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Using Remote Sensing to Explore the Time History of Emergent Vegetation at Malheur Lake, Oregon

Zola Yaa Apoakwaa Adjei

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Gustavious Paul Williams, Chair
A. Woodruff Miller
Everett James Nelson

Department of Civil and Environmental Engineering

Brigham Young University

March 2015

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ABSTRACT

Using Remote Sensing to Explore the Time History of Emergent Vegetation at Malheur Lake, Oregon

Zola Yaa Apoakwaa Adjei
Department of Civil and Environmental Engineering, BYU
Master of Science

The growth patterns of emergent vegetation can be a useful indicator for factors affecting lake health. However, field data to characterize emergent vegetation at many reservoirs may not be available or may be limited to small, isolated areas. We present a case study using remotely sensed data from the Landsat satellite to generate data to represent emergent vegetation in the near-shoreline and tributary delta areas of Malheur Lake, Oregon. We selected late June images for this study as vegetation is relatively mature in late June and visible, but has not completely grown-in providing a better indication of vegetation coverage in satellite images. We investigated the correlation of vegetation coverage (an indicator of emergent vegetation) with lake area on the day of the satellite collection, average daily maximum temperatures for April, May, June, and July, and average daily precipitation in June, all parameters that could affect vegetation. To estimate historic emergent vegetation extent, we computed the Normalized Difference Vegetation Index (NDVI) for 30 years of Landsat satellite images from 1984 to 2013. Around Malheur Lake we identified eight regions-of-interest (ROI): three inlet areas, three wet-shore areas (swampy areas), and two dry-shore areas (less swampy areas). For each ROI we generated time-series data to quantify the emergent vegetation as determined by the percent of area covered by pixels with NDVI values greater than 0.2. We measured lake area by computing the Modified Normalized Difference Water Index (MNDWI) and computing the area by summing the pixels that indicated water. We compared NDVI time-series values with the time series for lake area, June precipitation, and maximum daily temperatures for April, May, June, and July to determine if these parameters were correlated. Correlation would imply that emergent vegetation was influenced by the parameter.

We found that correlations of vegetative extent in any of the eight ROIs with the selected parameters were minimal, indicating that there are other factors besides the ones chosen that drive emergent vegetation levels in Malheur Lake. This study demonstrates that Landsat data have sufficient spatial and temporal detail for quantification and description of ecosystem changes and thus offer a good source of information to understand historic trends in reservoir health. We expect that future work will explore other potential drivers for emergent vegetation extent, such as carp populations in Malheur Lake which are known to affect emergent vegetation. Carp were not considered in this study as we did not have access to data that reflect carp numbers over this 30 year period.

Keywords: remote sensing, emergent vegetation, Landsat, NDVI time series, MNDWI

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TABLE OF CONTENTS

LIST OF TABLES v

LIST OF FIGURES vi

1 INTRODUCTION 1

1.1 Study Site 4

1.2 Background 6

2 METHODS 12

2.1 Remotely Sensed Data 12

2.1.1 Calibration and Processing 15

2.2 Normalized Difference Vegetation Index Analysis (NDVI) 15

2.3 Modified Normalized Difference Water Index (MNDWI) 17

2.4 Statistical Analysis 17

3 RESULTS AND DISCUSSION 18

3.1 NDVI Time Series Trends at 3 Selected Sites 18

3.2 Correlation Plots of NDVI Time Series with Climate Conditions 22

4 CONCLUSION 27

REFERENCES 29

APPENDIX A. CLIPPED VIEW OF REGIONS OF INTEREST 32

APPENDIX B. INDEX OF PRECIPITATION AND LAKE AREA INFORMATION 36

APPENDIX C. HISTORICAL TRENDS BY SEASON AND REGION OF INTEREST 39

LIST OF TABLES

Table 1-1 Landsat 5 TM and 7 ETM Band Distribution and Applications 2

Table 3-1 R-squared Dataset for Each of the Variable Comparisons 22

Table B- 1 Log of Malheur Lake Area Represented as Number of Pixels 36

Table B- 2 Average Precipitation Data Recorded for June from 1959 – 2013 37

Table C- 1 Late June Data for the 8 Regions of Interest by Date 39

LIST OF FIGURES

Figure 1-1 A False-Color Landsat 7 Image of Malheur Lake Acquired on July 30, 2013. Malheur Lake is the Location of the Malheur Lake National Wildlife Refuge in Harney County, Oregon 5

Figure 2-1 A False Color Landsat 7 Image Acquired on April 12, 2011 Showing Scan Line Correction Failures and Clouds, Both Issues that Affect the Data. 12

Figure 2-2 Labelled Sampling Locations where NDVI Data was Extracted to Examine the Trends in Emergent Vegetation from 1984 to 2013 14

Figure 2-3 Schematic of the Results Obtained from the NDVI Analysis. The Order was Applied to Vegetation Index Data from April 1984 to July 2013 16

Figure 3-1 Long Term Estimated Average of 0.2 – 0.4 Range of NDVI Values in Inlet 1 for Late June from 1984 to 2013.....19

Figure 3-2 Long Term Estimated Average of 0.2 – 0.4 Range of NDVI Values in Dry Shore 1 for Late June from 1984 to 2013 19

Figure 3-3 Long Term Estimated Average of 0.2 – 0.4 Range of NDVI Values in Wet Shore 1 for Late June from 1984 to 2013 20

Figure 3-4 Average Daily Precipitation for the Growing Season of Late June on Malheur Lake from 1987 to 2013.....20

Figure 3-5 Average Daily Precipitation for the Growing Season of Late June on Malheur Lake from 1987 to 2013. Note: There is Missing Data for 2007.....21

Figure 3-6 Comparison between NDVI Index at Inlet 1 and Malheur Lake Average May daily Maximum Temperature 24

Figure 3-7 Comparison between NDVI Index at Inlet 1 and Malheur Lake Average May Daily Maximum Temperature.....24

Figure 3-8 Comparison between NDVI Index at Inlet 1 and Malheur Lake Average June daily Maximum Temperature 25

Figure 3-9 Comparison between NDVI Index at Inlet 1 and Malheur Lake Average July Daily Maximum Temperature.....25

Figure 3-10 Comparison between NDVI Index at Inlet 1 and Malheur Lake Area (1984 - 2013) 26

Figure 3-11 Comparison between NDVI Index at Inlet 1 and Malheur Lake Average June Daily Precipitation (1984 – 2013).....26

Figure A- 1 Location of Inlet 1 Found at the Southwestern Region of Malheur Lake.....32

Figure A- 2 Location of Inlet 2 Found at the Southeastern Region of Malheur Lake.....33

Figure A- 3 Location of Inlet 2 found at the Northeastern Region of Malheur Lake.....33

Figure A- 4 Location of Wet Shore 1 Found at the Western Region of Malheur Lake.....34

Figure A- 5 Location of Wet Shore 1 Found at the Western Region of Malheur Lake.....34

Figure A- 6 Location Dry shore 1, Dry Shore 2 and Wet Shore 3 Found at the Western Region of Malheur Lake 35

Figure B- 1 True Color Image of the Extreme Wet Year Captured on June 28, 1984 and Extreme Drought Captured on June 18, 1992.....38

Figure C- 1 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Early April from 1984 to 2013 40

Figure C- 2 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Early April from 1984 to 2013 40

Figure C- 3 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Early April from 1984 to 2013 41

Figure C- 4 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Early April from 1984 to 2013.....41

Figure C- 5 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Early April from 1984 to 2013.....42

Figure C- 6 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Early April from 1984 to 2013.....42

Figure C- 7 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Early April from 1984 to 2013.....43

Figure C- 8 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Early April from 1984 to 2013.....43

Figure C- 9 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Late April from 1984 to 2013 44

Figure C- 10 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Late April from 1984 to 2013 44

Figure C- 11 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Late April from 1984 to 2013 45

Figure C- 12 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Late April from 1984 to 2013 45

Figure C- 13 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Late April from 1984 to 2013 46

Figure C- 14 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Late April from 1984 to 2013 46

Figure C- 15 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Late April from 1984 to 2013 47

Figure C- 16 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Late April from 1984 to 2013 47

Figure C- 17 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Early May from 1984 to 2013 48

Figure C- 18 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Early May from 1984 to 2013 48

Figure C- 19 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Early May from 1984 to 2013 49

Figure C- 20 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Early May from 1984 to 2013 49

Figure C- 21 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Early May from 1984 to 2013 50

Figure C- 22 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Early May from 1984 to 2013 50

Figure C- 23 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Early May from 1984 to 2013 51

Figure C- 24 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Early May from 1984 to 2013 51

Figure C- 25 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Late May from 1984 to 2013 52

Figure C- 26 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Late May from 1984 to 2013 52

Figure C- 27 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Late May from 1984 to 2013 53

Figure C- 28 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Late May from 1984 to 2013 53

Figure C- 29 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Late May from 1984 to 2013 54

Figure C- 30 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Late May from 1984 to 2013 54

Figure C- 31 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Late May from 1984 to 2013 55

Figure C- 32 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Late May from 1984 to 2013 55

Figure C- 33 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Early June from 1984 to 2013 56

Figure C- 34 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Early June from 1984 to 2013 56

Figure C- 35 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Early June from 1984 to 2013 57

Figure C- 36 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Early June from 1984 to 2013 57

Figure C- 37 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Early June from 1984 to 2013 58

Figure C- 38 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Early June from 1984 to 2013 58

Figure C- 39 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Early June from 1984 to 2013 59

Figure C- 40 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Early June from 1984 to 2013 59

Figure C- 41 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Late June from 1984 to 2013 60

Figure C- 42 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Late June from 1984 to 2013 60

Figure C- 43 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Late June from 1984 to 2013 61

Figure C- 44 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Late June from 1984 to 2013 61

Figure C- 45 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Late June from 1984 to 2013 62

Figure C- 46 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Early July from 1984 to 2013 62

Figure C- 47 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Early July from 1984 to 2013 63

Figure C- 48 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Early July from 1984 to 2013 63

Figure C- 49 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Early July from 1984 to 2013 64

Figure C- 50 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Early July from 1984 to 2013 64

Figure C- 51 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Early July from 1984 to 2013 65

Figure C- 52 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Early July from 1984 to 2013 65

Figure C- 53 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Early July from 1984 to 2013 66

Figure C- 54 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Late July from 1984 to 2013 66

Figure C- 55 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Late July from 1984 to 2013 67

Figure C- 56 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Late July from 1984 to 2013 67

Figure C- 57 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Late July from 1984 to 2013 68

Figure C- 58 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Late July from 1984 to 2013 68

Figure C- 59 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Late July from 1984 to 2013 69

Figure C- 60 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Late July from 1984 to 2013.....69

Figure C- 61 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Late July from 1984 to 2013.....70

1 INTRODUCTION

Remote sensing has proven to be a useful information source for understanding complex global change issues. Optical remote sensing relies on the principle that various materials absorb and reflect different wavelengths of light and that different materials can be identified using their reflective properties. Studies using remote sensing data have benefited many applications in the earth sciences and engineering fields, such as mapping and monitoring land covers and uses or characterizing hydrologic features, all based on reflective properties.

Remote sensing is an effective method for monitoring single lakes or comparing different lakes over a long period of time (Dekker, 1993). The Landsat TM sensor provides spatial and spectral characteristics suitable for analyzing reservoir conditions and has archival data well suited for performing long-term studies. Although Landsat Thematic Mapper TM provides a long term archive of spatial data, only a few studies have been done using this sensor to assess and analyze long term trends. The spatial resolution of TM imagery is approximately 30 m with three of the eight bands located in the visible portion of the spectrum, band 1 (0.45 – 0.52 μm), band 2 (0.52 – 0.60 μm) and band 3 (0.63 – 0.369 μm). The size of the lake used in this study, Malheur Lake, is large enough that the 30m pixel resolution is suitable (Sawaya, et al., 2003). The reflectance data measured by this sensor and its corresponding wavelengths allow for performing several applications and developing models as described in Table 1-1.

Table 1-1 Landsat 5 TM and 7 ETM Band Distribution and Applications

Band Number	Description	Wavelength (μm)	Example Use
Band 1	Blue	0.45-0.52	Bathymetry, soil/vegetation distinction
Band 2	Green	0.52-0.60	Peak vegetation, plant vigor
Band 3	Red	0.63-0.69	Discriminates vegetation slopes
Band 4	Near Infrared	0.77-0.90	Emphasizes biomass content, distinguishing shorelines
Band 5	Short-wave Infrared	1.55-1.75	Moisture content
Band 6	Thermal Infrared	10.40-12.50	Observes the effects of temperature
Band 7	Short-wave Infrared	2.09-2.35	Hydrothermally altered rocks, mineral deposits
Band 8 (Landsat 7 only)	Panchromatic	0.52-0.9	15 meter resolution

Ratios of these bands can be used to calculate various vegetation indices which are used in ecological research in predicting environmental changes in an ecosystem. These indices exploit the spectral differences based on the strong vegetation absorbance in the red and strong reflectance in the near-infrared part of the spectrum which allows vegetation to be identified (Singh, 1989). Singh's comparison of the different indices showed that the most accurate index for detecting change in vegetation is the Normalized Difference Vegetation Index (NDVI). This index is widely used to quantify vegetation coverage in remote sensing images and provides information on vegetation amounts and can be used to define land-use categories and differentiate types of vegetative cover (Justice, et al., 1985). NDVI and how it is computed will further be discussed later in the thesis.

Remote sensing applications are commonly used to perform spatial water quality analysis — typically looking at chlorophyll distributions as an indicator of algal populations ((Hansen, et al., 2013; Han & Rundquist, 1997; Mishra & Mishra, 2012; Kutser, et al., 2006). This area is still an active area of research with new methods recently reported such as a sub-seasonal approach based on seasonal algal succession to generate time histories of seasonal phytoplankton growth in reservoirs (Hansen, et al., 2014; Hansen, et al., 2013). Sub-seasonal models proved to be a more accurate method for mapping the distribution of chlorophyll-a across seasons by exploiting the change in reflectance of different algal communities. In this approach, estimates of the algae spatial distribution were computed. The metrics reported included averages, maximums, and other estimates of chlorophyll-a concentrations in a reservoir over a growing season, information that may not be available historically and data that are not feasible to collect with in-field sampling. Hansen et al. (2013) presented a case study that covered a period of 30 years – demonstrating the use of historic remote sensing data to study long-term trends in reservoir water quality. For many reservoirs or lakes, historic field data do not exist and remote sensing is the only method available to generate time histories. Such spatial time series analysis is possible because Landsat satellite images are available from the early 80s through the present which allows for temporal measurements, observations and analysis of change over time of various objects on the earth. In addition to presenting seasonal models, Hansen's team was the only set of researchers I could find who have published studies that exploit the long time history available in the Landsat data archive.

This study extends the work done by Hansen and coauthors, by applying the use of the long time period of available Landsat data to create and analyze time series of water quality in a reservoir. The main focus of the study evaluates the use of NDVI calculated using Landsat spectral measurements to generate time series and analyze the growth of emergent vegetation on

the Malheur lake perimeter from 1984 to 2013. This study also uses the long Landsat record to create a time series of lake area over the same time period and for the same collection used to calculate the NDVI. The NDVI time series was used to develop quantitative estimates of emergent vegetation and the correlation of this time series with other factors was computed to identify possible factors influencing trends in growth patterns. We evaluated historical trends for a number of parameters that could influence the extent of emergent vegetation. This study could continue and be extended as Landsat collects data every 16 days. New remote sensing information could be combined with additional field measurements to explore other correlations and determine the main drivers for the extent of emergent vegetation.

1.1 Study Site

The focus of this study is Malheur Lake (Figure 1-1), a terminal lake that has an average area of 35,000 to 45,000 acres with an approximate volume of 85,000 acre-feet and an elevation of about 4, 000 feet. The average depth is approximately 2 feet with a maximum depth of 5 feet. The primary inflows are the Donner und Blitzen River, the Silvies River, and Sodhouse Spring with a total watershed of approximately 3,000 square miles. Malheur Lake water flows into Mud Lake during above average water years and is a terminal lake in other years. In extreme flood conditions, Malheur, Mud and Harney Lake become one alkaline lake with no outflow.

Malheur Lake is located in the Malheur National Wildlife Refuge. The Refuge was established on August 18, 1908 by President Theodore Roosevelt as the Lake Malheur Bird Reservation. These unclaimed lands encompassed by Malheur, Mud and Harney Lakes were the 19th of 51 wildlife Refuges created by Roosevelt during his tenure as president. At the time Malheur was the third Refuge in Oregon and one of only six Refuges west of the Mississippi. The Refuge is located 30 miles south of Burns, Oregon in the southeast corner of the state.

Figure 1-1 A False-Color Landsat 7 Image of Malheur Lake Acquired on July 30, 2013. Malheur Lake is the Location of the Malheur Lake National Wildlife Refuge in Harney County, Oregon

While the Refuge's primary mission is to conserve habitat of the resident 320 species of birds and 58 mammals, fish habitat has become an important aspect of the habitat management program. As part of this program the Refuge has implemented research studies to help

understand how fish use the waterways, including studies of the migration of redband trout and other native fish, native fish spawning areas; population dynamics, and fish densities.

In the 1950's, common carp (Cyprinus carpio) were introduced to Malheur Lake with significant impacts to the ecological systems; in the absence of predators carp numbers exploded and led to decreased native submerged plant communities and diminished waterfowl use; estimated at 10-20% of historic values.

One of the biggest challenges in understanding the impacts carp have had on emergent vegetation health and how this relates to bird use on the Refuge—especially when trying to determine historic trends—is determining how the carp affect the vegetation in wetlands and ponds. Since carp are bottom feeders, sifting through mud searching for insects and plants, they can significantly impact wetlands (Roberts, et al., 1995). Carp not only uproot emergent vegetation, but feeding can also produce silt plumes in the water column, which makes it difficult for plant synthesis and insect production.

To address these issues the Refuge is developing a long-term strategy to control the carp and restore the local ecosystems. As a first step the Refuge has begun a number of studies, including this work, to better understand water quality and historic trends and to determine the various system drivers. This study specifically looks at late-June near-shoreline vegetation extent in eight regions-of-interest (ROIs), as an indicator of emergent vegetation, and evaluates water levels, spring temperatures, and June precipitation as potential drivers.

1.2 Background

The objective of this study is to use Landsat-5 TM and Landsat-7 Enhanced Thematic Mapper (ETM) band reflectance values to understand the time history of emergent vegetation

growth on the perimeter of the Malheur Lake assuming that late-June vegetation extent in near-shore areas can be used as an index to emergent vegetation.

We use NDVI to compute the extent of vegetation in the ROIs we selected. NDVI is the most widely used method in mapping vegetation with Landsat data because it produces the best discrimination statistics and provides data for visual interpretations from images and from field evaluations (Lyon, et al., 1998). The satellite-based NDVI is used globally as an indicator of the presence or absence of vegetation. NDVI is calculated as a normalized transform of the near-infrared (NIR) band and red band reflectance ratio and is an index of the absorptive and reflective characteristics of vegetation in the red and near-infrared portions of the electromagnetic spectrum.

The NDVI is computed as:

$$NDVI = \left(\frac{NIR - RED}{NIR + RED} \right) \qquad (1\text{-}1)$$

where NIR and RED represents the amount of near-infrared and red light, respectively, reflected by the vegetation and captured by the satellite sensor (Myneni, et al., 1995). The formula is based on the principle that chlorophyll absorbs RED (Landsat band 3) and the mesophyll leaf structure scatters NIR (Landsat band 4). For this study we use NDVI, light reflected and absorbed by green aquatic plants, to estimate plant cover, and by implication emergent vegetation extent, on the perimeter of Malheur Lake in eight ROIs. For purposes of this study we assume late-June vegetation cover area can be used as an indicator for emergent vegetation. We selected late-June vegetation to use as an indicator as by this date vegetation is visible, but not completely grown in, so areal coverage estimates are more accurate.

One issue with NDVI datasets is the problem of mixed pixels (Pettorelli, et al., 2005; Justice, et al., 1985). Mixed pixels result when a single pixel encompasses areas of water, land,

and vegetation. Traditionally NDVI is used over land, not water, and the NDVI value can be used as an indication of what percent of a pixel is covered with vegetation—though correlations change for different types of plants. However, when a pixel includes vegetation, water, and land, the NDVI value decreases because water has a negative NDVI value. While this is a known issue, we did not have any ground truth information to address the problem. We assume that we use enough pixels (several thousand in each ROI) that, on average, the general trends in emergent vegetation are correct, even though the actual ground cover percentage may be incorrect. In acknowledgement, we do not present the data as representing percent plant cover, but rather as a non-dimensional index to emergent vegetation.

To approximately quantify emergent vegetation extents, we computed the area in each ROI with an NDVI index from 0.2 to 0.4. This range lies within the corresponding scale of vegetation reflectance pixels for which emergent plants are found (USGS, 2015). This assumption, which may not be applicable for single pixels, on average should provide a good estimate of the amount of emergent vegetation in a given ROI that contains thousands of pixels. Also, while this value may not accurately reflect actual vegetation aerial extent, the relative values from year to year should allow development of a long-term series that approximates the behavior of emergent vegetation over time—showing relative increases and decreases in emergent vegetation even if the quantitative values are less accurate.

We computed the correlation of measured vegetation with lake levels for each ROI. If there was a significant impact from the mixed pixels, we would have expected a good, or at least some, correlation between NDVI and lake levels, as during high water levels pixels would include more water and during low levels more soil. Instead, the computed correlation was very low and is discussed later. This indicates that while mixed pixels containing water are a potential issue, the impact seems to be minimal.

There are other well documented potential issues with computed NDVI values such as the effect of cloud contamination, varying solar zenith angles and surface topography, which can be minimized using a maximum value compositing procedure (Holben, 1986; Pettorelli, et al., 2005; Fuller, 1998). The method smooths NDVI time series by retaining the highest NDVI value for the period and area considered. For a similar outcome in removing noise in NDVI datasets, we used the average of index values in an ROI yielding the same effect as the maximum value compositing approach.

High spatial satellite resolution datasets from LANDSAT, SPOT, and MODIS provide spatial quantification and description that are suitable for performing such vegetation studies and also appropriate for detecting long-term land-use/cover changes (Anyamba & Tucker, 2005; Chen, et al., 2004; Pettorelli, et al., 2005). Many of these studies apply NDVI time-series studies to identify fairly dense plant coverage constituting grasslands, shrubs or thorny trees in the ecosystem; the reflectance of emergent plants and other aquatic species have been less studied because of the difficulty in understanding results from water absorption in the infrared (Ackleson & V., 1987; Dervieux & Tamisier, 1987). At Searsville Lake, in coastal central California, the reflectance spectra of aquatic vegetation have been studied using a high-resolution hand-held spectroradiometer (Penuelas, et al., 1993). The size of the lake (approximately 49 acres) makes it ideal to use a spectral camera to capture few regions on the lake, an approach inapplicable to a lake as large as Malheur (approximately 45, 000 acres). The spectral camera used in the reported study has a large number of narrow bands that could better quantify different types of vegetation, while the Landsat spectral resolution gives less accurate spectral measurements because of a broad band image and relatively wide spectral range. However, while the Landsat spectral resolution does not match the camera used in the Searsville study, the large aerial coverage, long

data history, and frequent collection schedule make the use of Landsat data an appropriate choice for the size of the lake under study.

To analyze long-term emergent vegetation dynamics based on late-June vegetation extent in eight ROIs, we computed the correlation of the NDVI time series with time series of various potential drivers of emergent vegetation: lake level, June precipitation, and average maximum temperatures for April, May, June, and July. Similar approaches have been used in other studies which try to identify the drivers of change in emergent vegetation and biomass patterns (Anyamba & Tucker, 2005; Yu, et al., 2003; Wang, et al., 2003). These studies all showed a positive correlation of the rainfall and temperature time series with NDVI values, especially during the growing seasons.

We used Landsat images (the same images used to compute NDVI so they match in time) to determine lake area. We computed the lake area using the Modified Normalized Difference Water Index (MNDWI) to identify pixels that represented water, and then summed the area of each individual water pixel to determine lake area. Lake area for Malheur Lake was computed for each late-June Landsat image from 1984 to 2013. The MNDWI index was originally developed to delineate open water features and enhance their presence in remotely-sensed digital imagery. The initial normalized difference water index (NDWI) used a ratio of the near-infrared band (Landsat Band 4) and the visible green (Landsat Band 2) to identify water pixels (McFeeters, 1996). The NDWI was modified (called the MNDWI) for greater enhancement of water in satellite images by using the short wave infrared band (Landsat Band 5) of the Landsat sensor in place of the near-infrared band (Xu, 2006). The MNDWI is calculated as follows:

$$MNDWI = \frac{(GREEN - SWIR)}{(GREEN + SWIR)} \quad (1\text{-}2)$$

where GREEN is the green band (Landsat Band 2) and SWIR (Landsat Band 5) is the short-wave infrared band of Landsat TM satellite sensor. MNDWI will represent water features with greater positive values as water has higher absorption in the short-wave infrared region than in the near-infrared region. This approach proved to be a very useful method for estimating reservoir area as shorelines are constantly changing and information on the lake area can be difficult to measure for lakes or reservoirs without monitored outfalls. Similar to the manner in which NDVI has proven to be a simple and effective method in mapping vegetation, MNDWI has been used in several remote sensing applications to map shores or compute the volume of water in lake ecosystems (Lu, et al., 2013; Ouma & Tateishi, 2006).

2 METHODS

2.1 Remotely Sensed Data

The images used in this study were downloaded as Geotiff files from the USGS Explorer website from both Landsat 5 TM and 7 ETM satellites. All the Landsat images are located within path 43 and row 30 of the Landsat satellite orbit which captures the entire extent of the lake and its surrounding areas. Landsat 7 images acquired after May 2003, such as those used in this study, often exhibit black stripes. These missing pixels in the image are due to a scan line correction (SLC) failure on the satellite, and can cause errors in averaging NDVI values for an ROI if failed pixels are included in the average. Pixels affected by either SLC failures or clouds cannot be used to estimate vegetation coverage. Figure 2-1 shows an example of SLC failure and clouds in a Landsat 7 image acquired on April 12, 2011.

