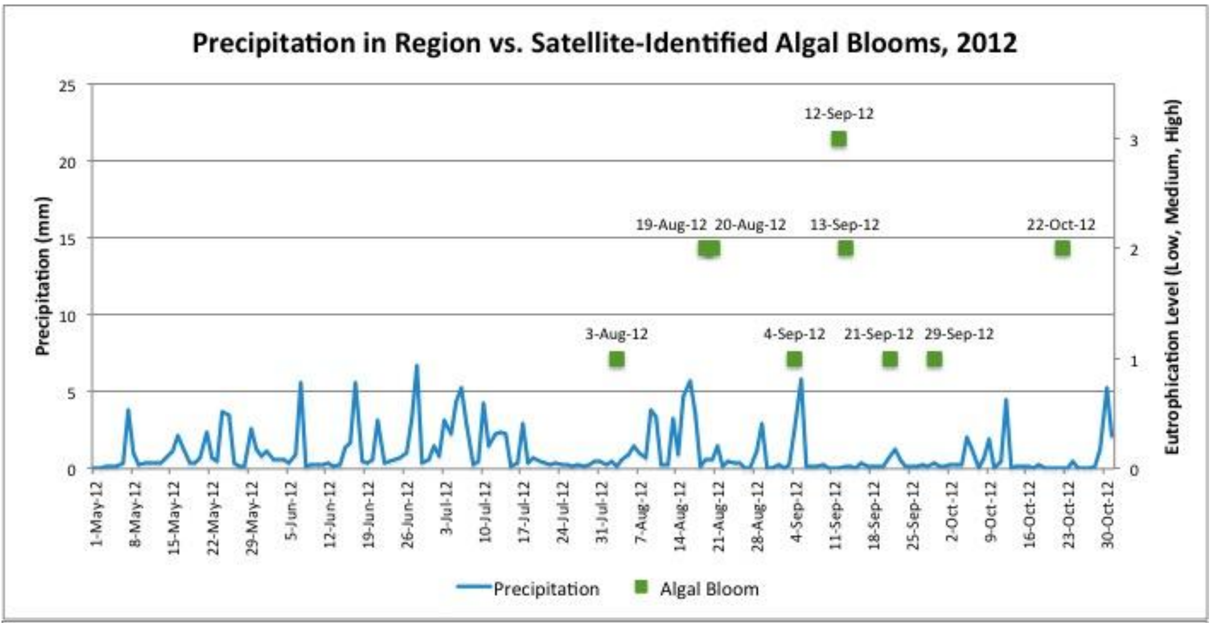

Precipitation in Region vs. Satellite-Identified Algal Blooms, 2007
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
29-Jul-07
6-Aug-07
28-Jun-07
13-Jul-07
22-Jul-07
Precipitation
Algal Bloom

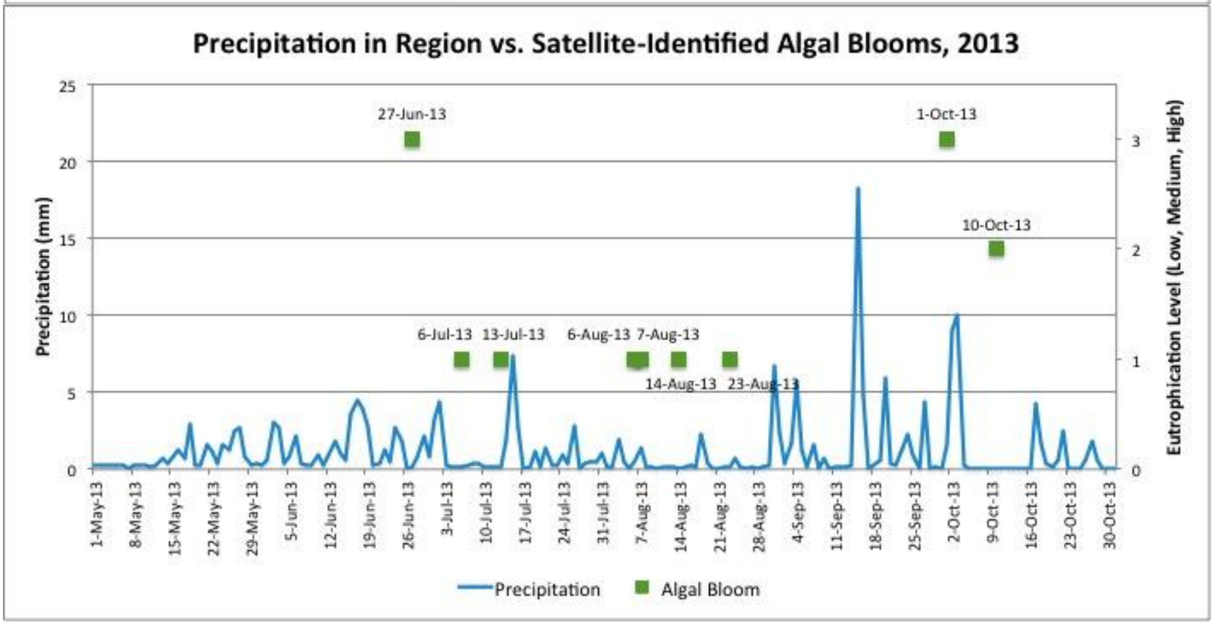

Precipitation in Region vs. Satellite-Identified Algal Blooms, 2008
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
2-Sep-08
9-Sep-08
Precipitation
Algal Bloom


Precipitation in Region vs. Satellite-Identified Algal Blooms, 2009
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
19-Aug-09
29-Sep-09
24-Jun-09
26-Jul-09
3-Aug-09
13-Sep-09
Precipitation
Algal Bloom


Precipitation in Region vs. Satellite-Identified Algal Blooms, 2010
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
30-Jul-10
Precipitation
Algal Bloom


Precipitation in Region vs. Satellite-Identified Algal Blooms, 2011
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
18-Sep-11
26-Aug-11
11-Jul-11
24-Jul-11
17-Aug-11
2-Sep-11
19-Sep-11
Precipitation
Algal Bloom


Precipitation in Region vs. Satellite-Identified Algal Blooms, 2012
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
3-Aug-12
19-Aug-12
20-Aug-12
4-Sep-12
12-Sep-12
13-Sep-12
21-Sep-12
29-Sep-12
22-Oct-12
Precipitation
Algal Bloom


Precipitation in Region vs. Satellite-Identified Algal Blooms, 2013
Precipitation (mm)
Eutrophication Level (Low, Medium, High)
27-Jun-13
6-Jul-13
13-Jul-13
6-Aug-13
7-Aug-13
14-Aug-13
23-Aug-13
1-Oct-13
10-Oct-13
Precipitation
Algal Bloom