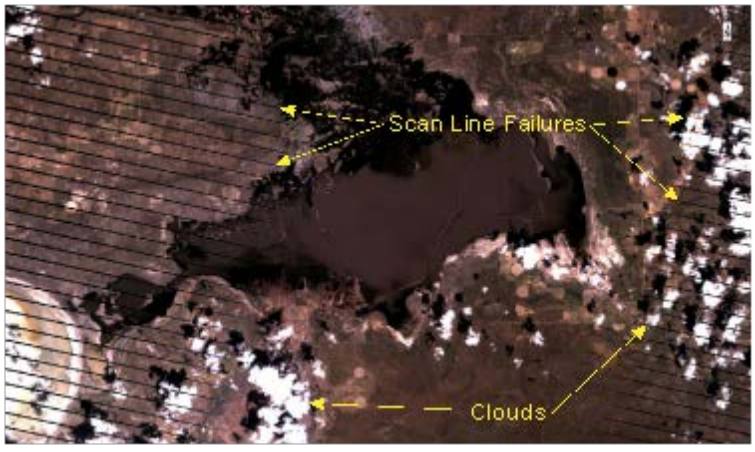

Figure 2-1 A False Color Landsat 7 Image Acquired on April 12, 2011 Showing Scan Line Correction Failures and Clouds, Both Issues that Affect the Data.

In addition to poor pixels, Landsat data must be corrected or calibrated to remove the effects of the atmosphere from the recorded data. Atmospheric effects are similar to haze that can be seen when looking over large distances. We calibrated the Landsat images to address this issue using standard routines in ENVI (Exelis, 2015).

While the study focuses on data from late June, we used data from four months for this study; April, May, June and July. All of the available satellite images for this time period were downloaded and categorized into early and late dates for each month. The typical season of emergent vegetation growth at Malheur Lake, based on observations from by lake ecologists, is from mid-June to late-June. We also analyzed April, May and July vegetation data to try to understand variability in the start and end of the growing season. These results are presented in Appendix C. As mentioned earlier, the range of dates span from 1984 to 2013. Field lake monitoring of the lake began in 1976, and include records of water quality and some lake level measurements.

We selected ROIs locations and boundaries using an image from a wet year (1984) shown in Figure B-1 of Appendix B. If we had used a dry year instead, much of the area in the ROIs would be covered with water in high-water years, yielding negative values of NDVI. Eight ROIs were chosen. In each ROI we computed an average of pixels with NDVI values from 0.2 to 0.4 to represent the percentage cover of emergent vegetation growth. The computed number acts as a non-dimensional index to emergent vegetation and does not have a physical meaning. The ROIs included two dry shore areas, three inlets and three wet shores areas around the lake. The locations of all 8 ROIs with their labels are shown in Figure 2-2. We assume that the ROIs we selected accurately capture regions of concern to the Refuge management.

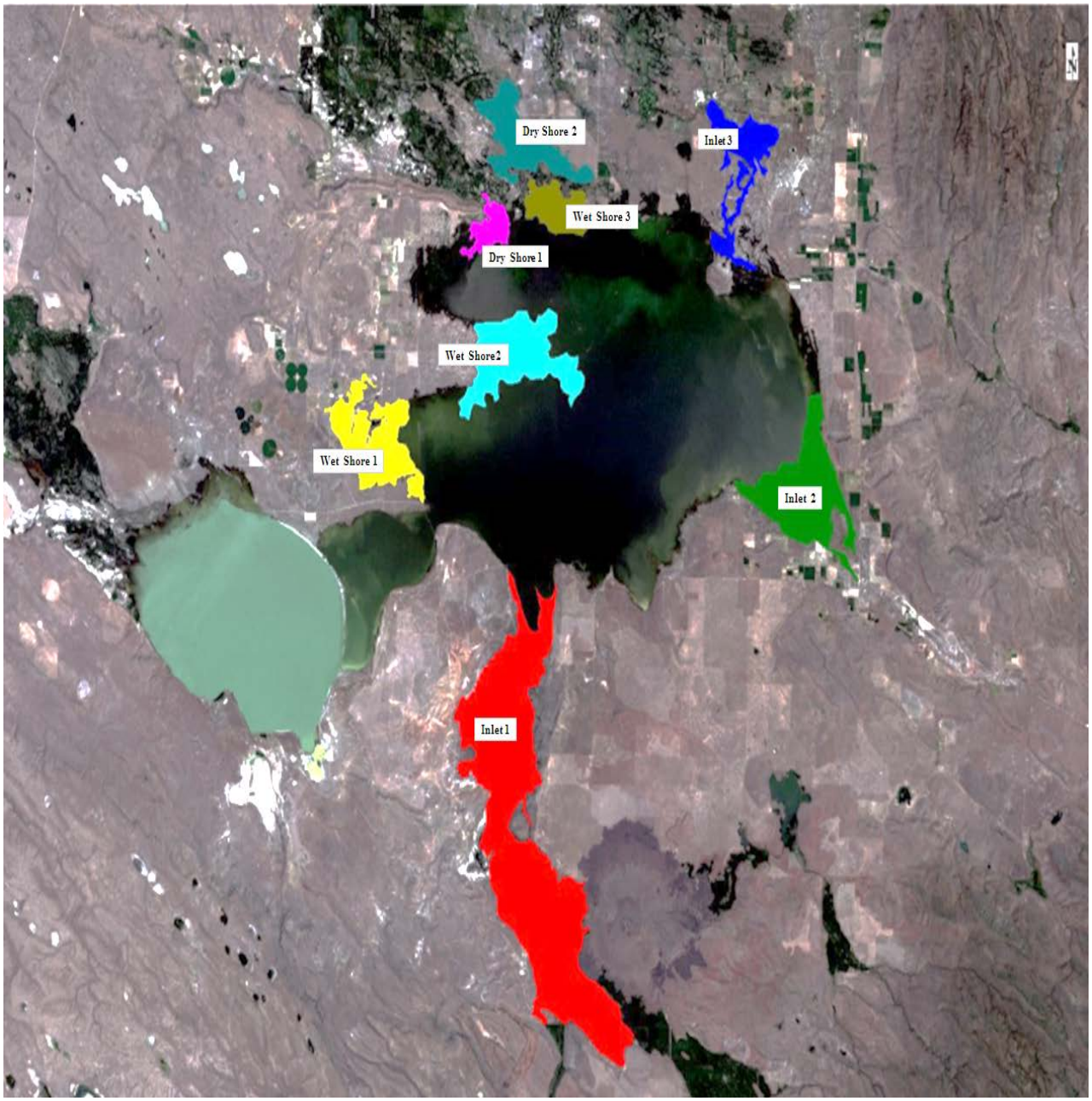

Figure 2-2 Labelled Sampling Locations where NDVI Data was Extracted to Examine the Trends in Emergent Vegetation from 1984 to 2013

2.1.1 Calibration and Processing

Prior to use, we calibrated and corrected the satellite images to remove atmospheric effects and standardize the images. We calibrated the images for top of the atmosphere reflectance using routines in the ENVI software package. This calibration computation requires satellite gains and offsets, solar irradiance, sun elevation, and acquisition time as input. These values are defined in the metadata associated with Landsat 7 images. We calibrated the images for reflectance in the range of 0 – 1 using the following equation:

$$\rho_\lambda = \frac{\pi L_\lambda d^2}{S_\lambda \sin\theta} \qquad (2\text{-}1)$$

where $\rho\lambda$ is the reflectance, $L\lambda$ is radiance in units of W/ (m^2 *sr* μm) measured by the sensor, d is the earth to sun distance in astronomical units, $S\lambda$ is the solar irradiance in unites of W/(m^2* μm), and θ is the sun elevation in degrees. We then atmospherically corrected the images using a dark subtraction algorithm. Atmospheric correction is necessary to account for interferences such as water vapor or pollution in the atmospheric column. The dark subtraction atmospheric correction algorithm locates the pixel with least recorded reflection and assumes that amount can be attributed to interferences (or backscatter) from the atmospheric column. That amount is then subtracted from all other pixels, correcting or removing the reflectance caused by atmospheric interference.

2.2 Normalized Difference Vegetation Index Analysis (NDVI)

We computed NDVI values from the calibrated images using the NDVI routine in the ENVI software. The output is a single band image with pixel values ranging from -1 to 1, with negative values indicating an absence of vegetation (Myneni, et al., 1995). The intermediate values represent the condition or extent of vegetation in a pixel. A value of approximately 0.6 to

0.9 corresponds to dense vegetation such as temperate and tropical forests or crops at their peak growth stage, sparse vegetation such as shrubs and grasslands or senescing crops result in moderate NDVI values of approximately 0.2 to 0.4 and areas of barren rock, sand, or snow show very low NDVI, for example 0.1 or less (USGS, 2015). Water typically has a negative NDVI value.

We computed the NDVI value over each of the 8 ROIs for each available April, May, June and July image from 1984 to 2013. For each ROI, we created subsets in 4 different ranges to group the different conditions of vegetation in the sample regions. The ranges were 0.2 -0.4, 0.4 – 0.6, 0.6 – 0.8 and 0.8 – 1.0. For the pixels in each ROI and in each subset, the average, minimum, maximum, kurtosis, and skew values were calculated. Figure 2-3 shows a flowchart illustrating how the NDVI data were sorted and used in the trend studies, using Inlet 1 as an example.

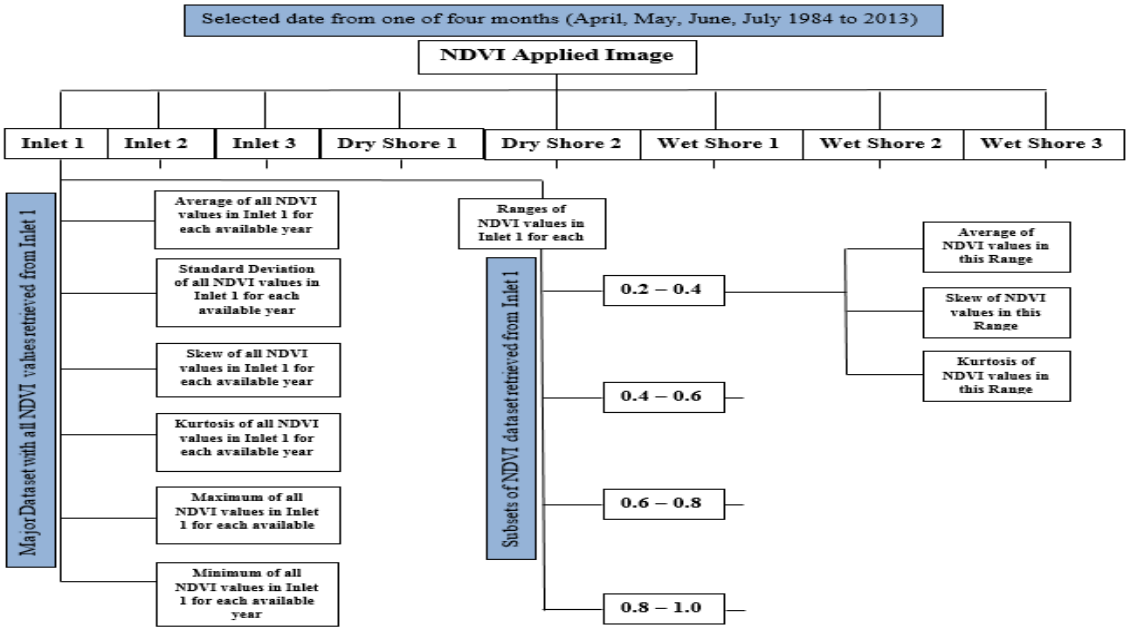

Figure 2-3 Schematic of the Results Obtained from the NDVI Analysis. The Order was Applied to Vegetation Index Data from April 1984 to July 2013

For the purposes of this study, only the average NDVI for the months of April to July from 1984 to 2013 were analyzed (Anyamba & Tucker, 2005); although the skew and kurtosis were calculated, they were not analyzed. The average in each range provides an index to the plant cover in that ROI.

2.3 Modified Normalized Difference Water Index (MNDWI)

We calculated the area covered by water on the lake using the late-June images. We report the lake area in units of pixels rather than more standard area units. We did this because the actual lake area might be somewhat different because of mixed pixels, but the relative area over time should still be accurate. The results are included in Table B-1 of the Appendix B. The lake area for a wet year (1984) was delineated and used as the clipping image for all the other years to eliminate the influence by other water filled regions such as wetlands or Mud Lake. To determine the clipping area we computed the MNDWI, then selected thresholds with a minimum data value of 0 and a maximum of 1 to select the pixels contained within Malheur Lake.

2.4 Statistical Analysis

We primarily used the SAS JMP 11.0 software to perform trend analysis, compute correlations, and generate plots. We validated normality for the data in the times series (an assumption for linear correlation computation) by examining the skew and kurtosis values computed for the NDVI data. We calculated R-squared values to determine correlation of the emergent vegetation with the various potential drivers. The correlation analysis is presented as comparison plots with accompanying R-squared values and is discussed later in the report.

3 RESULTS AND DISCUSSION

3.1 NDVI Time Series Trends at 3 Selected Sites

In this section, we present representative time series showing trends of emergent vegetation growth on Malheur Lake at 3 ROIs: Inlet 1, Wet Shore1 and Dry Shore 1. The data computed for late-June images are shown in figures 3-1 through 3-3. We have included plots of the other ROIs in Appendix B.

These results presented in figures 3-1 through 3-3 are the average NDVI values for the pixels in the ROI in the range from 0.2 to 0.4. This computed average for this range is used as an indicator for emergent plant growth in each ROI. As noted above, we selected late-June conditions as the best time to use remote sensing data to compute an indicator for emergent vegetation. Some years have missing data because of missing images or images that were not useable because of cloud cover or other issues. The study obtained 22 images for late-June over the 30-year time period. Data for April, May, early-June and July months are included in the Appendix C and are not analyzed in this report.

Data varied by year for Inlet 1 and Dry Shore 1, with the minimum average NDVI value occurring in 1992, with a value of 0.25. The Wet Shore 1 ROI minimum occurred in 1999 with a value of 0.22. The minimum values in the inlet and dry-shore areas—both areas affected strongly by lake levels—occurred in 1992, the year of the lowest lake level as shown in Figure 3-4.

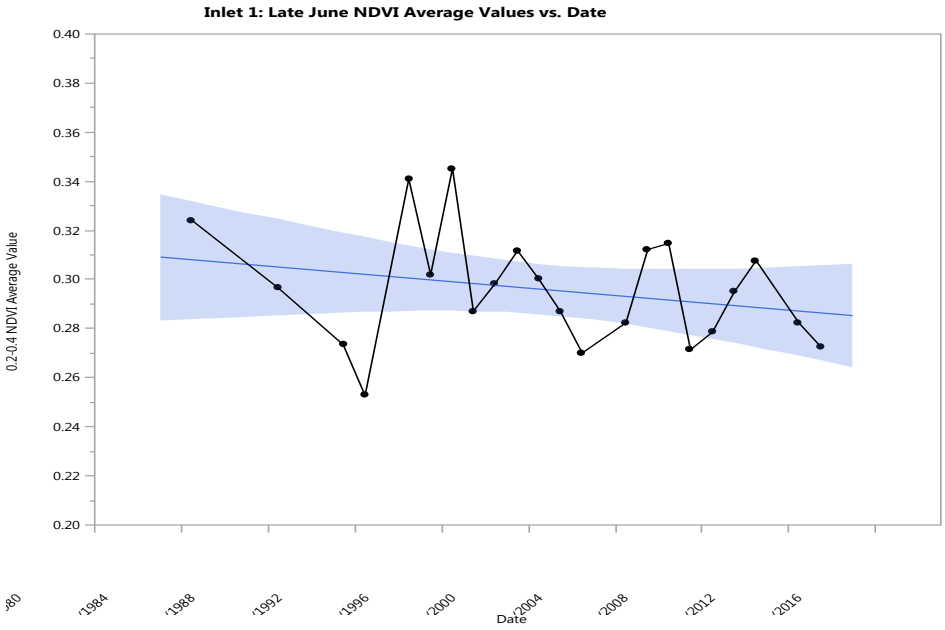

Figure 3-1 Long Term Estimated Average of 0.2 – 0.4 Range of NDVI Values in Inlet 1 for Late June from 1984 to 2013

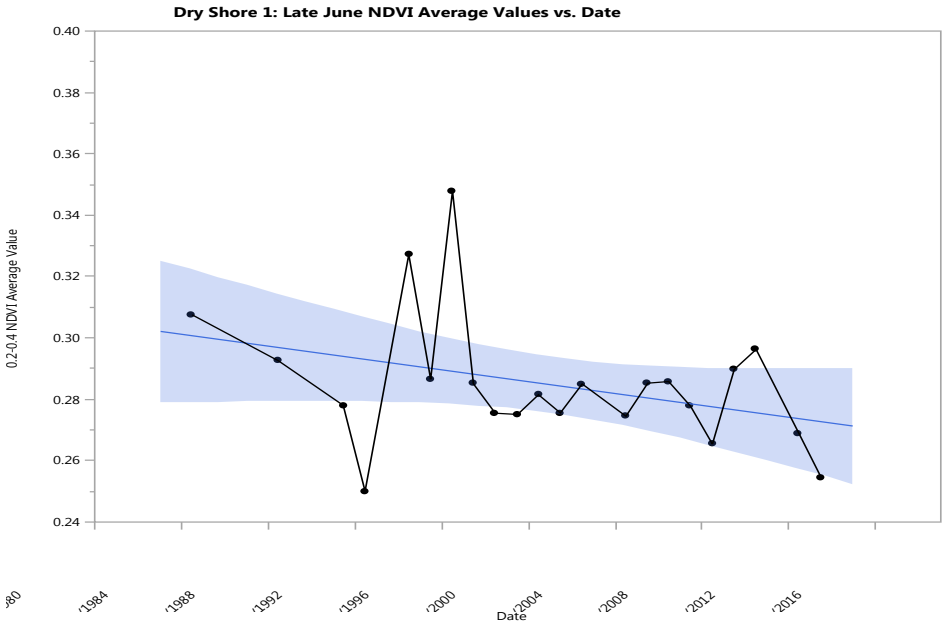

Figure 3-2 Long Term Estimated Average of 0.2 – 0.4 Range of NDVI Values in Dry Shore 1 for Late June from 1984 to 2013

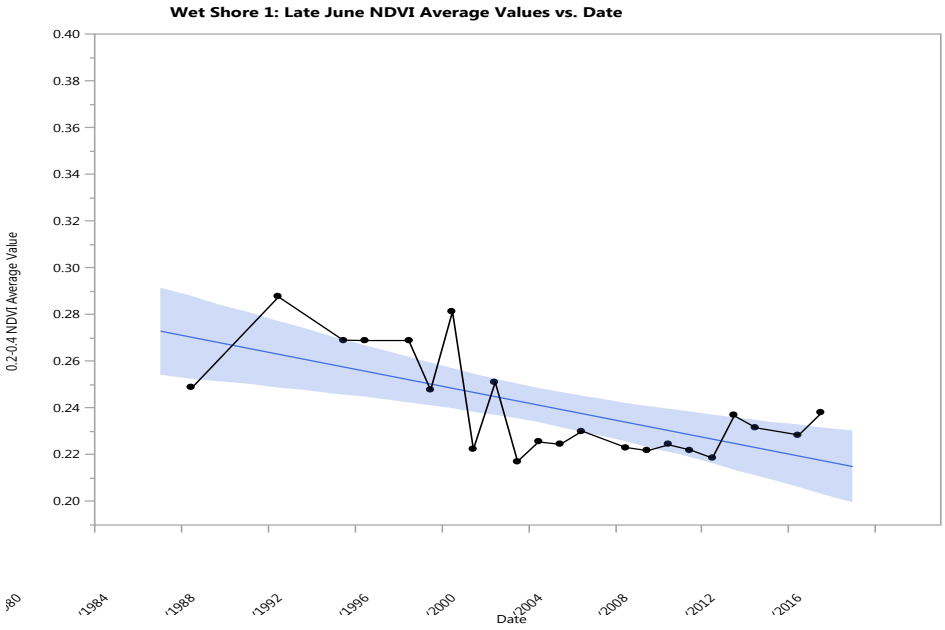

Figure 3-3 Long Term Estimated Average of 0.2 – 0.4 Range of NDVI Values in Wet Shore 1 for Late June from 1984 to 2013

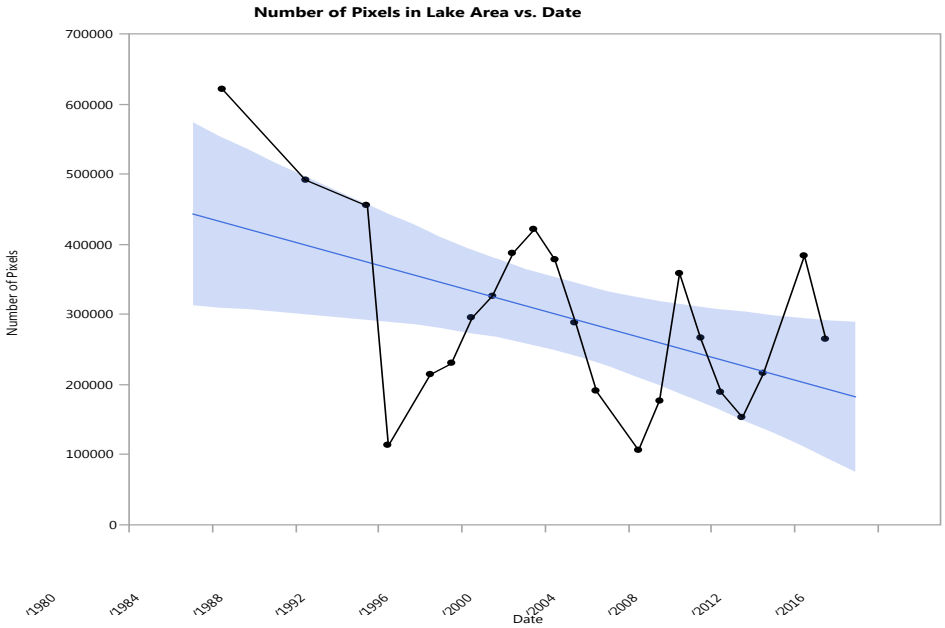

Figure 3-4 Average Daily Precipitation for the Growing Season of Late June on Malheur Lake from 1987 to 2013.

All three ROIs show a declining trend in emergent growth over the study period. Index values for Wet Shore 1 were comparably lower than the other two sites due to the presence of water which may have interfered with the NDVI values computed for this ROI. The lake level was at a maximum in 1984, which did not necessarily correspond to high NDVI values in the 3 sites selected, implying that water may not have had a significant impact. Without ground truth data, we cannot determine the actual impact of mixed water pixels, but as noted earlier, the trends should be representative, even if the actual values may not be as accurate.

Figure 3-5 shows the average daily precipitation measurements for June. Precipitation shows a slightly increasing trend, with significant variability. In 1992, the average daily precipitation was relatively high which does not correspond with the low NDVI values for the two sample sites discussed above. June precipitation does not correlate well with lake levels as runoff and lake levels are based on precipitation earlier in the year.

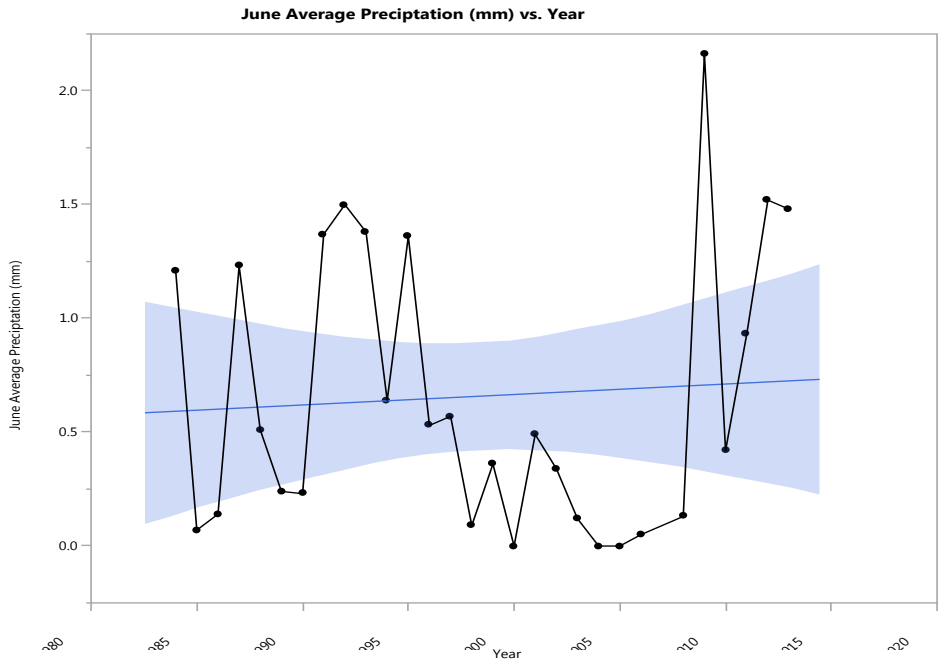

Figure 3-5 Average Daily Precipitation for the Growing Season of Late June on Malheur Lake from 1987 to 2013. Note: There is Missing Data for 2007

3.2 Correlation Plots of NDVI Time Series with Climate Conditions

Here we present the NDVI time series results from ROI Inlet 1 to analyze correlation with other climatic parameters. These other data were obtained from the Oregon Climate Service (OCS, 2015). In figures 3-6 through 3-9, we examine the correlation of the average daily maximum temperatures from April, May, June and July with NDVI values from Inlet 1. We computed an R-squared value to quantify the correlation between each of the time series with the NDVI index for emergent vegetation at all 8 locations, these values are reported in Table 3-1.

Table 3-1 R-squared Dataset for Each of the Variable Comparisons

Correlation with NDVI values (R^2)						
Region of Interest	Maximum Temperature				June Precipitation	Number of Lake Area Pixels
	April	May	June	July		
Inlet 1	0.005	0.013	0.000	0.003	0.070	0.077
Inlet 2	0.017	0.009	0.021	0.059	0.006	0.379
Inlet 3	0.011	0.004	0.009	0.044	0.003	0.182
Dry Shore 1	0.012	0.000	0.012	0.076	0.017	0.031
Dry Shore 2	0.012	0.000	0.010	0.012	0.013	0.189
Wet Shore 1	0.194	0.044	0.111	0.155	0.097	0.051
Wet Shore 2	0.066	0.006	0.039	0.029	0.005	0.012
Wet Shore 3	0.031	0.020	0.029	0.022	0.078	0.070

While the figures suggest some short periods of correlation—for example, there was a drop in NDVI values from 1984 to 1988 at Inlet 1 parallel to the decrease in average daily temperature values in April, May, June and July—the R-squared values show that these apparent correlations are not real, but are just periods of apparent correlation. R-square measures correlation between two series with values near 0 indicating no correlation and values near 1 indicating perfect correlation, for most studies values above 0.6 indicate that the correlation between the two series is significant (Kiemele & Schmidt, 1993). The R-squared values presented in Table 3-1 demonstrate that there is no correlation between any of these times series

and the emergent vegetation index. Figure 3-10 and Figure 3-11 show lake level and June precipitation time series along with the NDVI index, respectively. These plots show the NDVI index values at Inlet 1 peaked to a value of 0.34 in 1994 then dropped slightly in 1995, and went up even more in 1996. These patterns are not reflected in any of the other data series.

The largest deviation was seen with the daily maximum temperature measurements in 1992. We expected high temperatures in April would result in greater growth, and thus larger NDVI values for late-June and conversely, during colder springs the NDVI values would be lower. But as shown in Figure 3-6, even with relatively high temperatures in April of 1992, NDVI values at Inlets 1 were low compared to other years. This observation is consistent with 1992 temperatures in the other months, (Figures 3-7, 3-8, and 3-9). Temperatures were high, but the late-June NDVI values were low.

The R-squared values— for the data shown in figures 3-6 through 3-11showing the correlations of April, May, June and July average daily maximum temperatures with NDVI— reflect a very weak correlation, presented in Table 3-1. Temperatures in July have the highest R-squared values, which would be expected as late June growth was studied, which is close to records for July. However, while these are the highest values, they only average a value of 0.05, which indicates no correlation. The data from 1992, discussed above, along with the low correlation values, show that our hypothesis that daily maximum temperature in April, May, June, or July would be a driver for emergent growth, as measured by NDVI, does not hold.

We also did not find correlation with NDVI values and the other two variables we studied, June daily average precipitation and lake area measurements, represented in Figure 3-10 and Figure 3-11. Lake area exhibits the highest R-squared value of 0.379, which is the best correlation of all the variables, but so low as to indicate no correlation. This result suggests that variation in emergent vegetation cover on the perimeter of the lake, due to its exposure in dry

years or with water interfering in wet years, has the most effect of any of the variables studied, but the R-squared value indicates that this correlation is essentially non-existent.

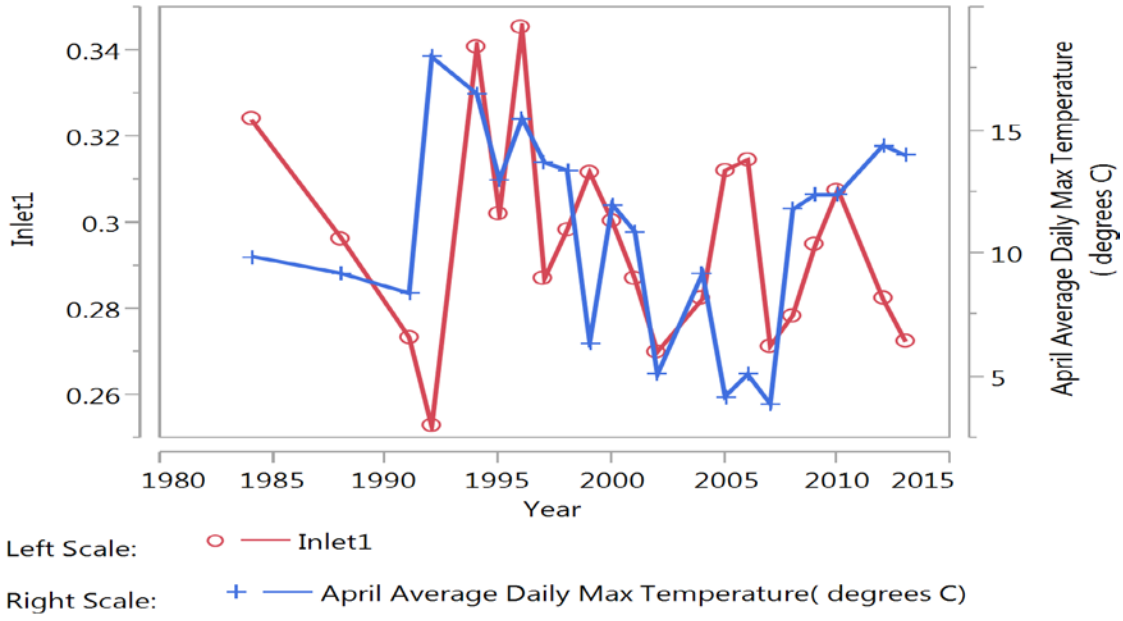

Figure 3-6 Comparison between NDVI Index at Inlet 1 and Malheur Lake Average May daily Maximum Temperature

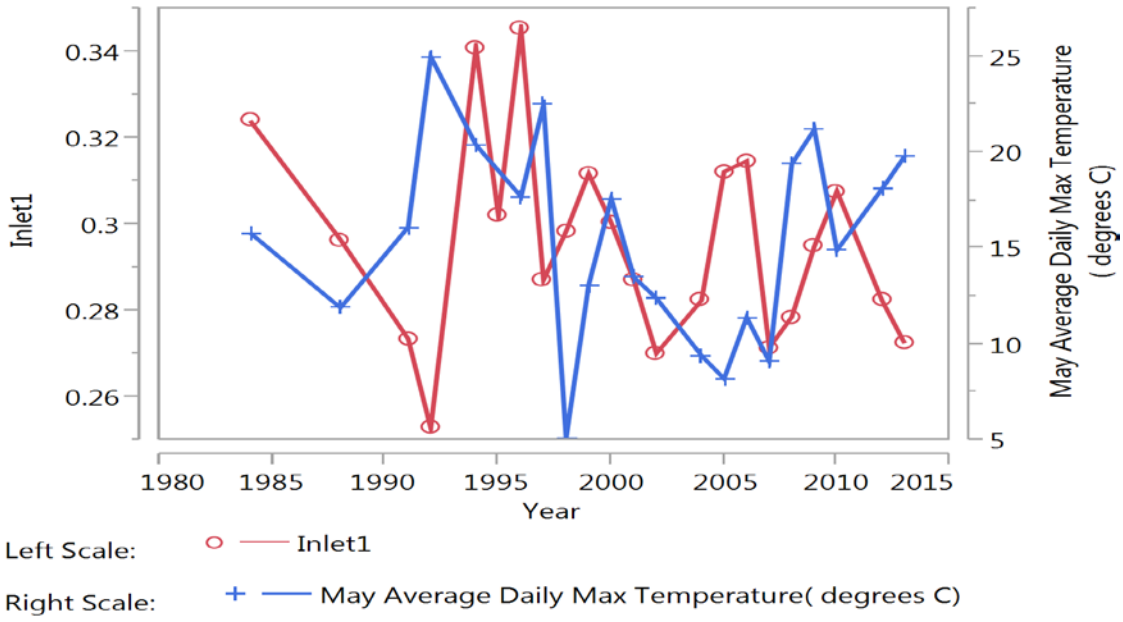

Figure 3-7 Comparison between NDVI Index at Inlet 1 and Malheur Lake Average May Daily Maximum Temperature

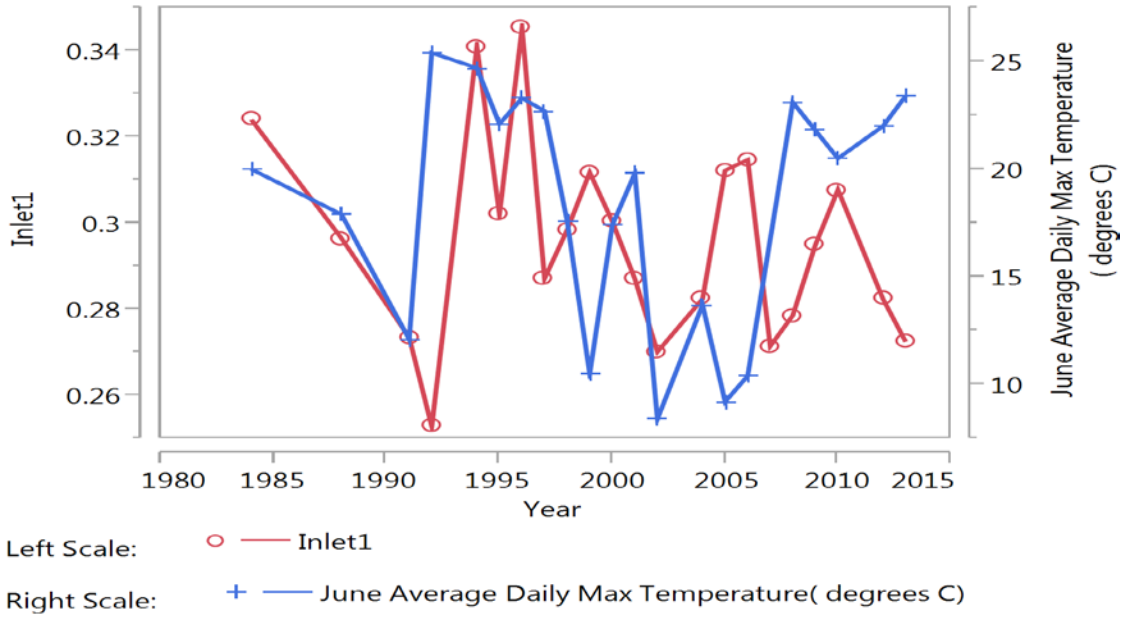

Figure 3-8 Comparison between NDVI Index at Inlet 1 and Malheur Lake Average June daily Maximum Temperature

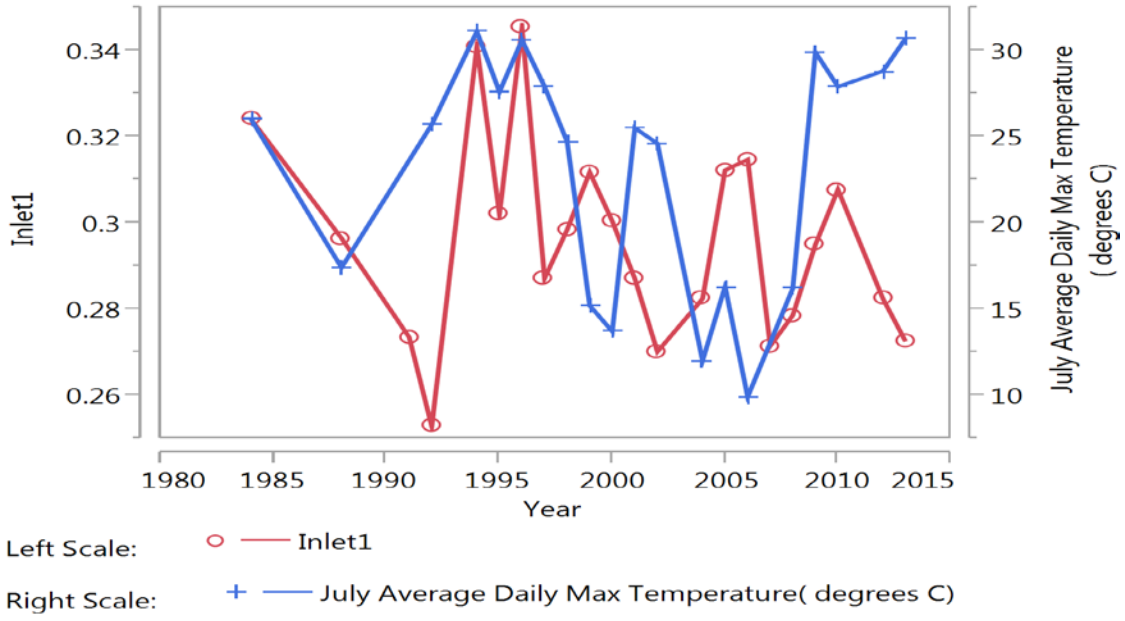

Figure 3-9 Comparison between NDVI Index at Inlet 1 and Malheur Lake Average July Daily Maximum Temperature

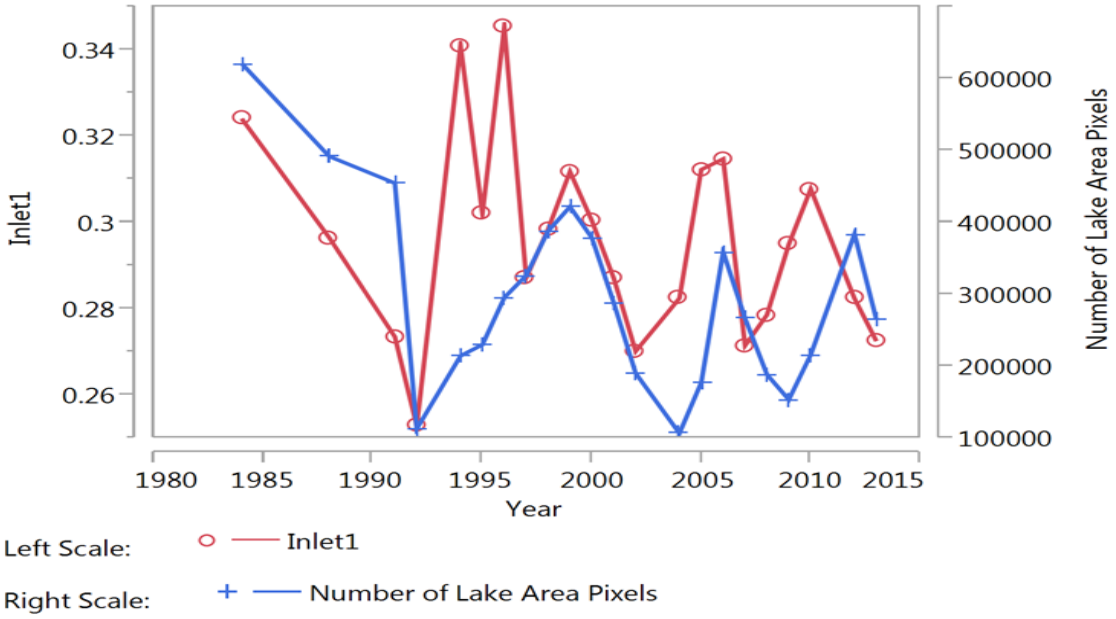

Figure 3-10 Comparison between NDVI Index at Inlet 1 and Malheur Lake Area (1984 - 2013)

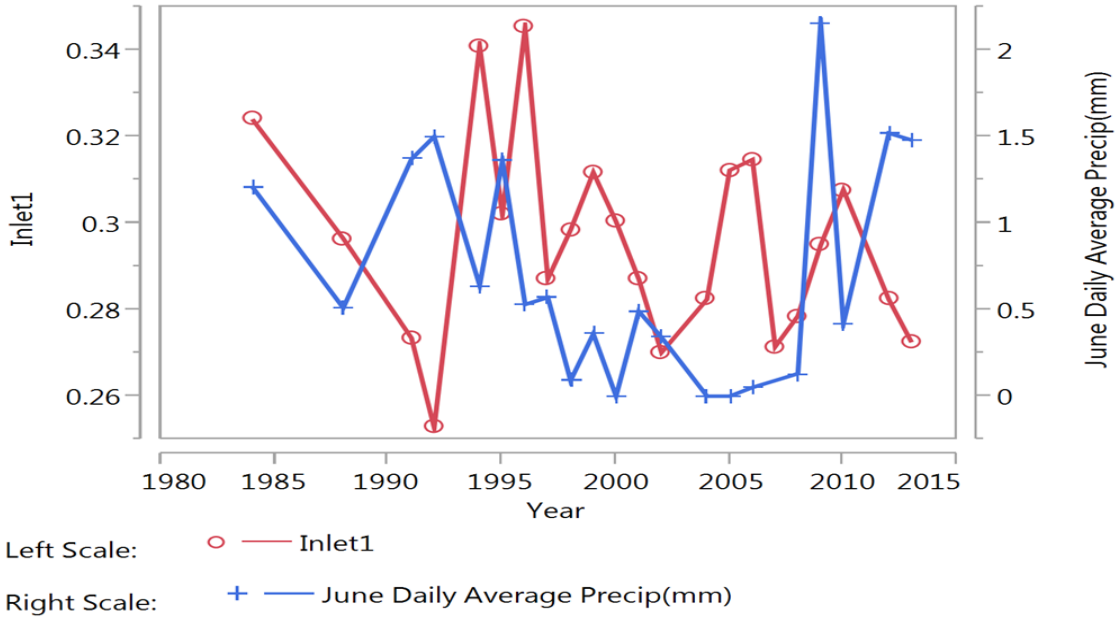

Figure 3-11 Comparison between NDVI Index at Inlet 1 and Malheur Lake Average June Daily Precipitation (1984 – 2013)

4 CONCLUSION

There are not any strong patterns or trends in the NDVI time series data. We do observe a slight trend represented as a small seemingly steady decline year after year in the emergent vegetation index in each of the selected ROIs. This implies that emergent vegetation growth on the perimeter of the Malheur Lake is getting smaller. We analyzed the correlation of emergent vegetation, as measured by NDVI with lake size, June precipitation, and April, May, June, July temperature maximum daily temperatures. These data exhibited no correlation with emergent vegetation, indicating that these variables do not drive emergent vegetation conditions.

We recommend additional studies. First, conduct field surveys to identify the most appropriate areas to use as ROIs. Since the satellite images have already been collected and processed to provide NDVI values, redoing this analysis with new areas would require minimal effort – once the areas are identified. We also recommend collecting field data to determine if using average NDVI values for pixels in the range of 0.2–0.4 provides an adequate index to emergent vegetation coverage. In addition to validating the approach used in this study, we also recommend exploring other factors that could potentially influence emergent vegetation such as carp or other stresses in the environment. Finally, we recommend field studies to determine the best time of year to measure emergent vegetation using remote sensing sensors. In this study we selected late-June based on our best understanding of the Malheur Lake area. However, this may not be the best time to measure emergent vegetation. Field studies should be conducted coincident with future satellite overpasses to determine the best time to measure emergent vegetation. This would also provide calibration data so that NDVI values could be linked to

actual emergent vegetation amounts, rather than being just used as an index as they were in this study.

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APPENDIX A. CLIPPED VIEW OF REGIONS OF INTEREST

In Figure A-1 through A-6, we provide clipped view of the 8 sample areas studied with the original colored scaled condition on the left and the delineated area of interest on the right.

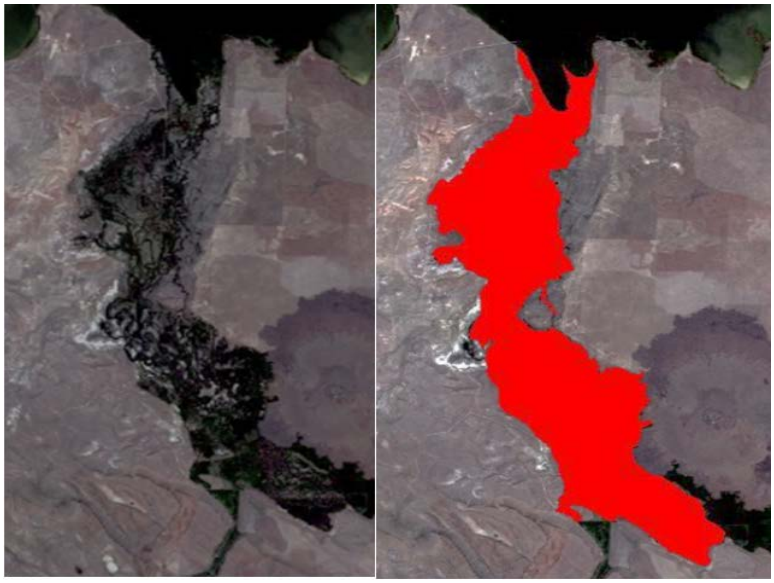

Figure A- 1 Location of Inlet 1 Found at the Southwestern Region of Malheur Lake

Figure A- 2 Location of Inlet 2 Found at the Southeastern Region of Malheur Lake

Figure A- 3 Location of Inlet 2 found at the Northeastern Region of Malheur Lake

Figure A- 4 Location of Wet Shore 1 Found at the Western Region of Malheur Lake

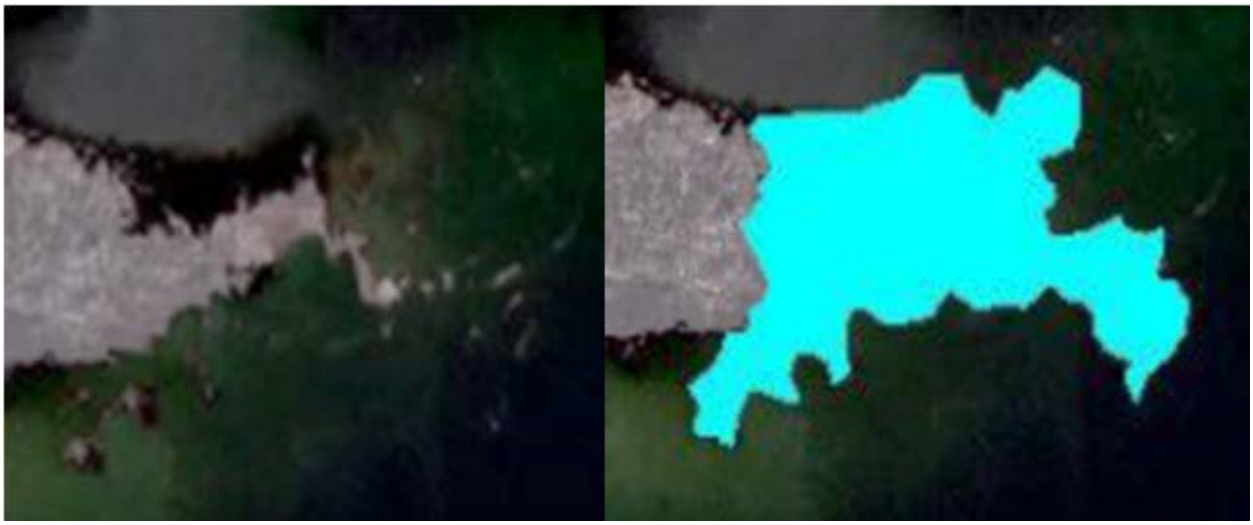

Figure A- 5 Location of Wet Shore 1 Found at the Western Region of Malheur Lake

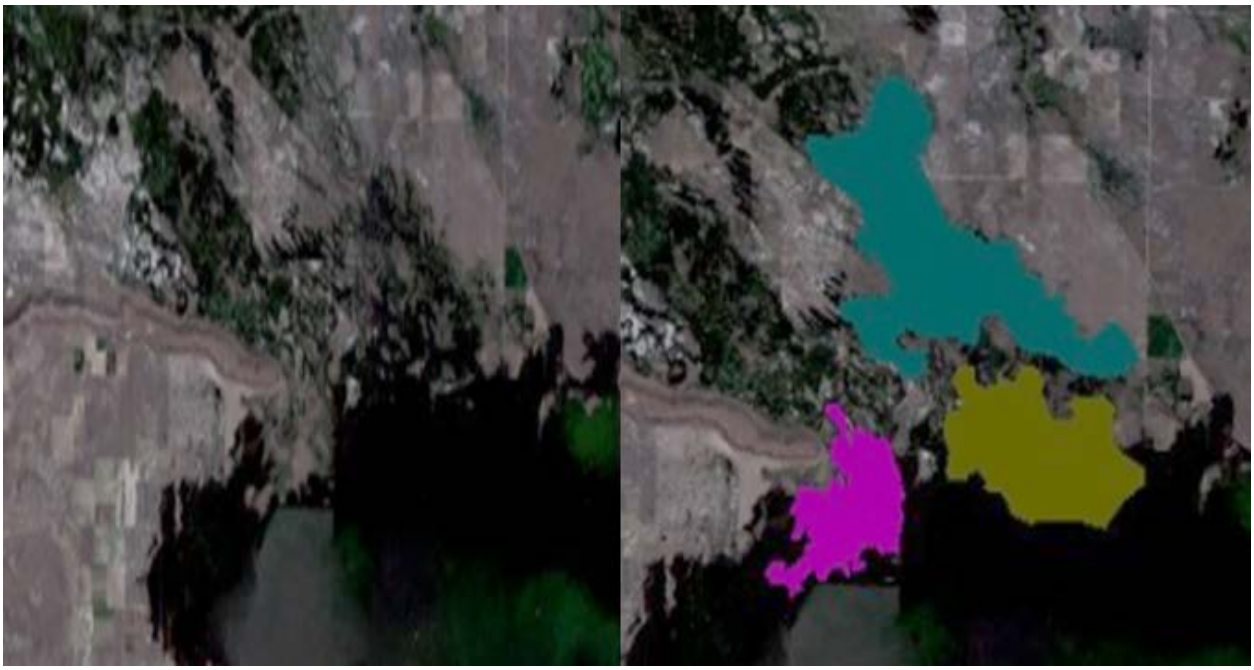

Figure A- 6 Location Dry shore 1, Dry Shore 2 and Wet Shore 3 Found at the Western Region of Malheur Lake

APPENDIX B. INDEX OF PRECIPITATION AND LAKE AREA INFORMATION

Precipitation and lake area data used in correlation with NDVI values are presented in the following tables. Color images showing the size of the lake during the identified extreme wet and dry years within the time period of our study is seen in Figure B- 1.

Table B- 1 Log of Malheur Lake Area Represented as Number of Pixels

Date	Number of Pixels
6/28/1984	620915
6/23/1988	491646
6/16/1991	454421
6/18/1992	112762
6/24/1994	214136
6/27/1995	229666
6/29/1996	295260
6/16/1997	326022
6/19/1998	387725
6/30/1999	421583
6/16/2000	378390
6/19/2001	287964
6/22/2002	190081
6/27/2004	106401
6/30/2005	177173
6/17/2006	358635
6/20/2007	266322
6/22/2008	188190
6/25/2009	153216
6/28/2010	215669
6/17/2012	383519
6/28/2013	264624

Table B- 2 Average Precipitation Data Recorded for June from 1959 – 2013

Average of PRCP		
Year	June Average Precip(tenths of mm)	June Average Precip(mm)
1959	0.20	0.02
1960	0.00	0.00
1961	7.23	0.72
1962	2.57	0.26
1963	9.33	0.93
1964	20.37	2.04
1965	18.57	1.86
1966	8.97	0.90
1967	9.97	1.00
1968	5.37	0.54
1969	9.73	0.97
1970	15.50	1.55
1971	11.03	1.10
1972	2.40	0.24
1973	1.10	0.11
1974	0.60	0.06
1975	15.60	1.56
1976	5.60	0.56
1977	6.67	0.67
1978	8.13	0.81
1979	4.40	0.44
1980	6.73	0.67
1981	5.37	0.54
1982	5.80	0.58
1983	4.33	0.43
1984	12.07	1.21
1985	0.70	0.07
1986	1.37	0.14
1987	12.33	1.23
1988	5.07	0.51
1989	2.37	0.24
1990	2.33	0.23
1991	13.73	1.37
1992	14.97	1.50
1993	13.83	1.38
1994	6.37	0.64
1995	13.57	1.36
1996	5.33	0.53
1997	5.73	0.57
1998	0.93	0.09
1999	3.63	0.36
2000	0.00	0.00
2001	4.87	0.49
2002	3.40	0.34
2003	1.17	0.12
2004	0.00	0.00
2005	0.00	0.00
2006	0.50	0.05
2008	1.27	0.13
2009	21.60	2.16
2010	4.23	0.42
2011	9.30	0.93
2012	15.23	1.52
2013	14.83	1.48

Figure B- 1 True Color Image of the Extreme Wet Year Captured on June 28, 1984 and Extreme Drought Captured on June 18, 1992

APPENDIX C. HISTORICAL TRENDS BY SEASON AND REGION OF INTEREST

The trend of NDVI dataset for the selected sample areas on the lake by seasons are presented in the following plots in this appendix. The raw data estimates for late June selected for analysis in the results in shown in Table C-1.

Table C- 1 Late June Data for the 8 Regions of Interest by Date

Date	Inlet1	Inlet2	Inlet3	Dry Shore1	Dry Shore2	Wet Shore1	Wet Shore2	Wet Shore3
6/28/1984	0.32403	0.29802	0.30336	0.30754	0.32786	0.24876	0.23781	0.30333
6/23/1988	0.29644	0.2754	0.25551	0.29251	0.2769	0.28757	0.29702	0.31633
6/16/1991	0.27344	0.28303	0.26512	0.27804	0.28503	0.26905	0.26061	0.3269
6/18/1992	0.25277	0.23054	0.21669	0.25005	0.24222	0.2689	0.26218	0.25052
6/24/1994	0.34091	0.27177	0.29068	0.32716	0.32276	0.2689	0.28132	0.34202
6/27/1995	0.30202	0.26283	0.26074	0.28656	0.28046	0.24774	0.25202	0.33238
6/29/1996	0.34521	0.29647	0.33967	0.34786	0.33547	0.28127	0.30842	0.35598
6/16/1997	0.28711	0.25344	0.23691	0.28506	0.28314	0.2224	0.23467	0.31478
6/19/1998	0.2984	0.27426	0.25967	0.27547	0.28579	0.25106	0.26766	0.29846
6/30/1999	0.31173	0.24091	0.23588	0.27506	0.28463	0.21717	0.23761	0.32734
6/16/2000	0.30037	0.24992	0.2376	0.28149	0.2821	0.22554	0.23998	0.32403
6/19/2001	0.28704	0.24049	0.22765	0.27556	0.25747	0.22449	0.23661	0.29672
6/22/2002	0.27008	0.23103	0.22408	0.28499	0.25384	0.23015	0.23654	0.2925
6/27/2004	0.28237	0.24425	0.22306	0.27449	0.27054	0.22315	0.24393	0.29169
6/30/2005	0.31222	0.24522	0.25473	0.28526	0.28516	0.22182	0.24758	0.32208
6/17/2006	0.31469	0.25961	0.27822	0.28579	0.29895	0.2243	0.25468	0.34202
6/20/2007	0.27142	0.25324	0.24114	0.27775	0.26748	0.22206	0.25576	0.3078
6/22/2008	0.27854	0.23904	0.22686	0.26541	0.27889	0.21865	0.23507	0.3153
6/25/2009	0.2949	0.24359	0.2298	0.28974	0.27862	0.23672	0.2386	0.31156
6/28/2010	0.3077	0.25021	0.24614	0.29625	0.2776	0.23156	0.25467	0.31006
6/17/2012	0.28233	0.23969	0.23712	0.26891	0.2785	0.22851	0.23999	0.3078
6/28/2013	0.27243	0.26049	0.23276	0.25448	0.25969	0.23781	0.24219	0.2686

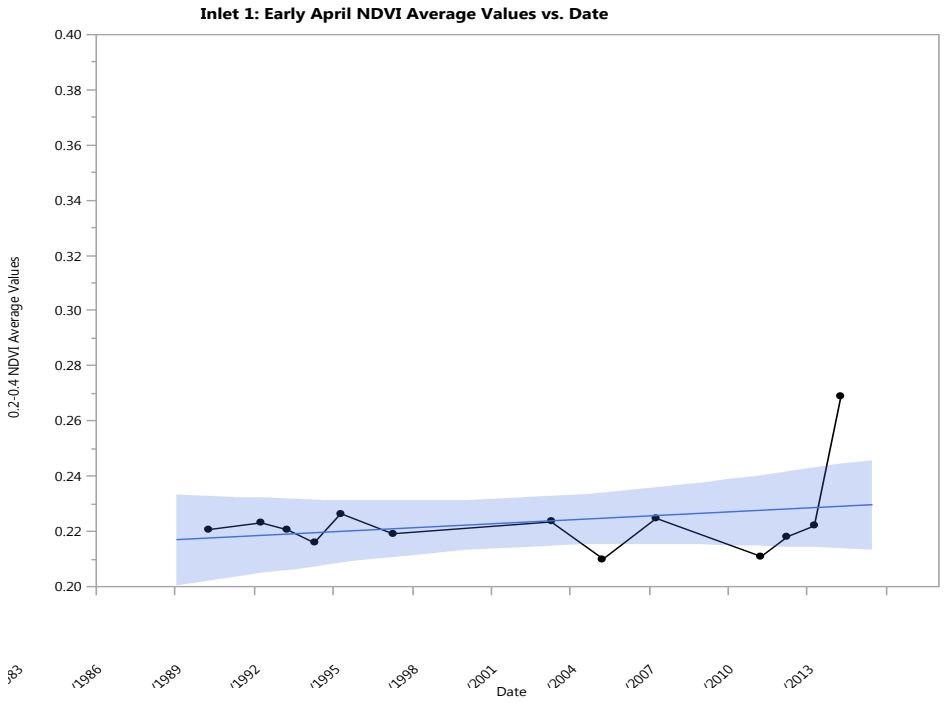

Figure C- 1 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Early April from 1984 to 2013

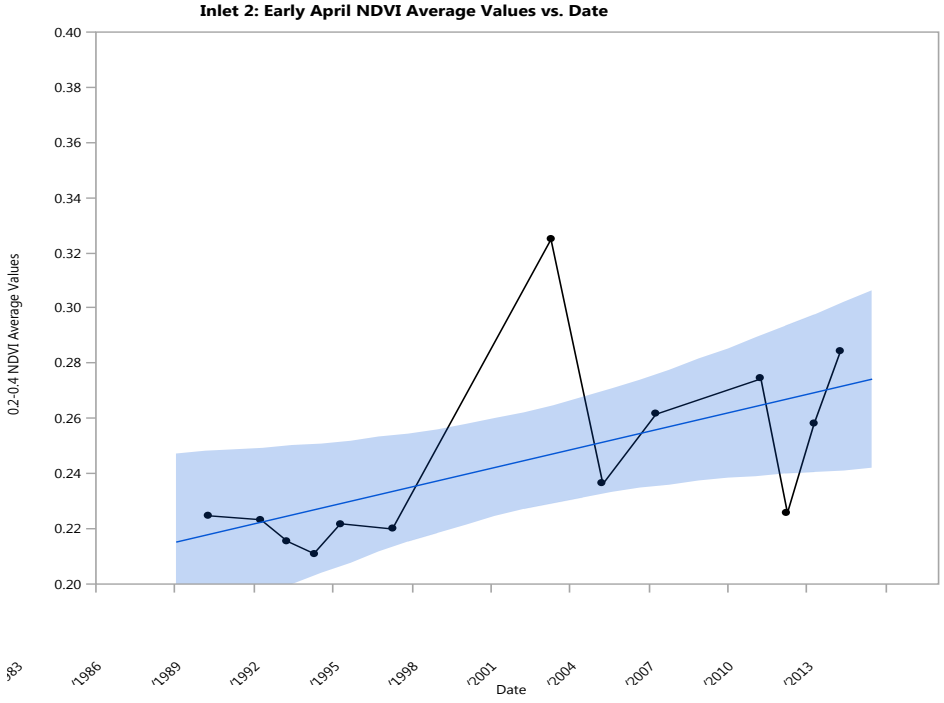

Figure C- 2 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Early April from 1984 to 2013

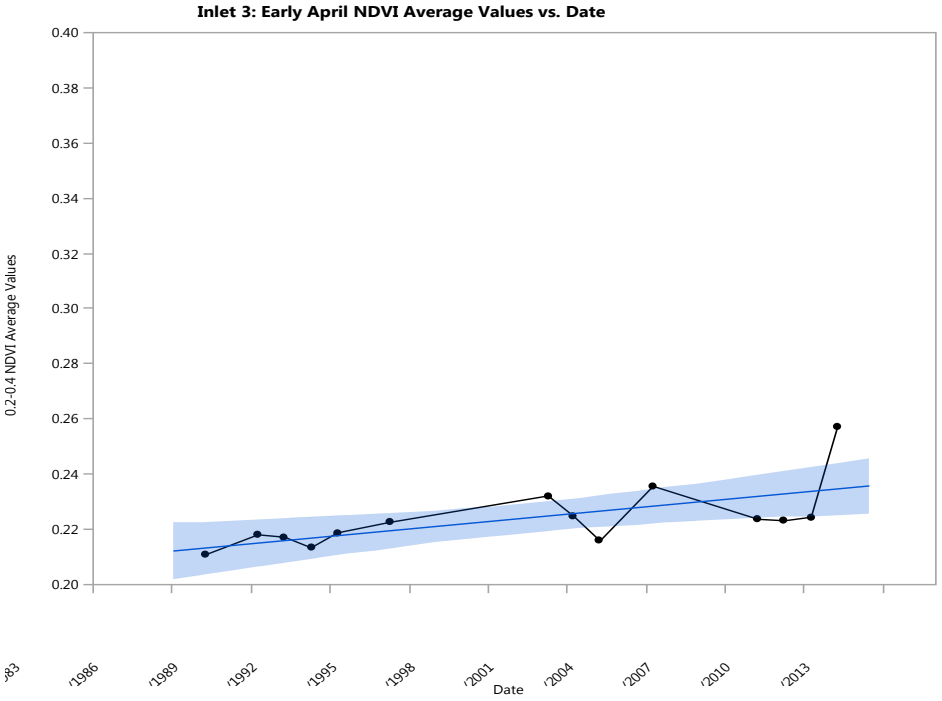

Figure C- 3 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Early April from 1984 to 2013

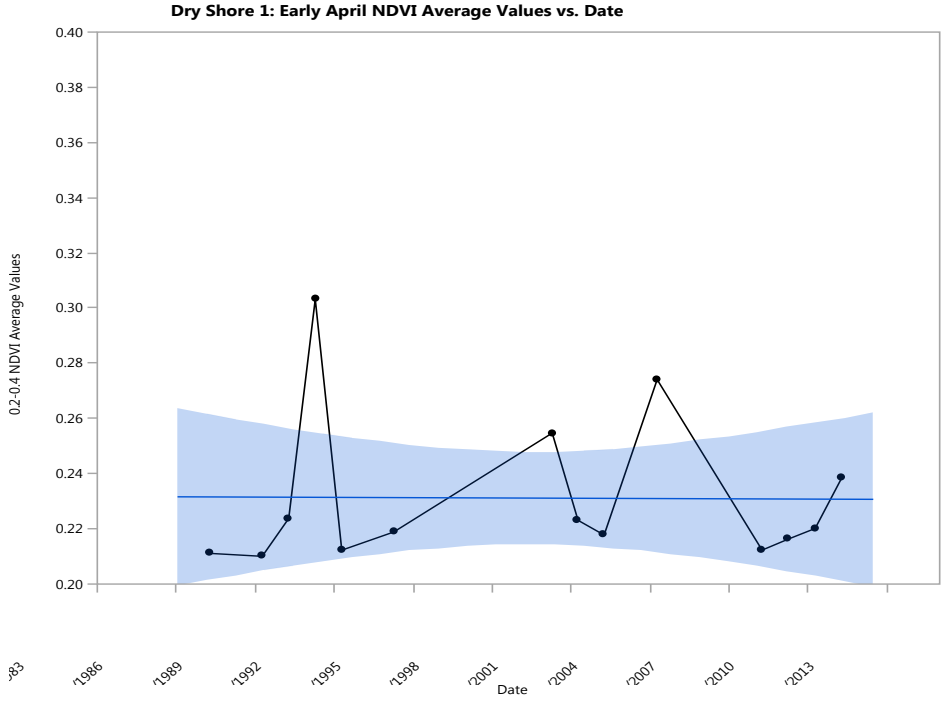

Figure C- 4 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Early April from 1984 to 2013

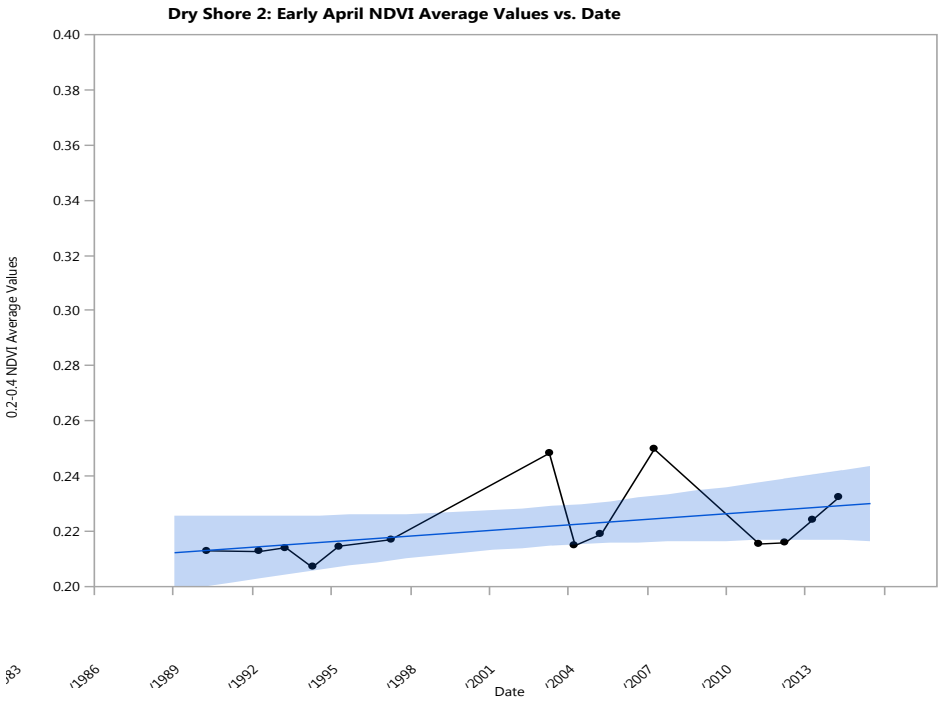

Figure C- 5 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Early April from 1984 to 2013

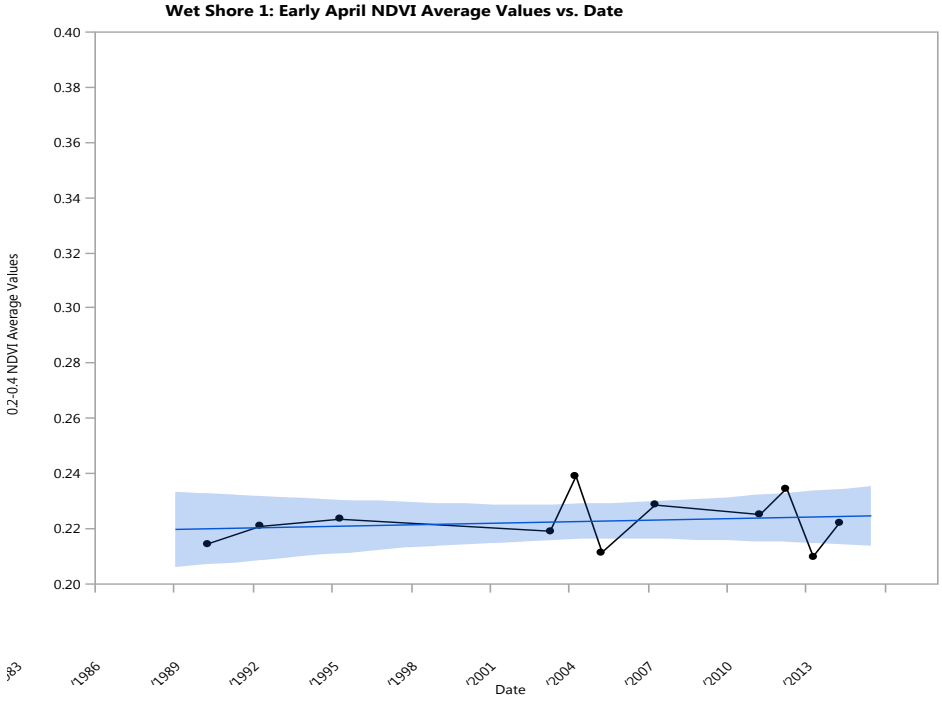

Figure C- 6 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Early April from 1984 to 2013

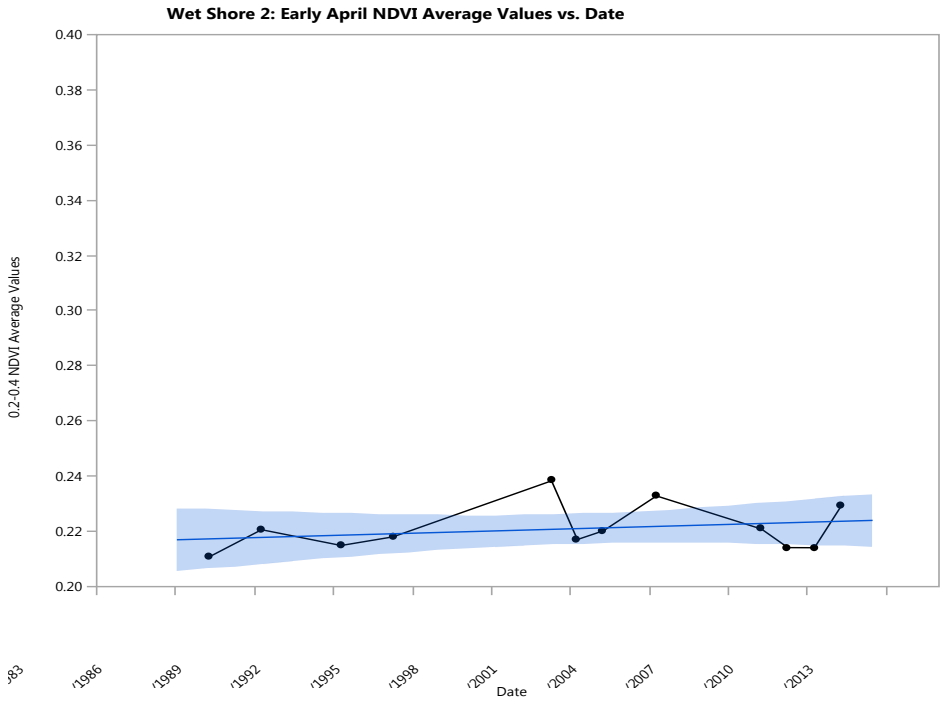

Figure C- 7 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Early April from 1984 to 2013

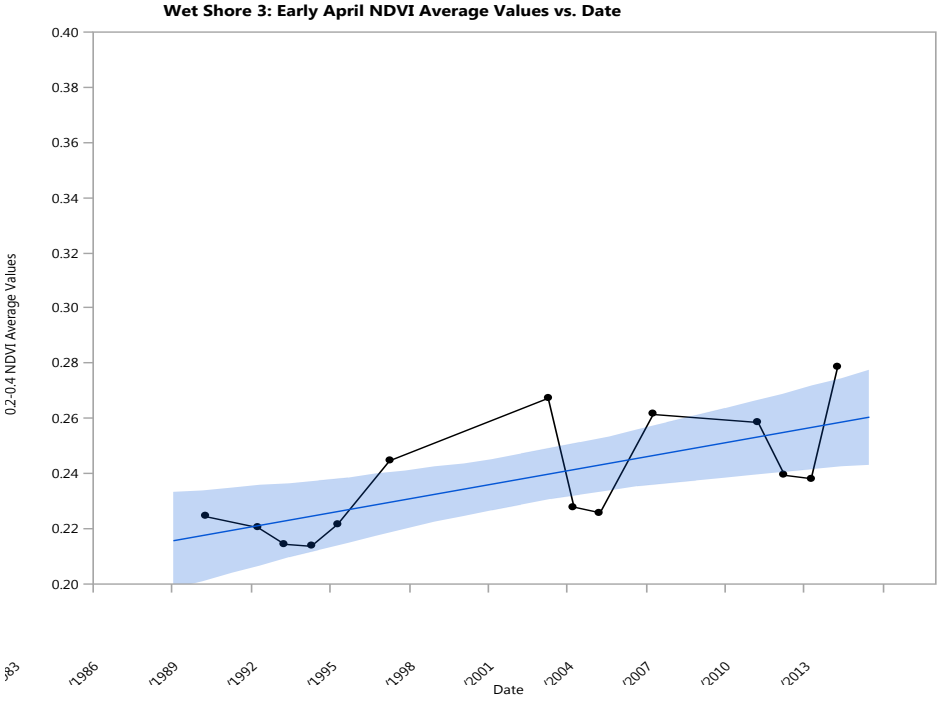

Figure C- 8 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Early April from 1984 to 2013

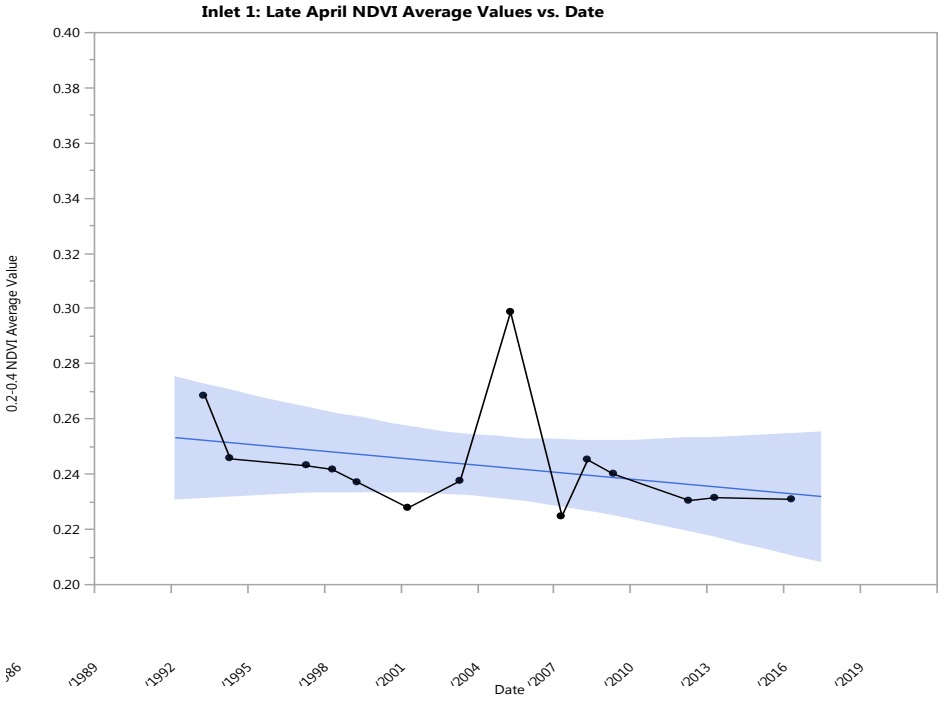

Figure C- 9 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Late April from 1984 to 2013

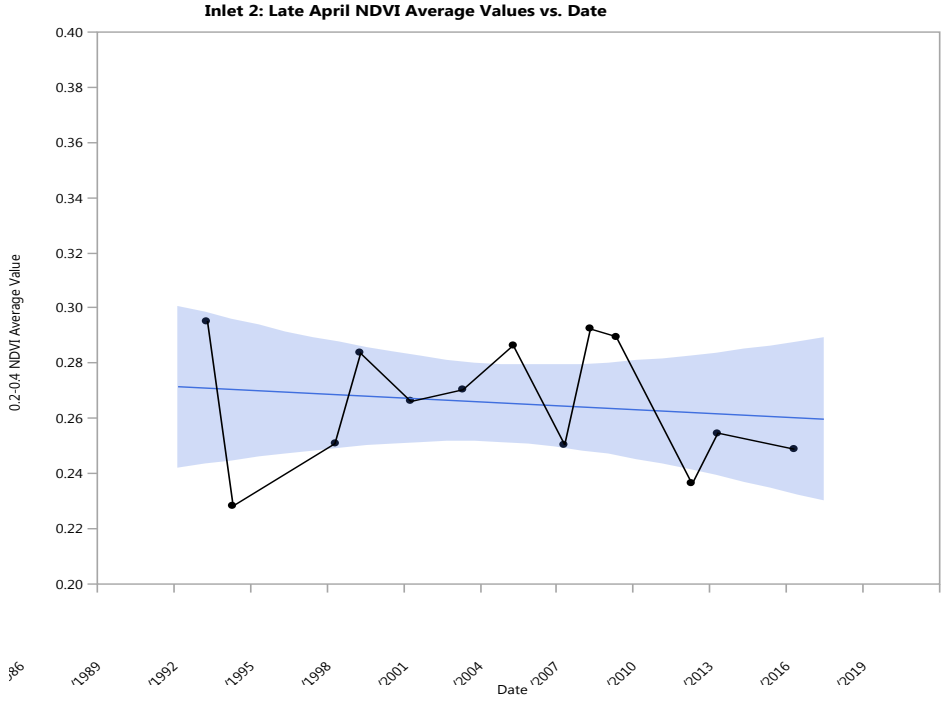

Figure C- 10 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Late April from 1984 to 2013

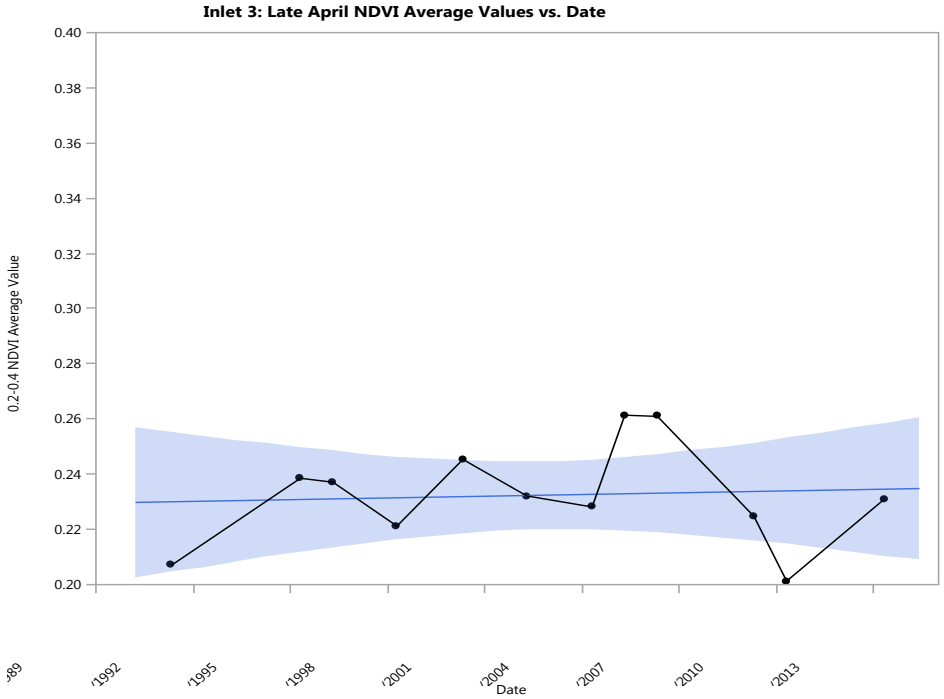

Figure C- 11 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Late April from 1984 to 2013

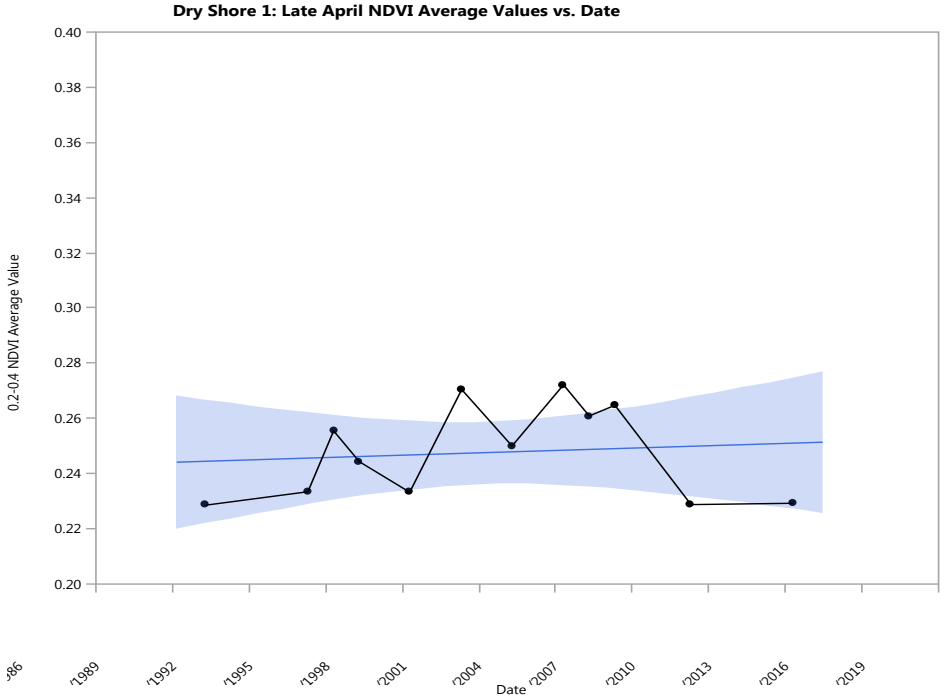

Figure C- 12 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Late April from 1984 to 2013

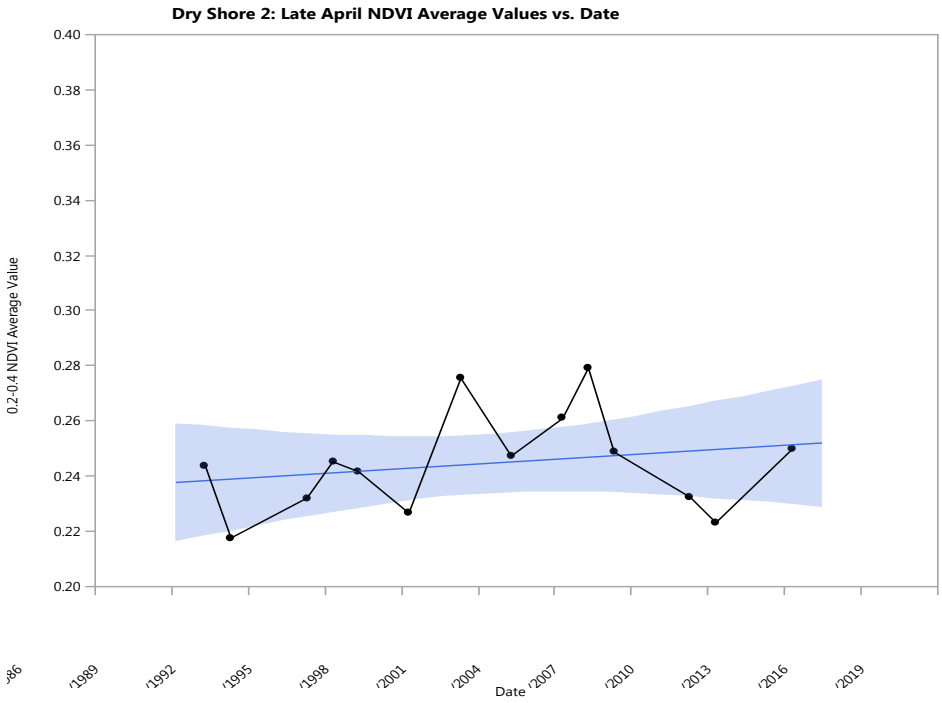

Figure C- 13 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Late April from 1984 to 2013

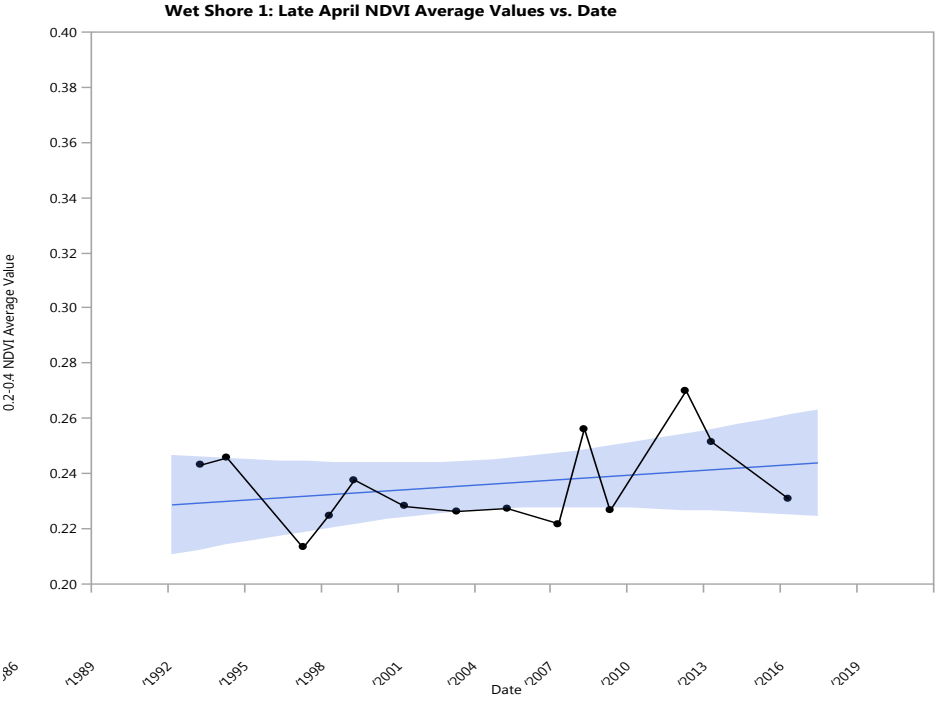

Figure C- 14 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Late April from 1984 to 2013

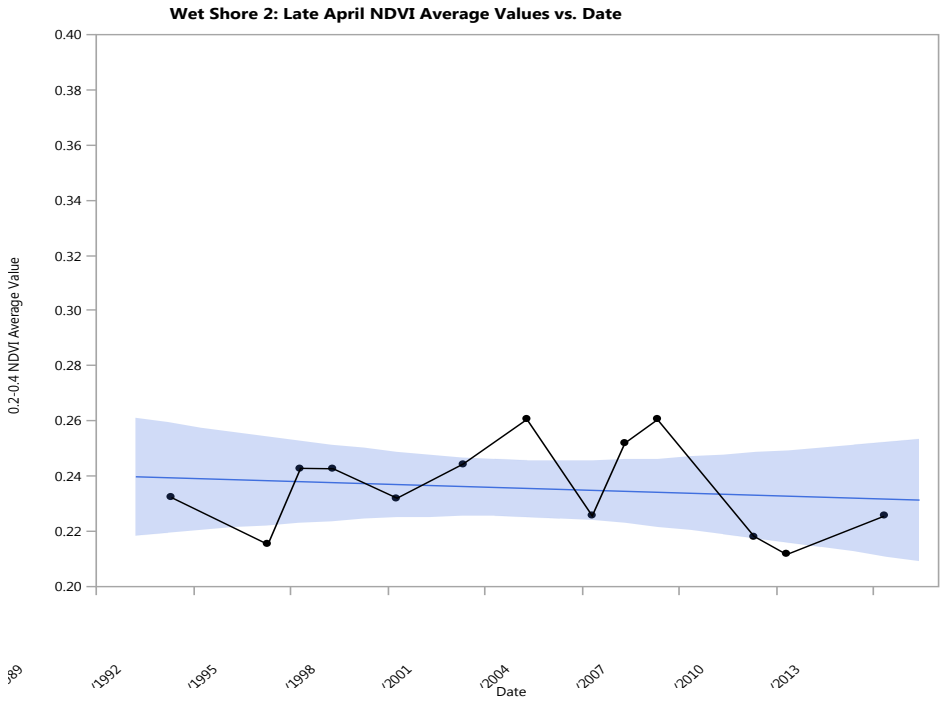

Figure C- 15 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Late April from 1984 to 2013

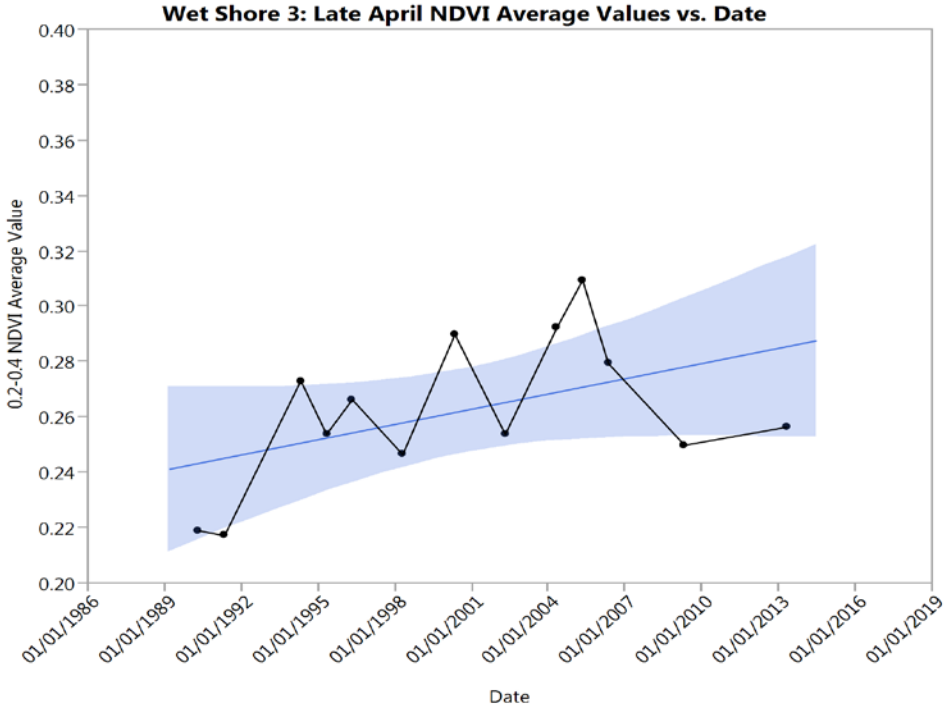

Figure C- 16 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Late April from 1984 to 2013

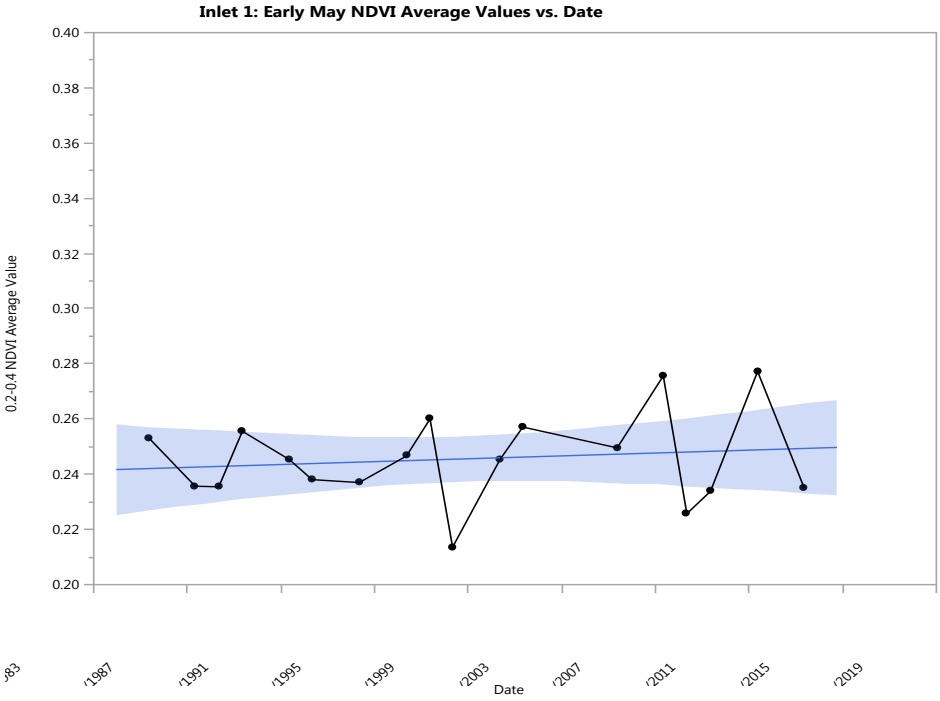

Figure C- 17 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Early May from 1984 to 2013

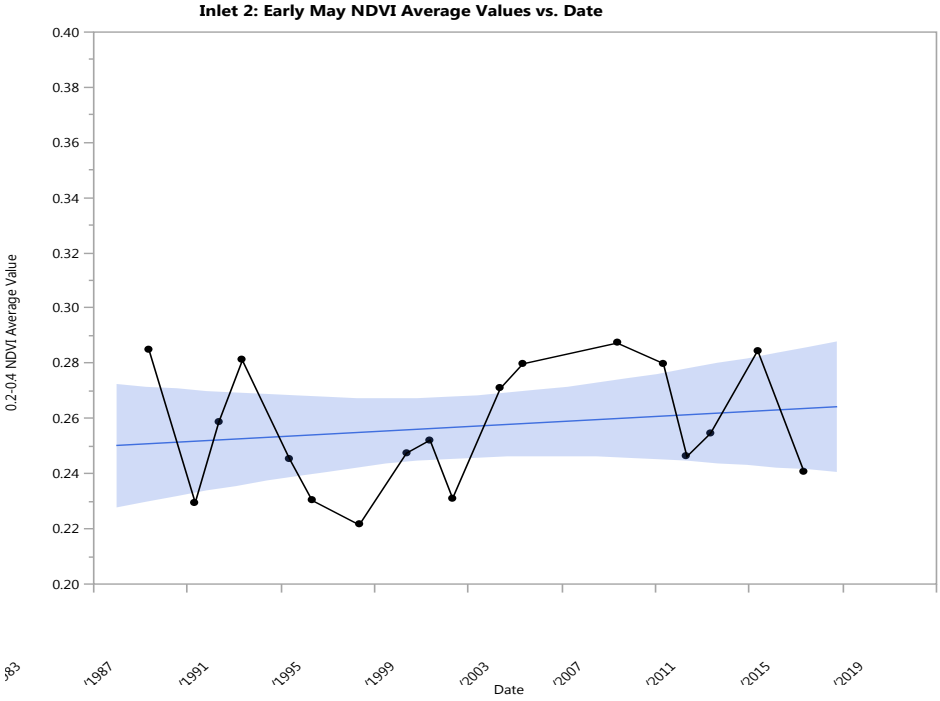

Figure C- 18 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Early May from 1984 to 2013

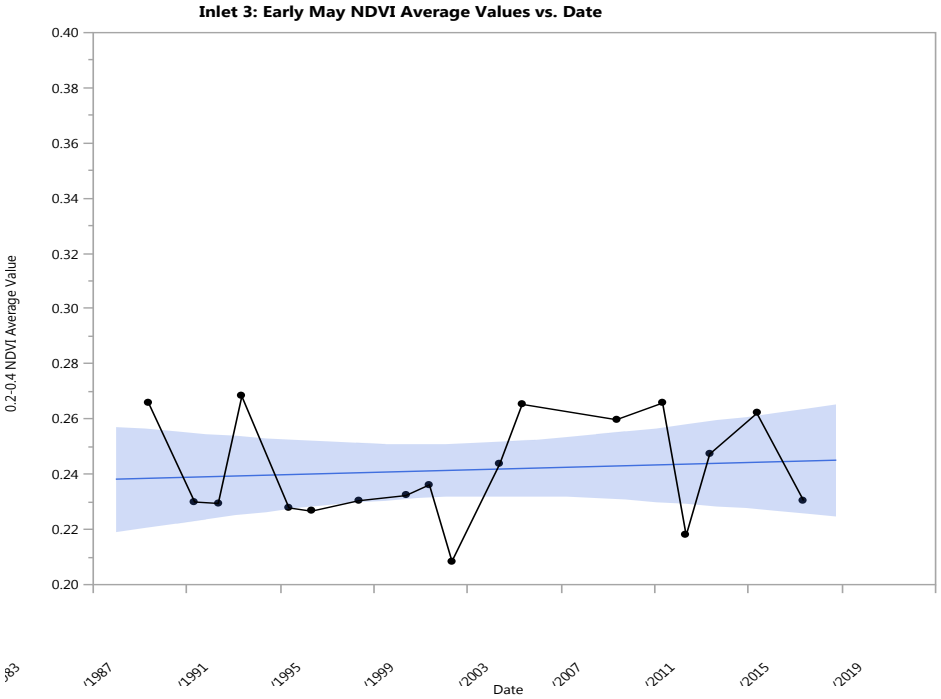

Figure C- 19 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Early May from 1984 to 2013

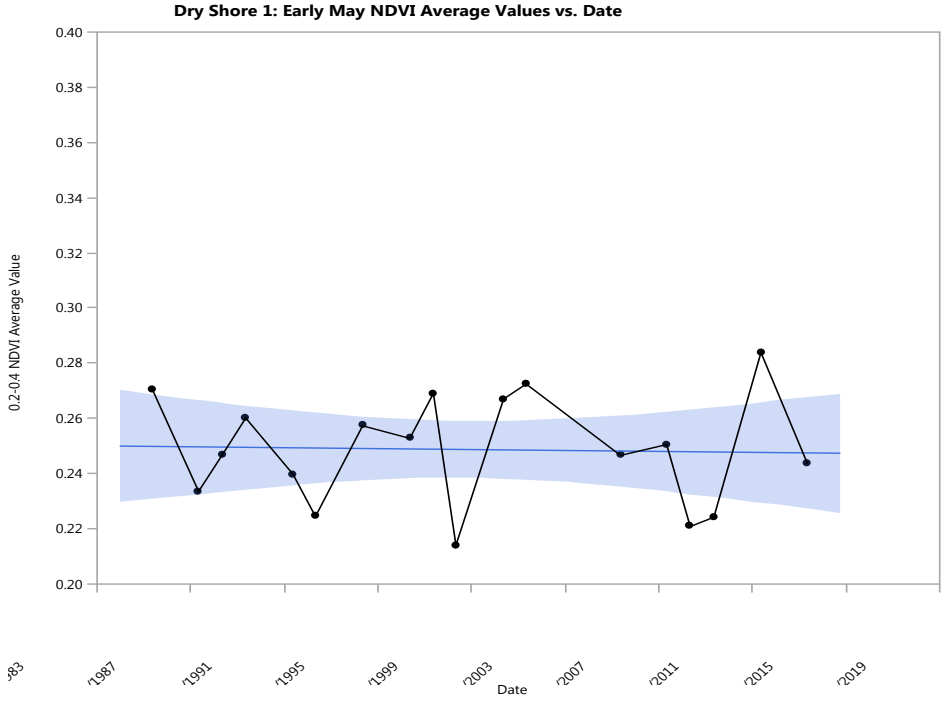

Figure C- 20 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Early May from 1984 to 2013

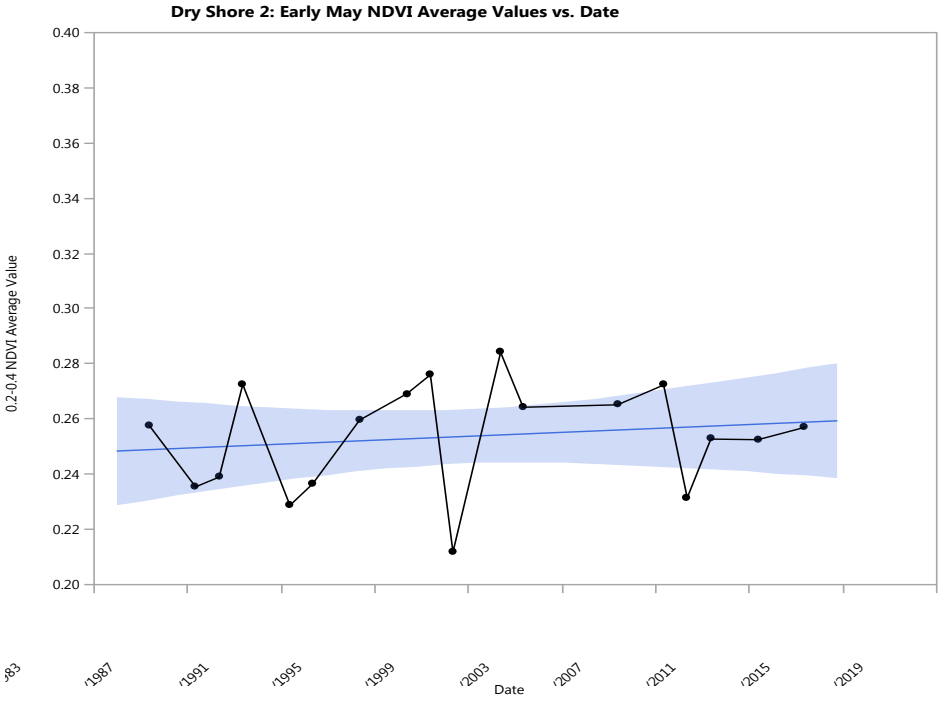

Figure C- 21 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Early May from 1984 to 2013

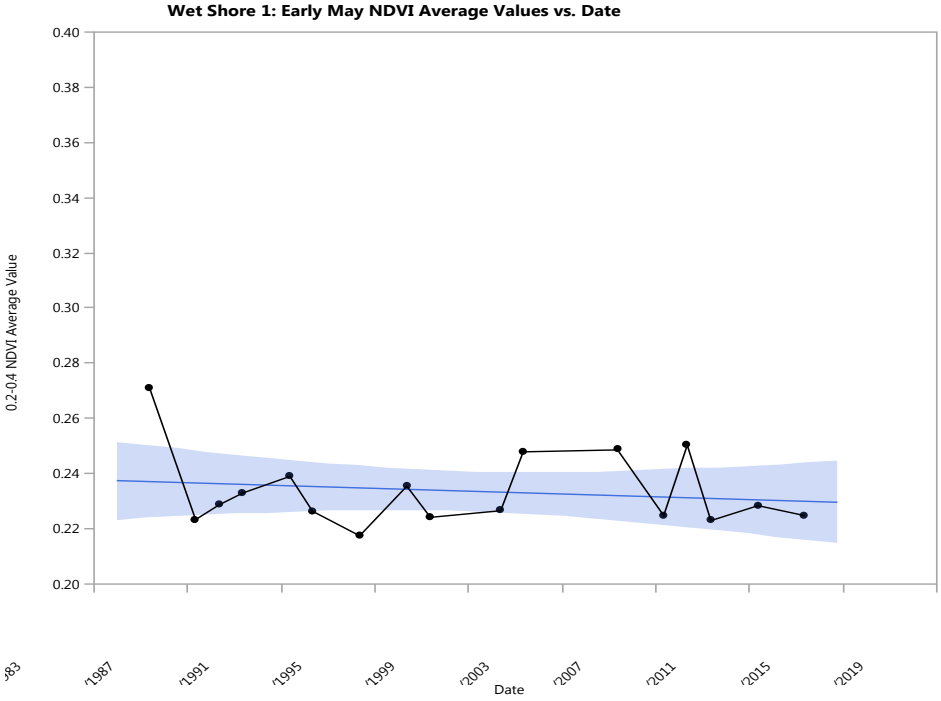

Figure C- 22 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Early May from 1984 to 2013

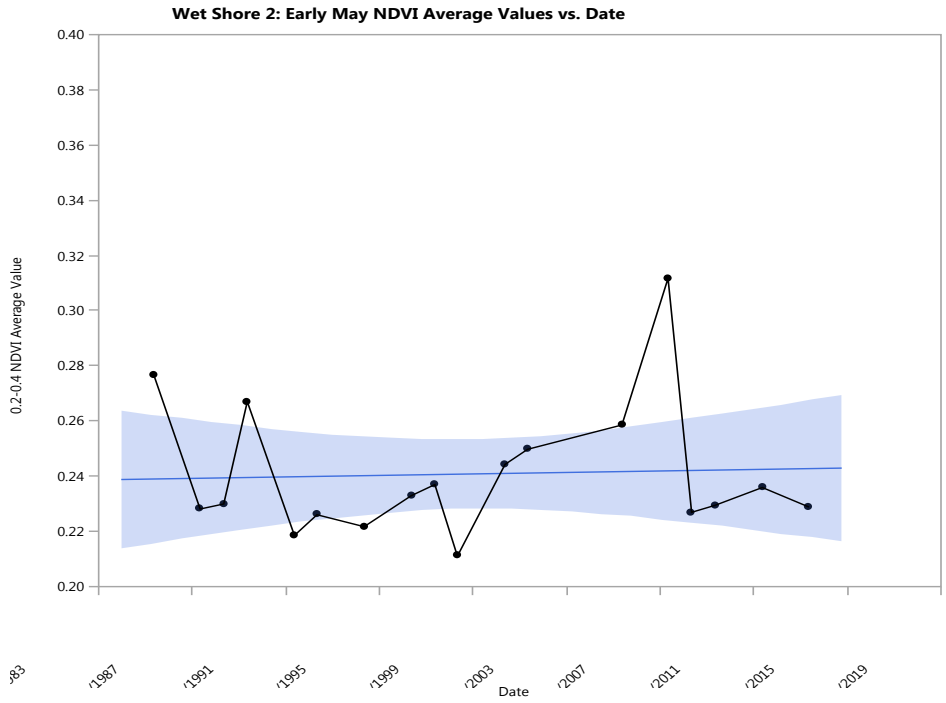

Figure C- 23 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Early May from 1984 to 2013

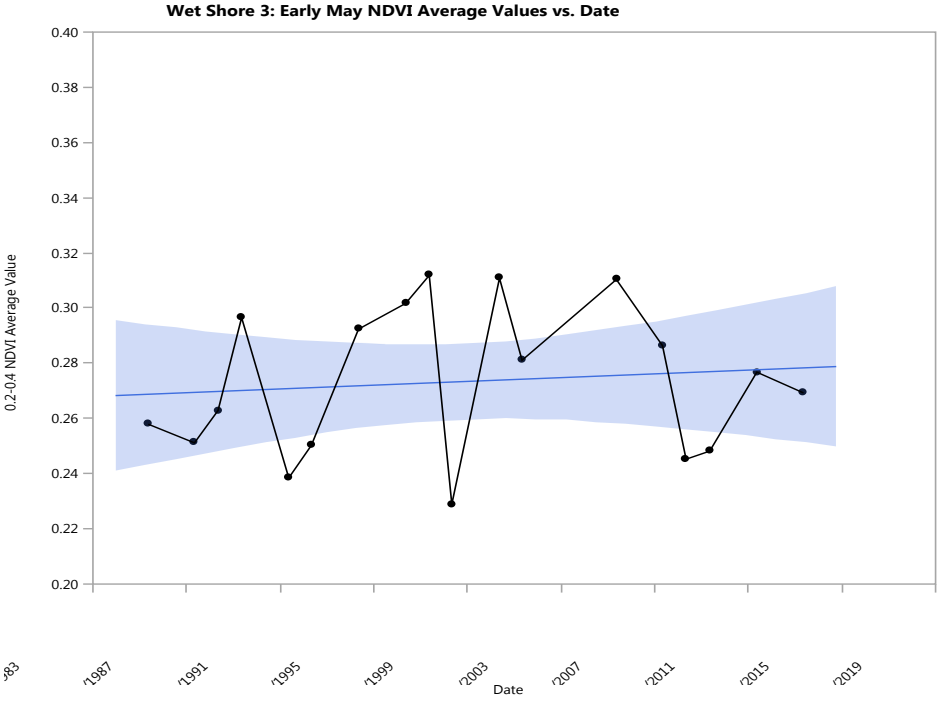

Figure C- 24 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Early May from 1984 to 2013

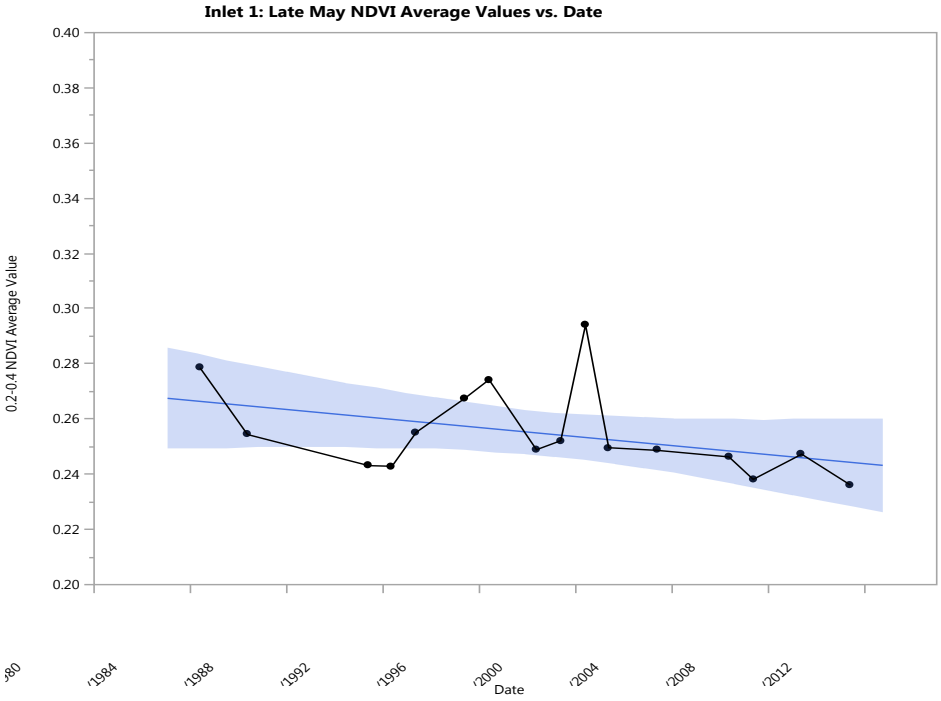

Figure C- 25 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Late May from 1984 to 2013

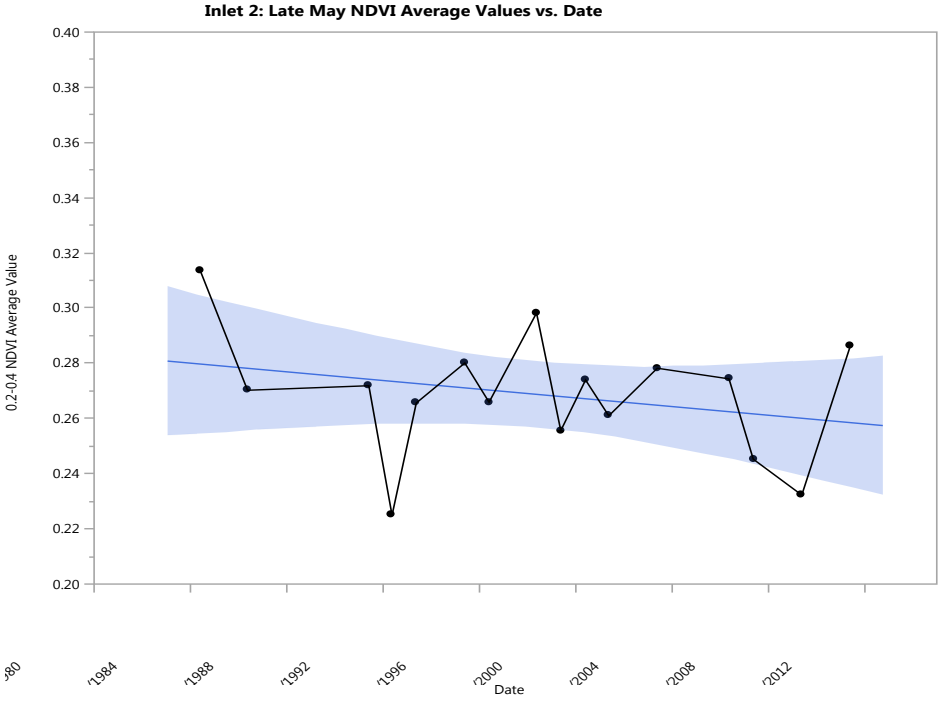

Figure C- 26 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Late May from 1984 to 2013

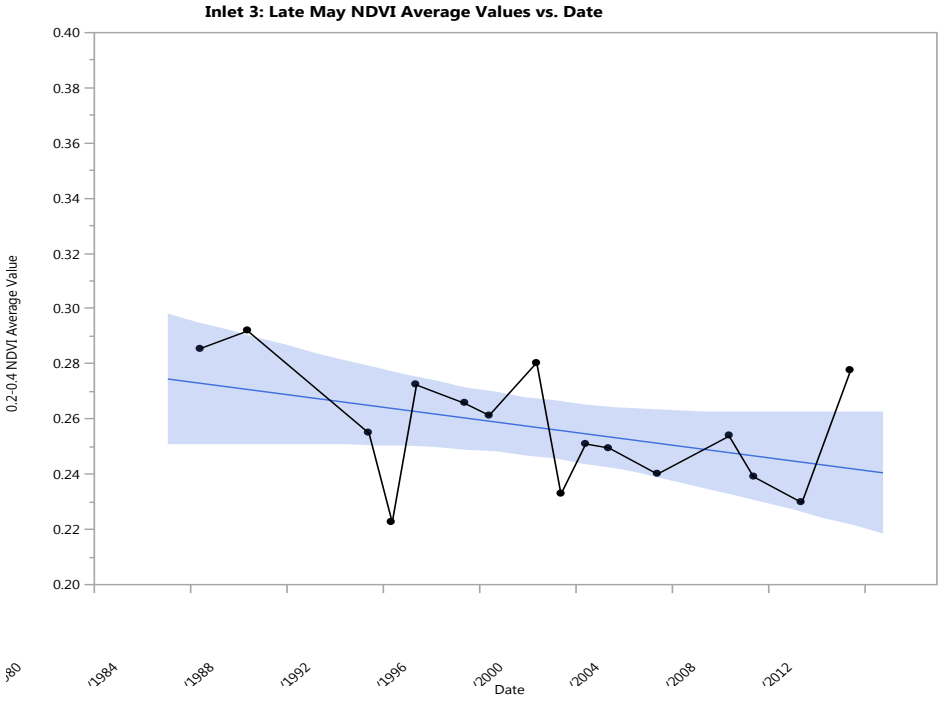

Figure C- 27 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Late May from 1984 to 2013

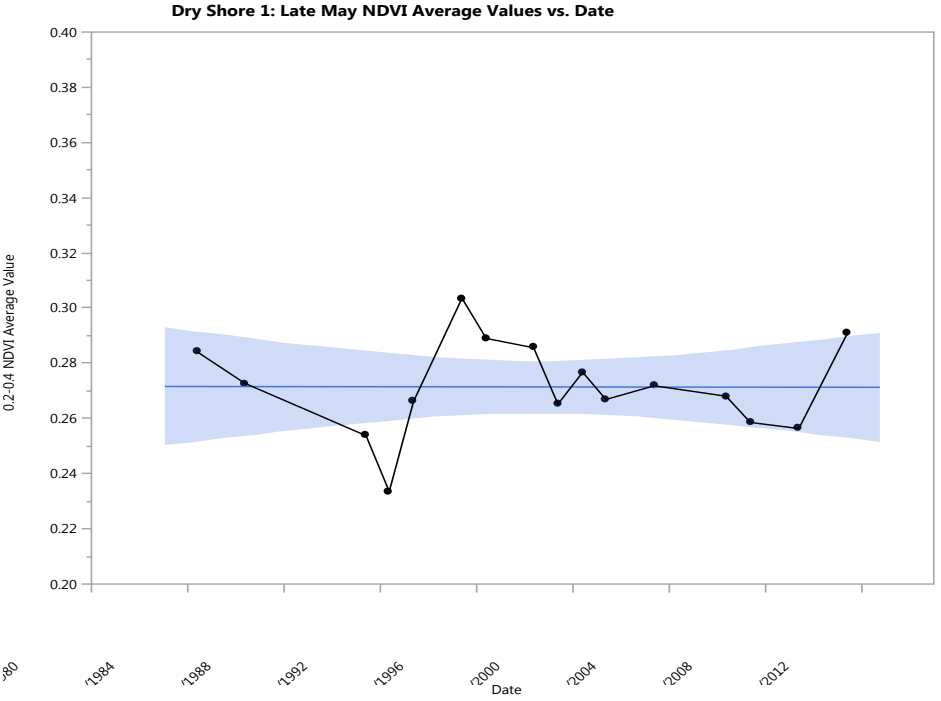

Figure C- 28 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Late May from 1984 to 2013

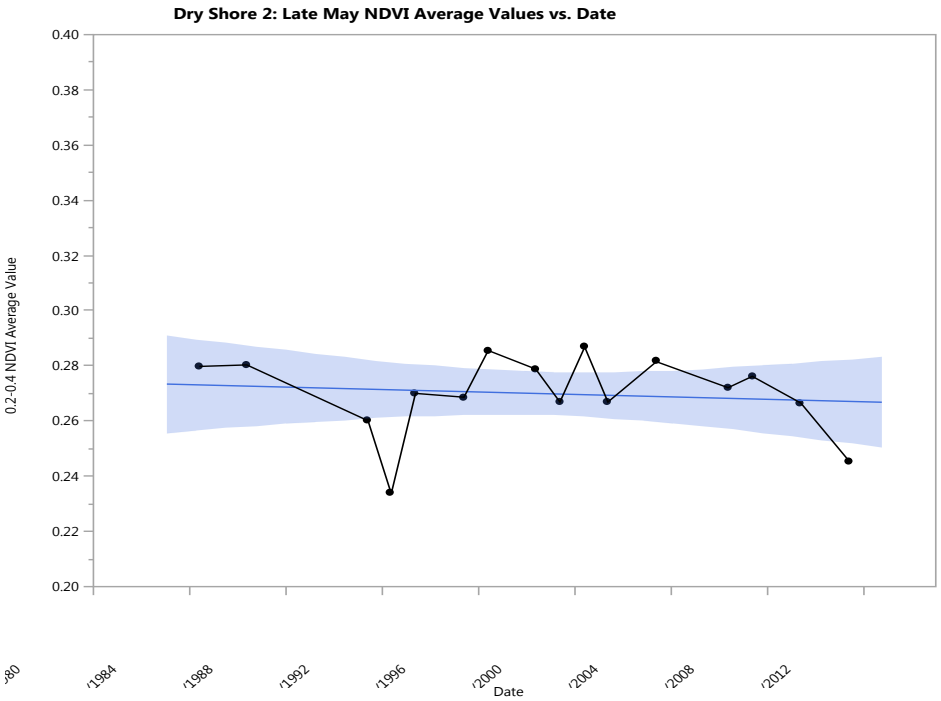

Figure C- 29 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Late May from 1984 to 2013

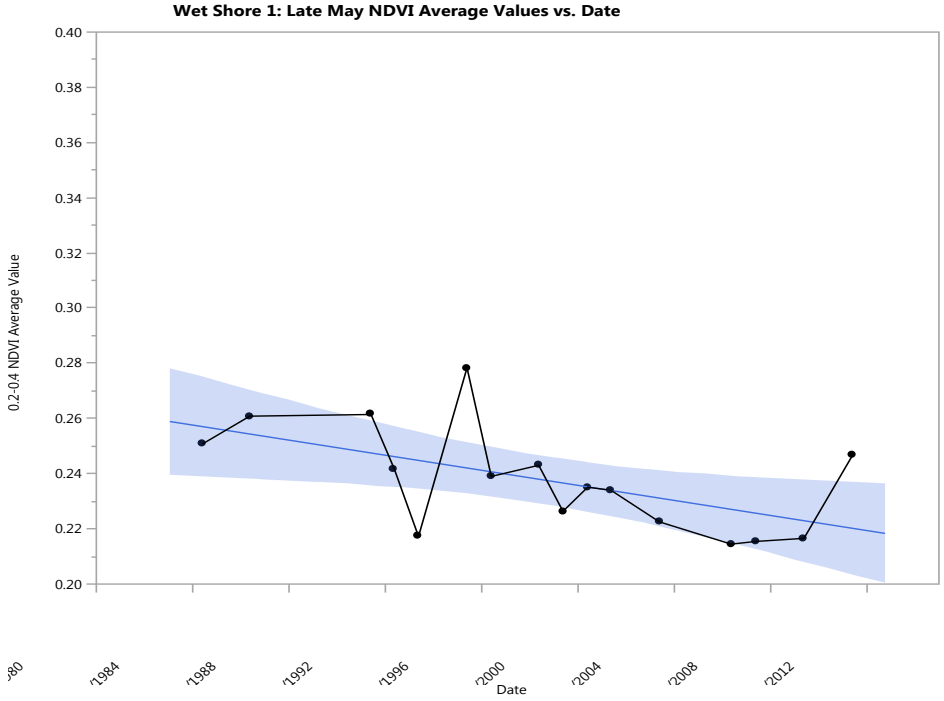

Figure C- 30 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Late May from 1984 to 2013

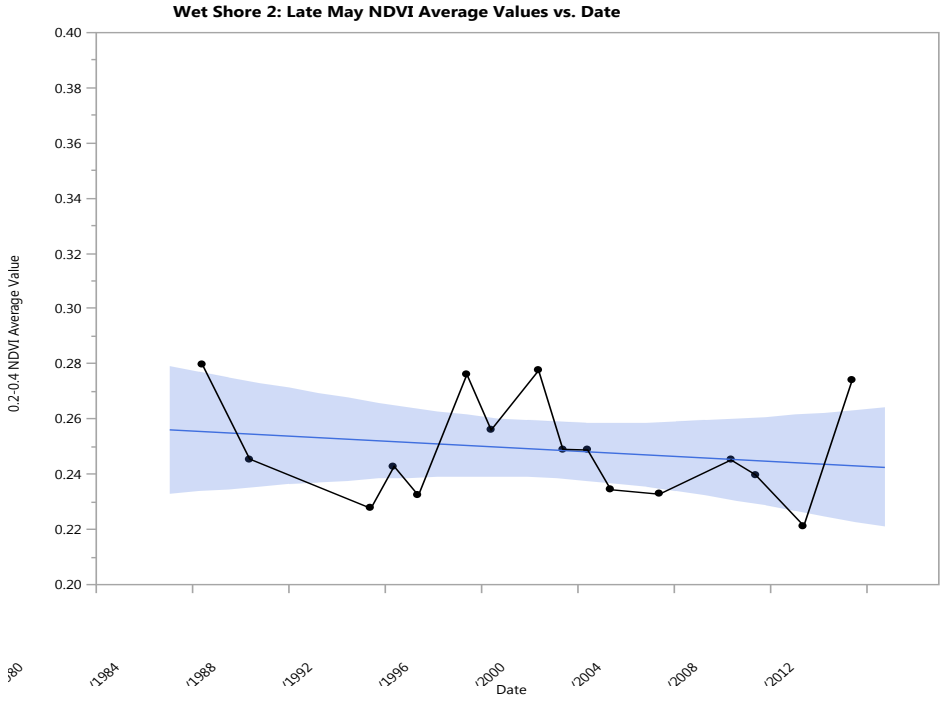

Figure C- 31 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Late May from 1984 to 2013

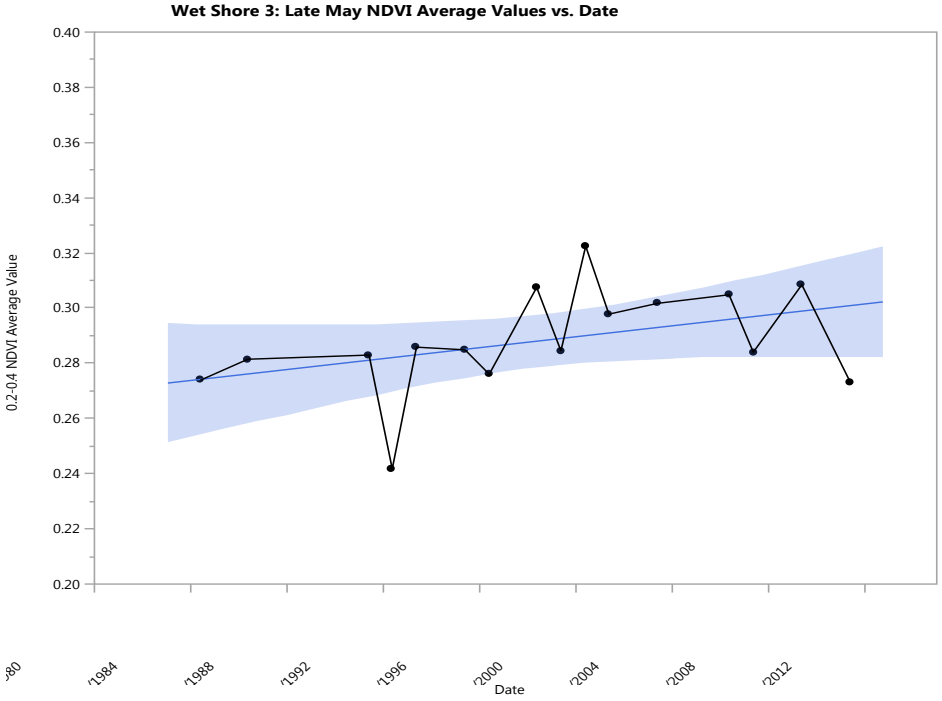

Figure C- 32 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Late May from 1984 to 2013

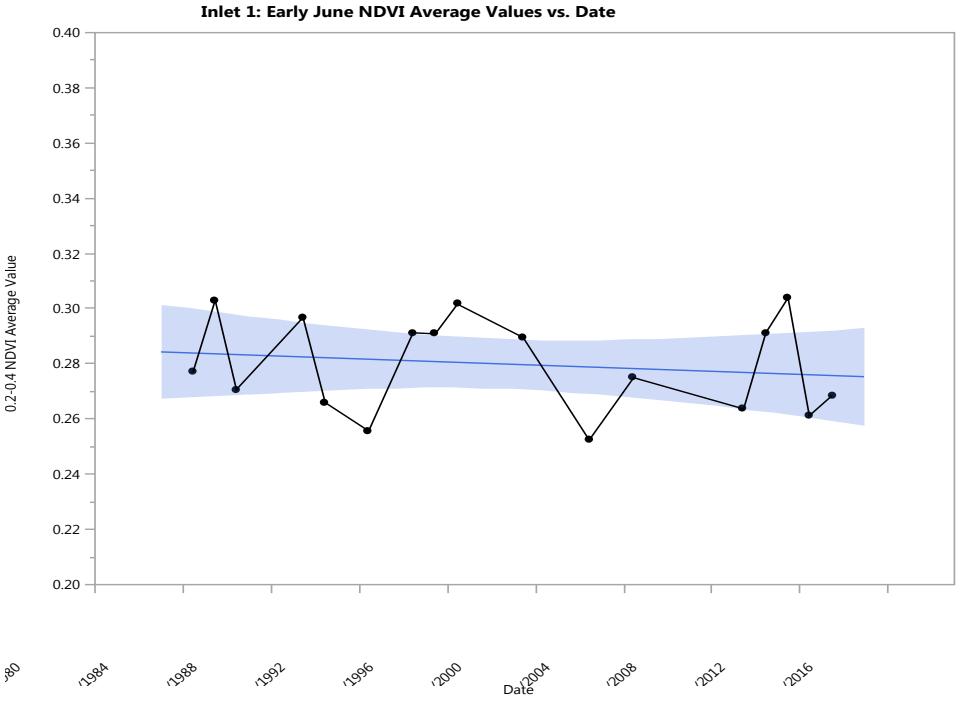

Figure C- 33 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Early June from 1984 to 2013

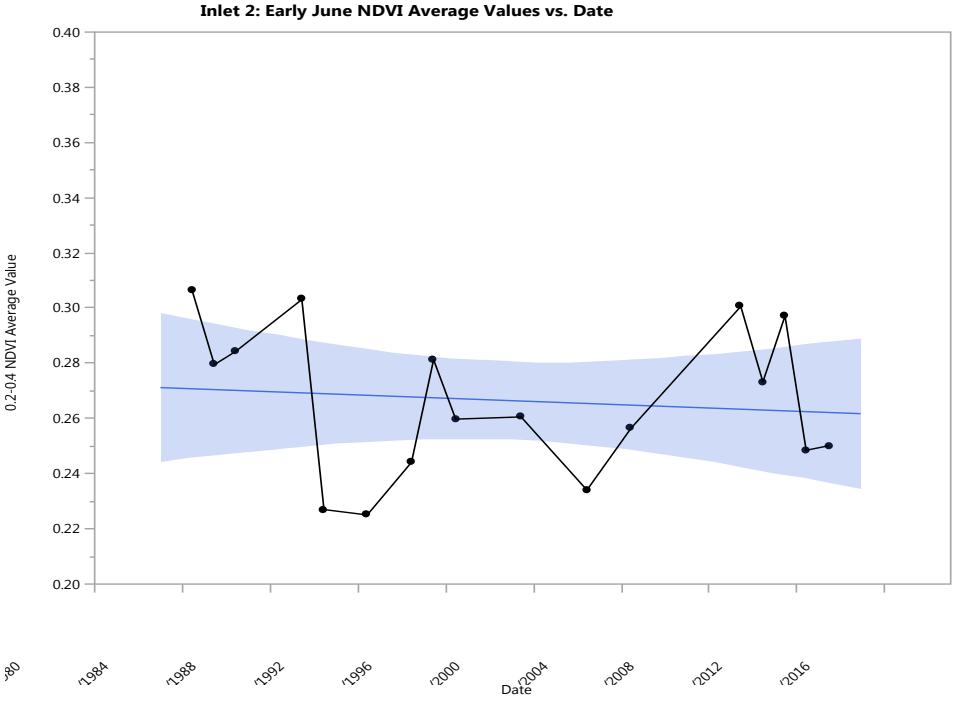

Figure C- 34 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Early June from 1984 to 2013

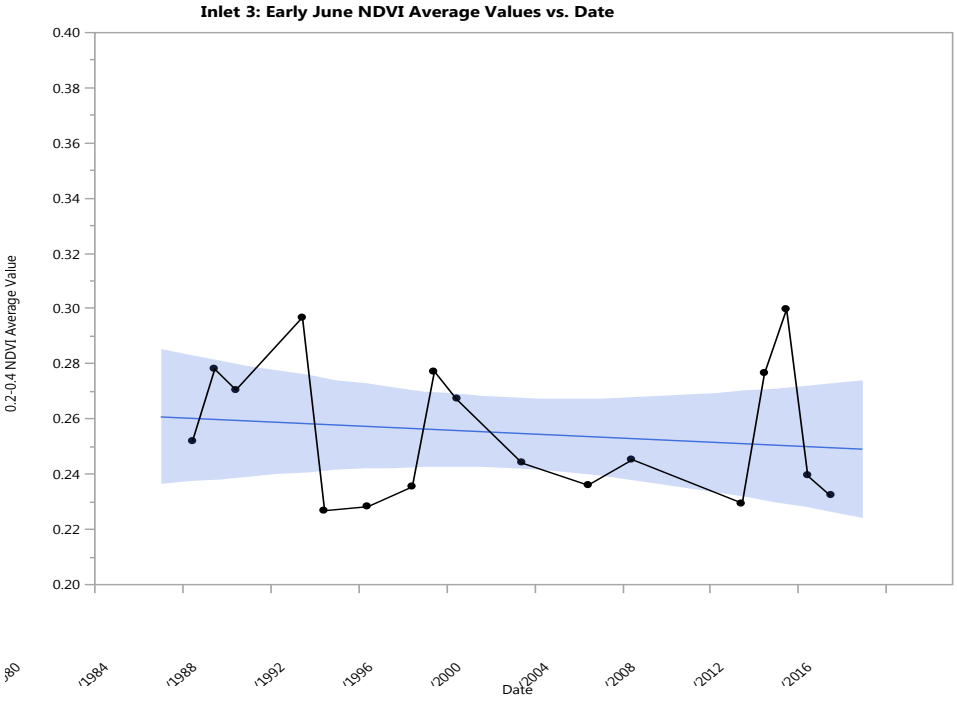

Figure C- 35 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Early June from 1984 to 2013

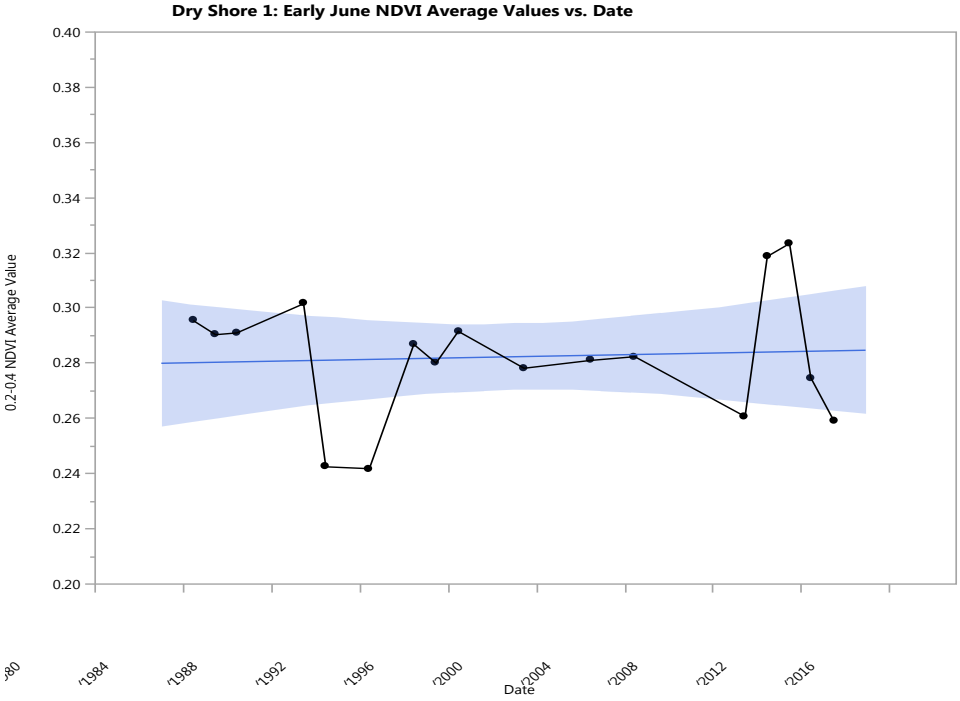

Figure C- 36 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Early June from 1984 to 2013

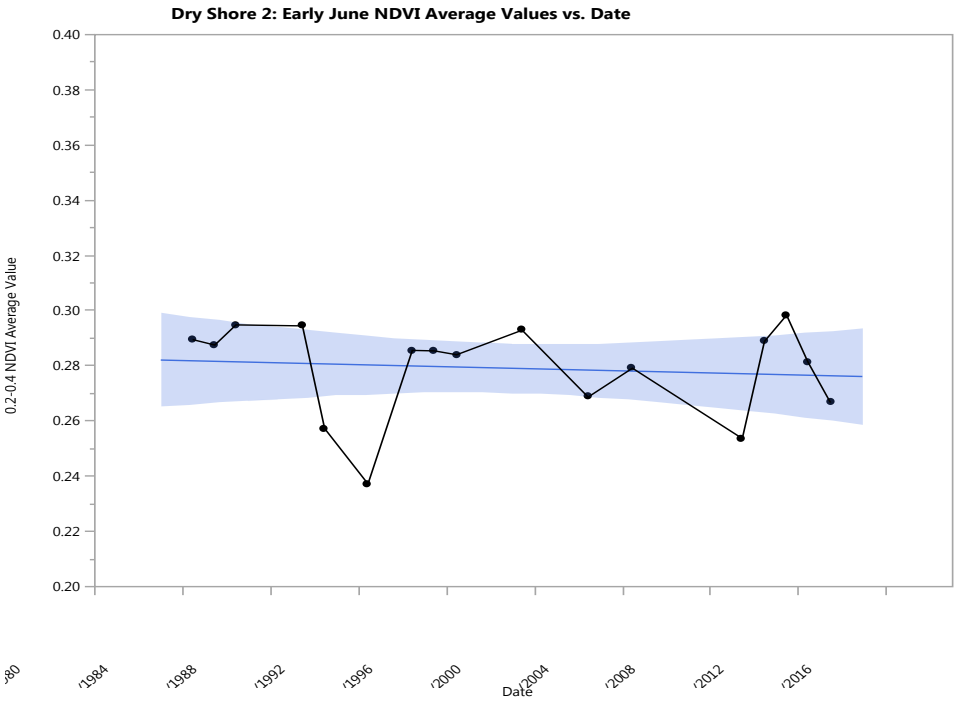

Figure C- 37 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Early June from 1984 to 2013

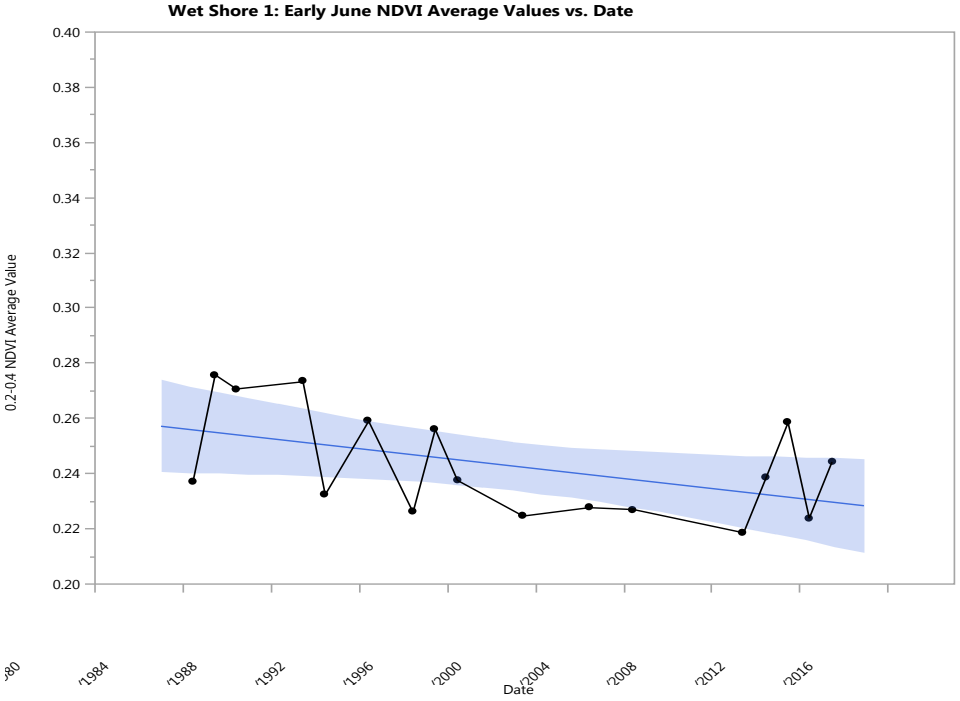

Figure C- 38 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Early June from 1984 to 2013

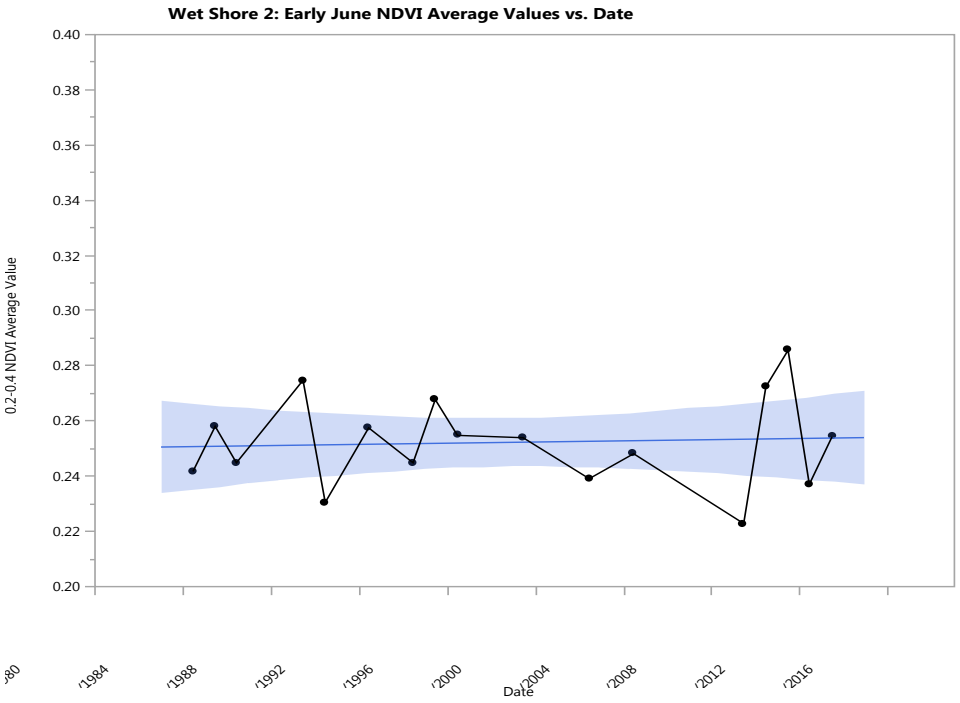

Figure C- 39 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Early June from 1984 to 2013

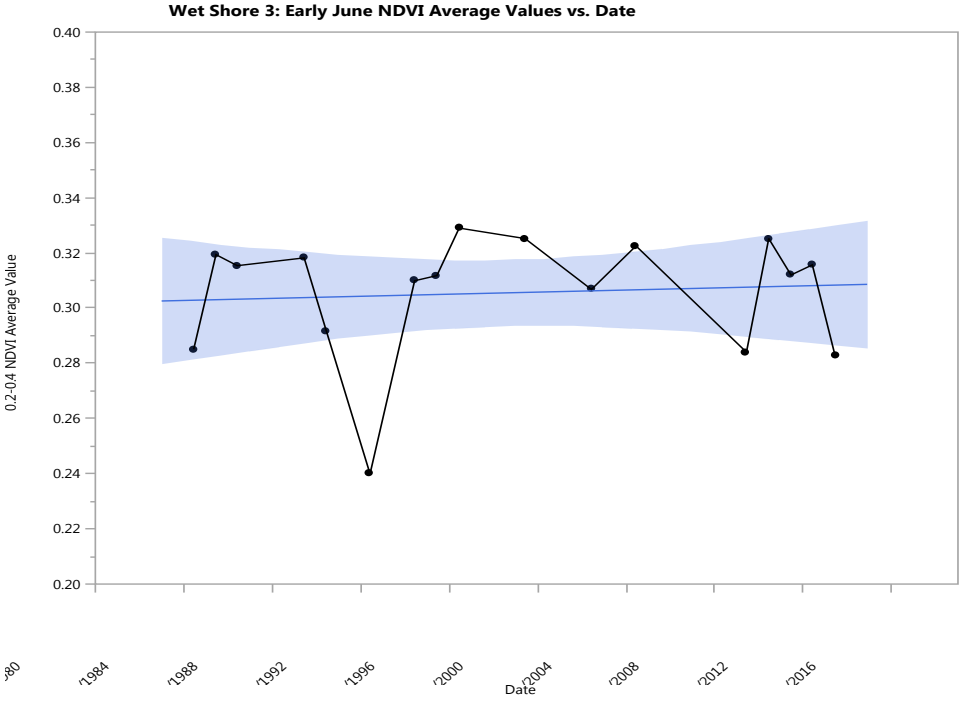

Figure C- 40 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Early June from 1984 to 2013

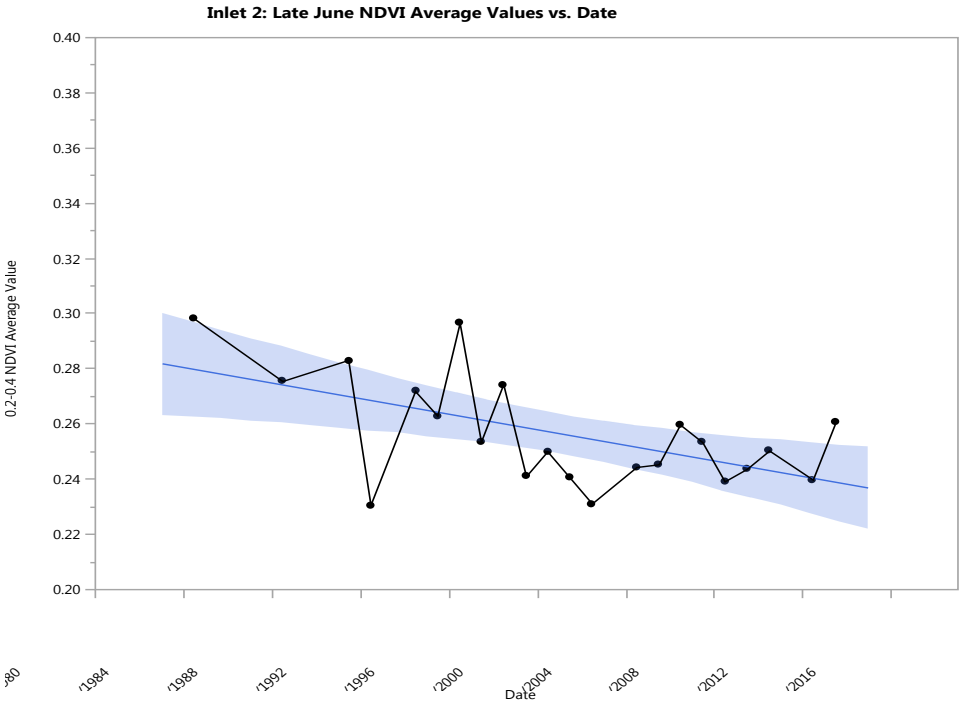

Figure C- 41 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Late June from 1984 to 2013

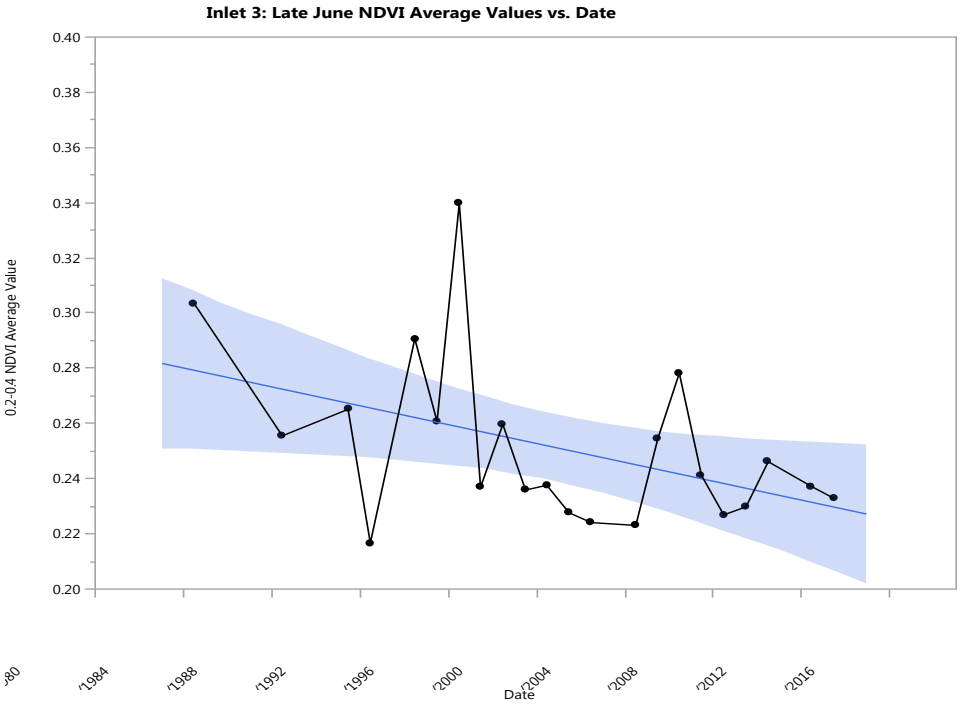

Figure C- 42 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Late June from 1984 to 2013

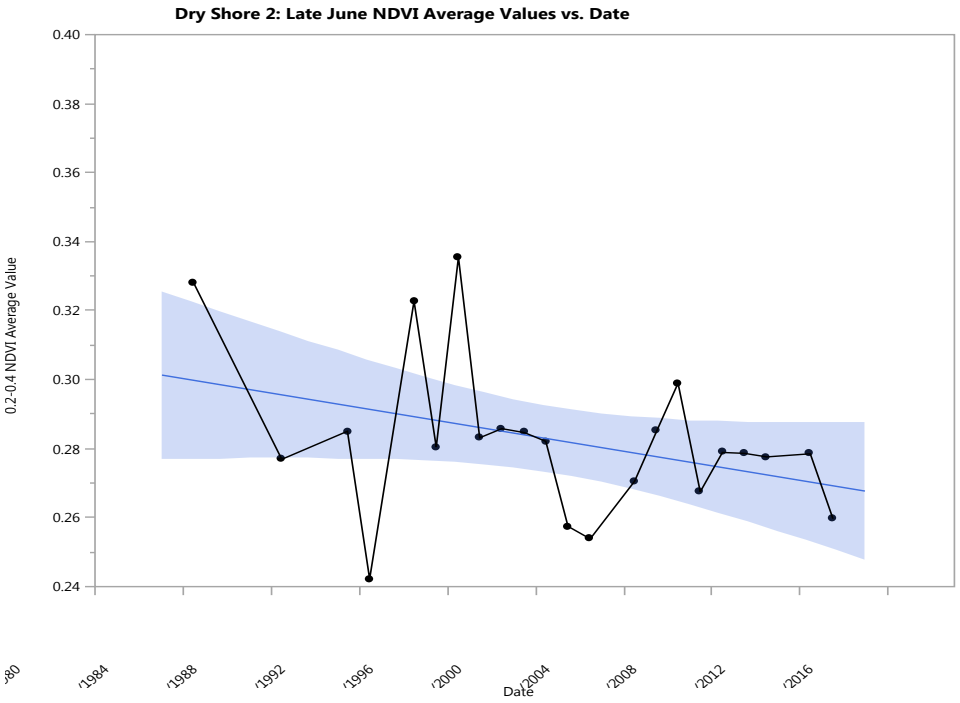

Figure C- 43 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Late June from 1984 to 2013

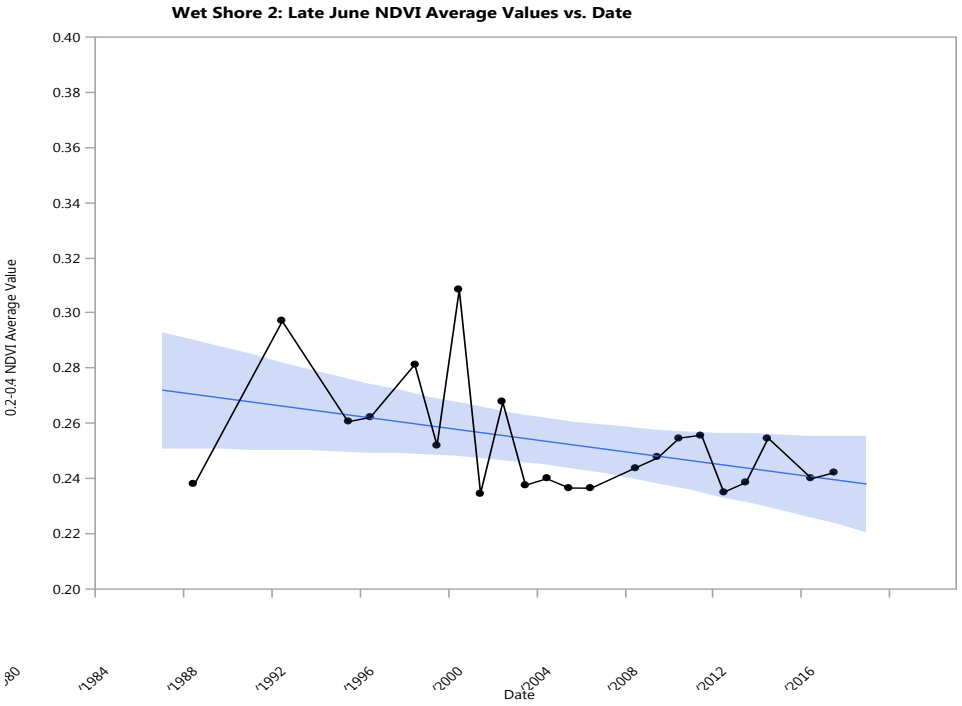

Figure C- 44 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Late June from 1984 to 2013

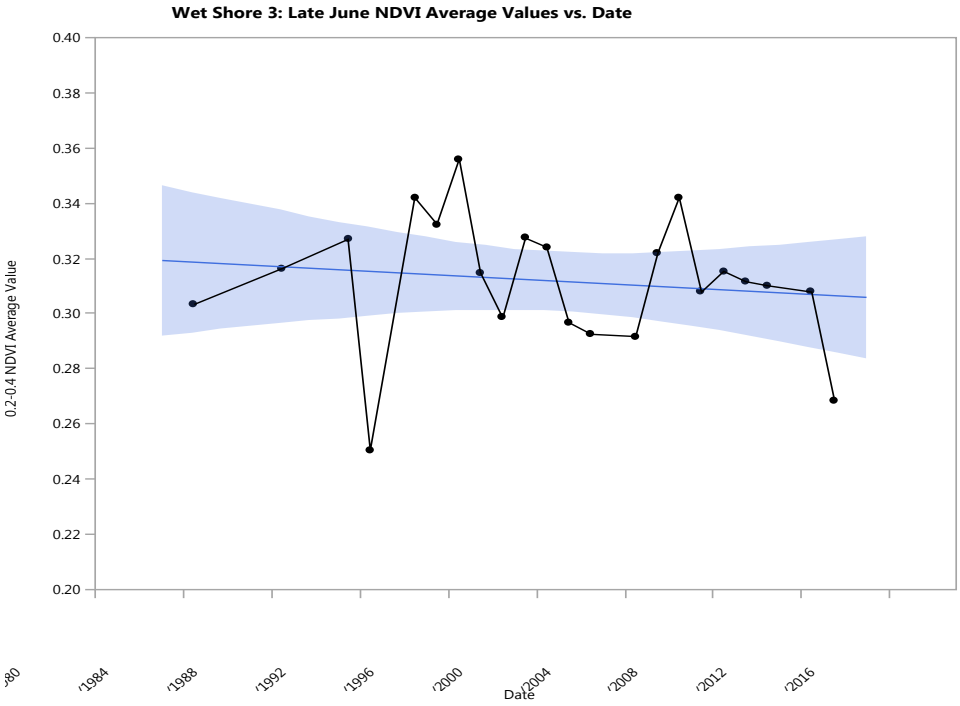

Figure C- 45 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Late June from 1984 to 2013

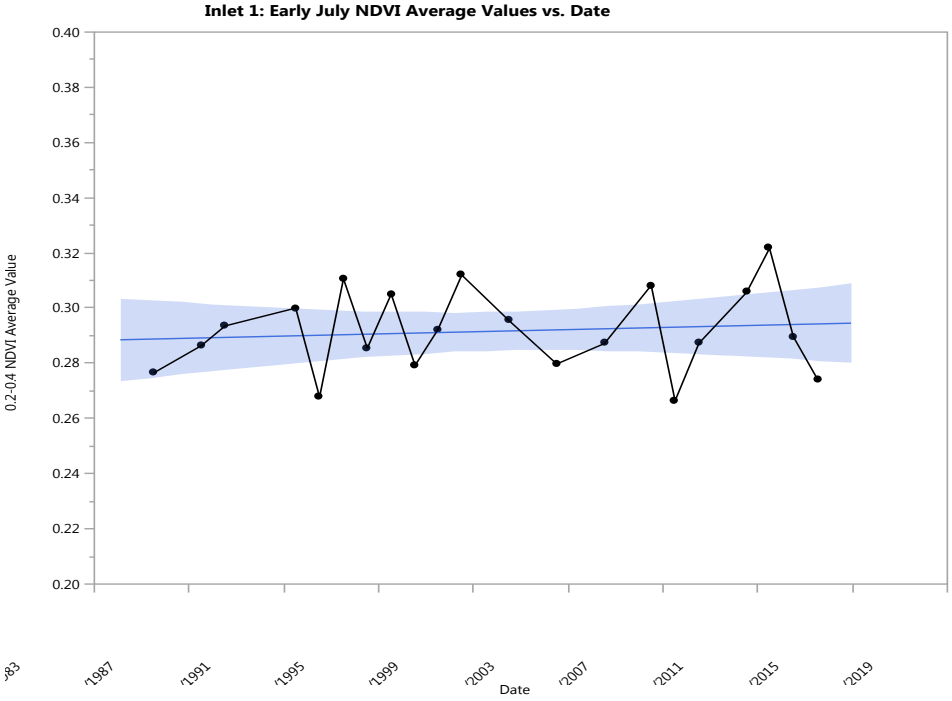

Figure C- 46 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Early July from 1984 to 2013

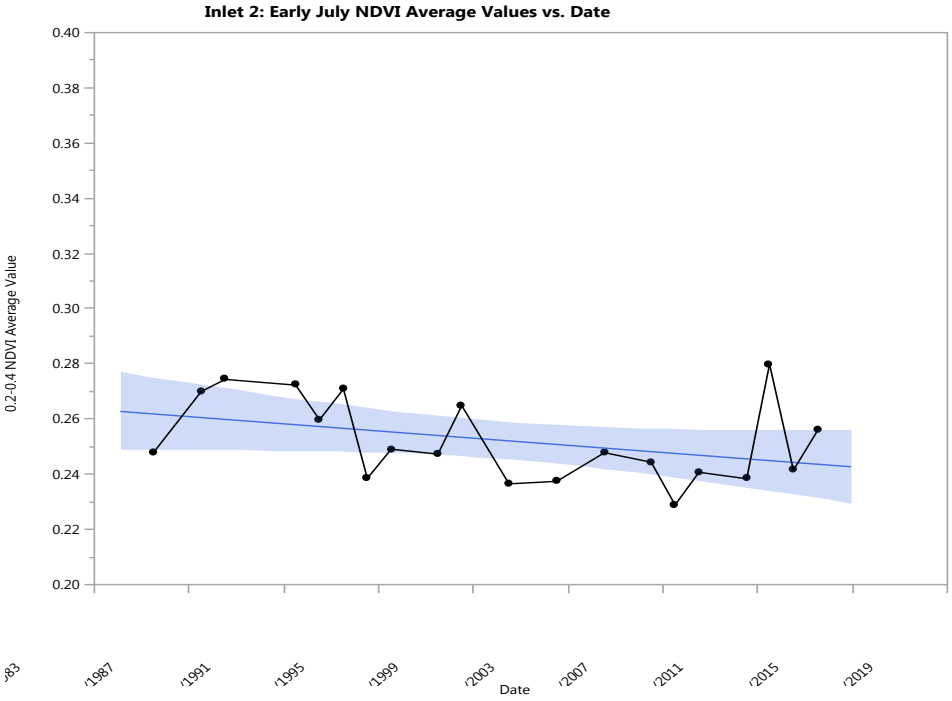

Figure C- 47 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Early July from 1984 to 2013

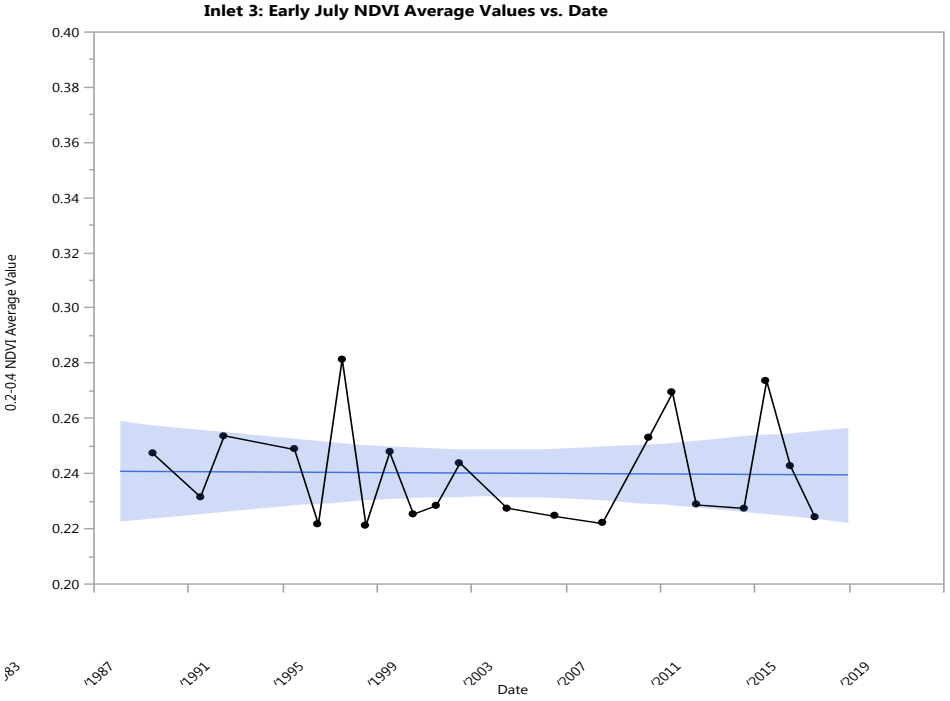

Figure C- 48 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Early July from 1984 to 2013

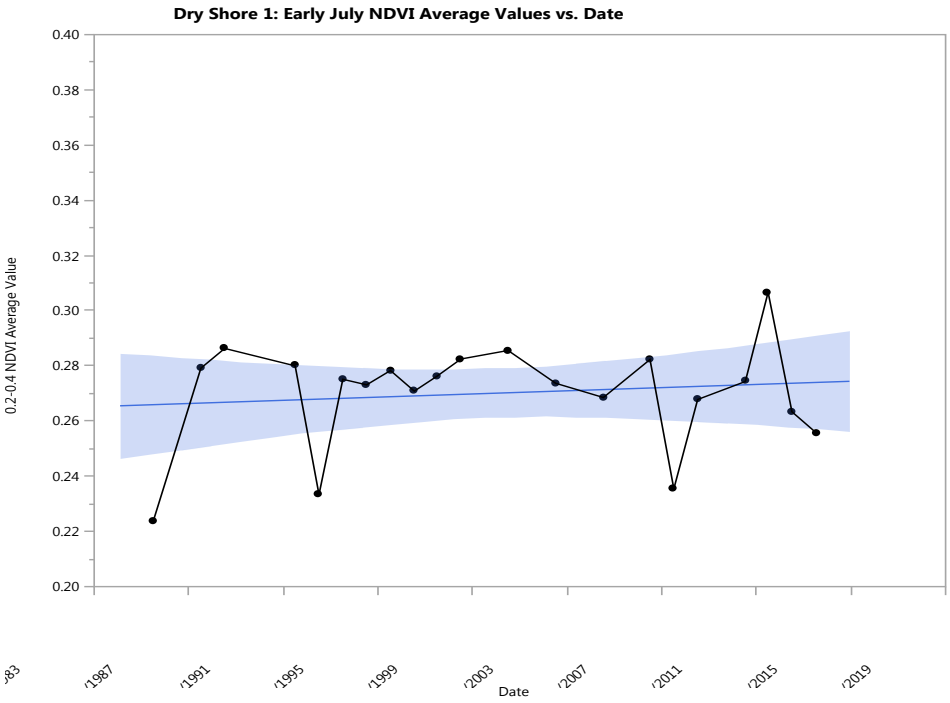

Figure C- 49 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Early July from 1984 to 2013

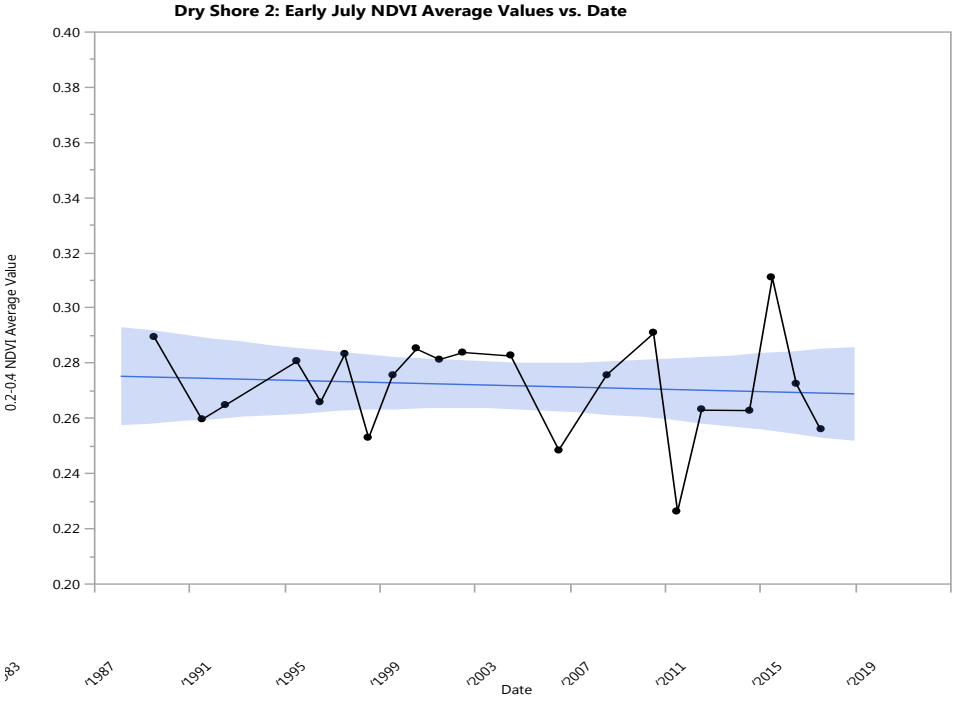

Figure C- 50 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Early July from 1984 to 2013

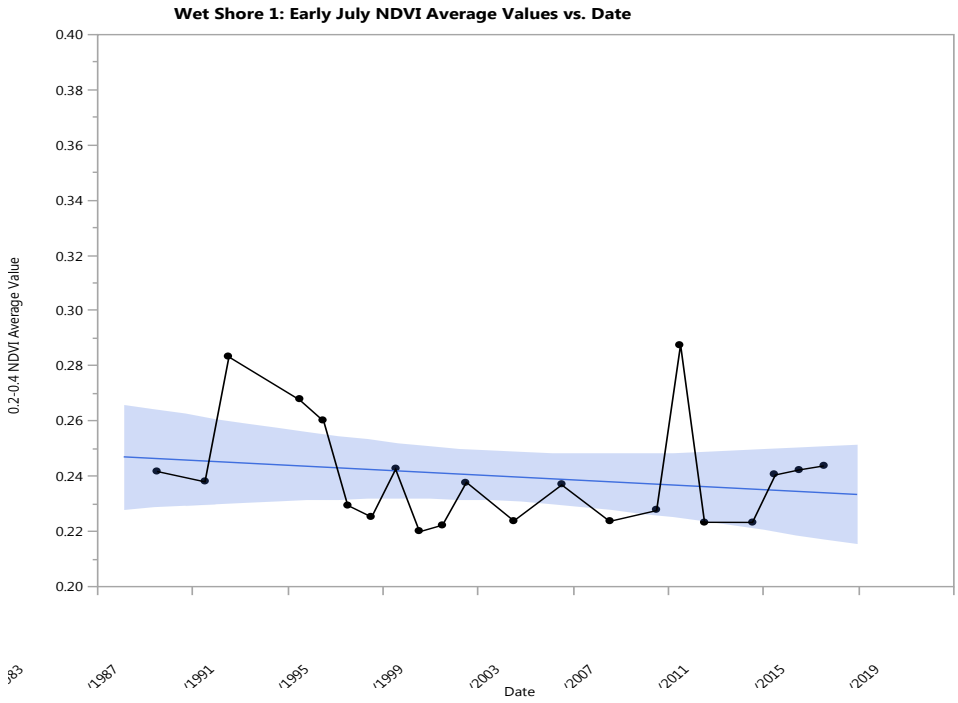

Figure C- 51 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Early July from 1984 to 2013

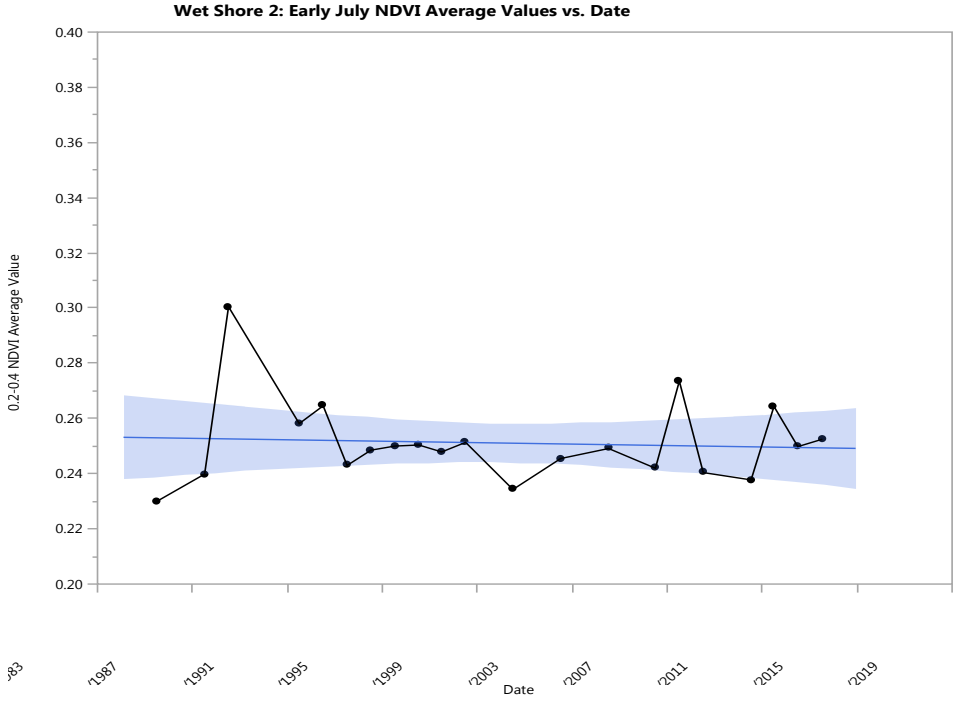

Figure C- 52 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Early July from 1984 to 2013

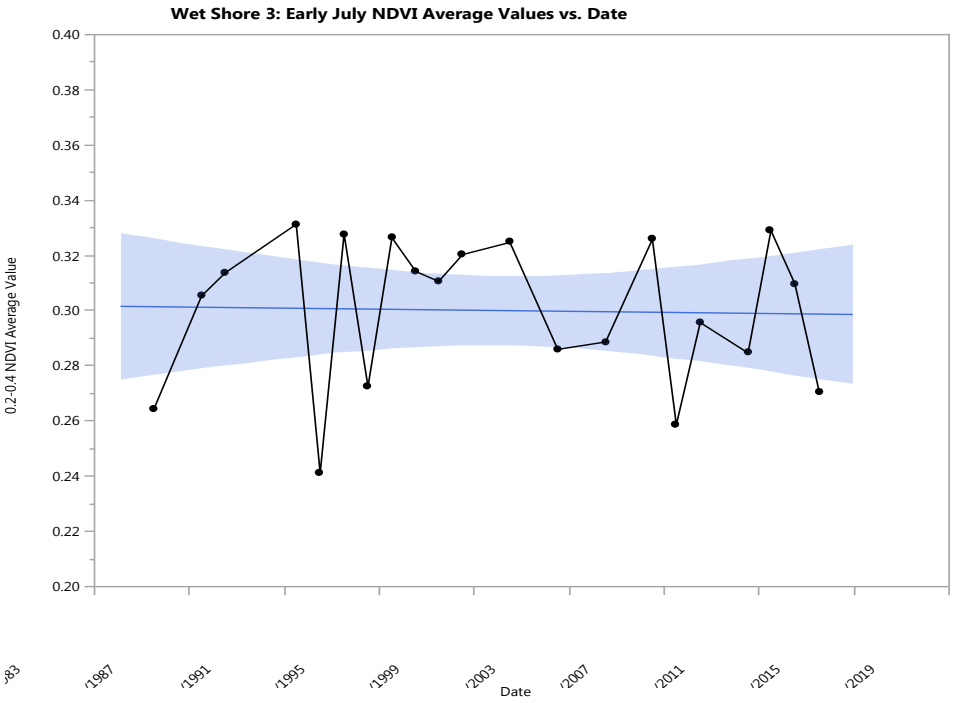

Figure C- 53 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Early July from 1984 to 2013

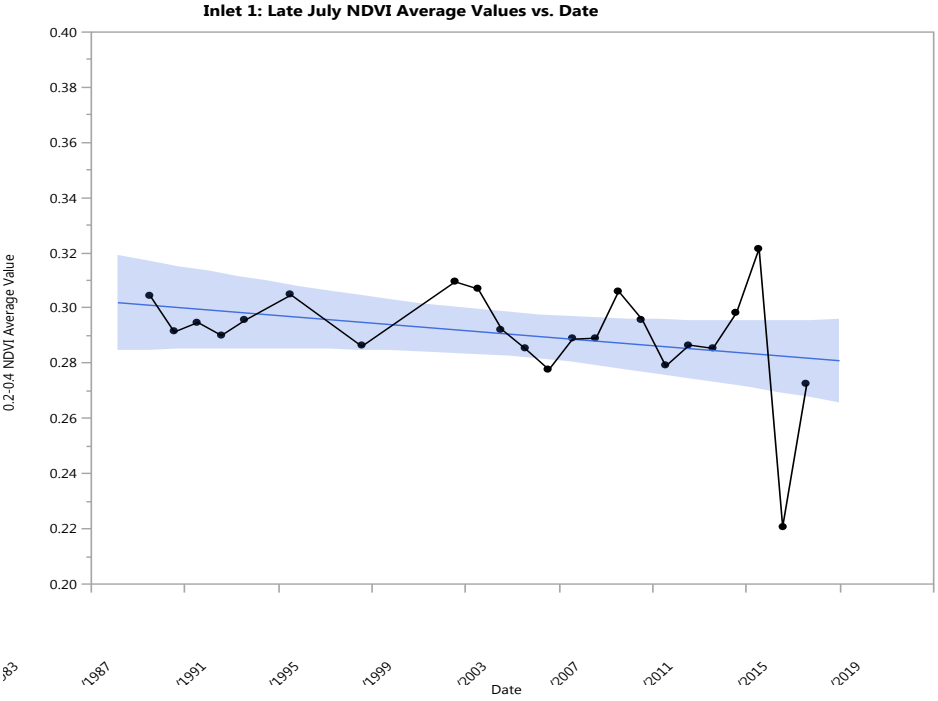

Figure C- 54 Average of 0.2-0.4 Range of NDVI Values in Inlet 1 for Late July from 1984 to 2013

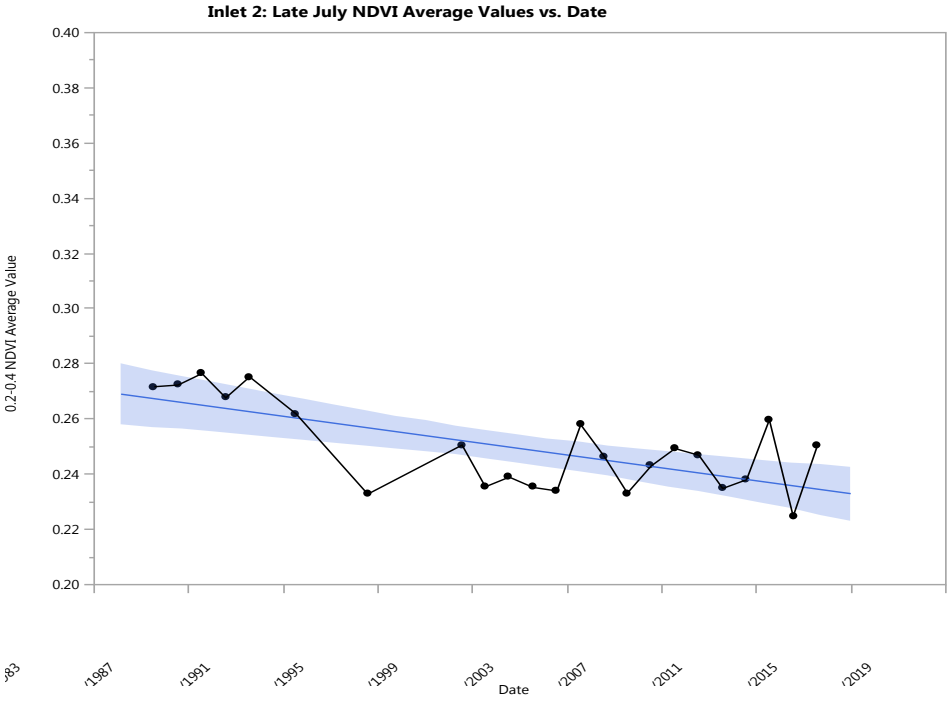

Figure C- 55 Average of 0.2-0.4 Range of NDVI Values in Inlet 2 for Late July from 1984 to 2013

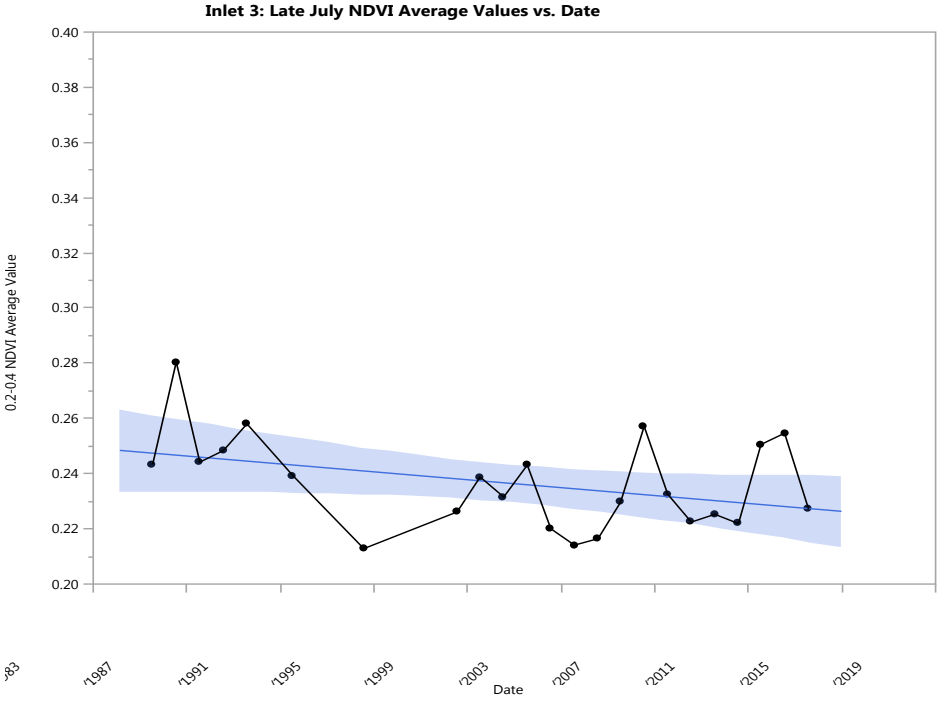

Figure C- 56 Average of 0.2-0.4 Range of NDVI Values in Inlet 3 for Late July from 1984 to 2013

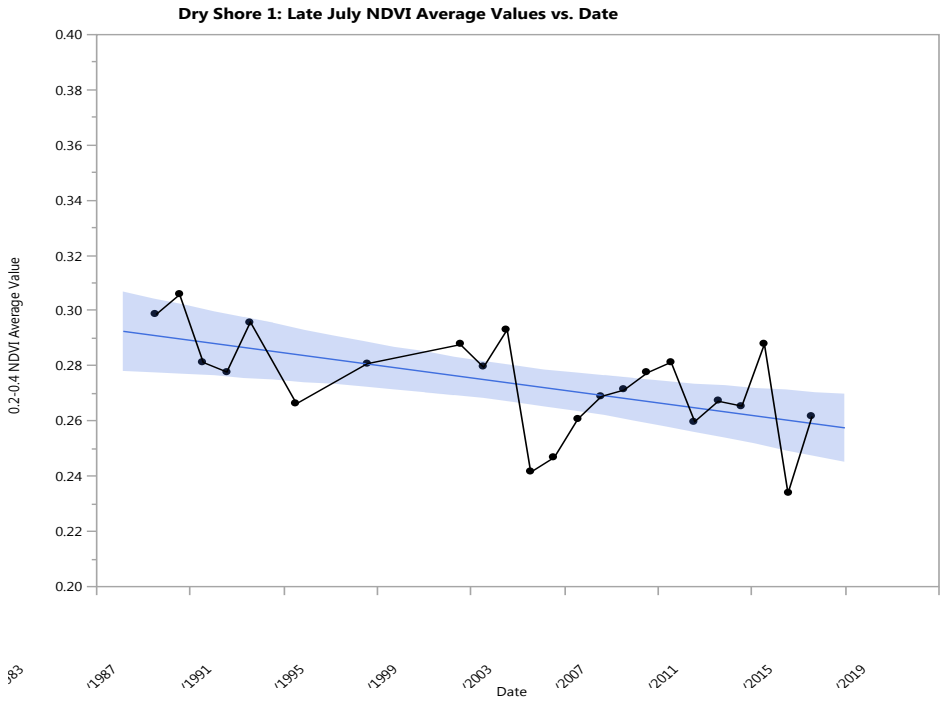

Figure C- 57 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 1 for Late July from 1984 to 2013

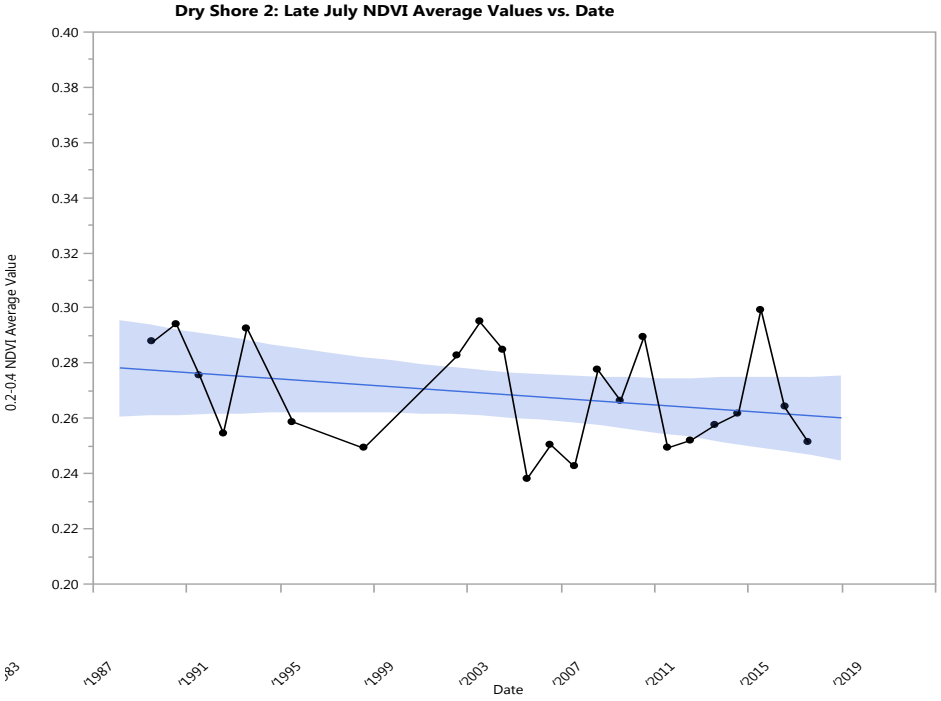

Figure C- 58 Average of 0.2-0.4 Range of NDVI Values in Dry Shore 2 for Late July from 1984 to 2013

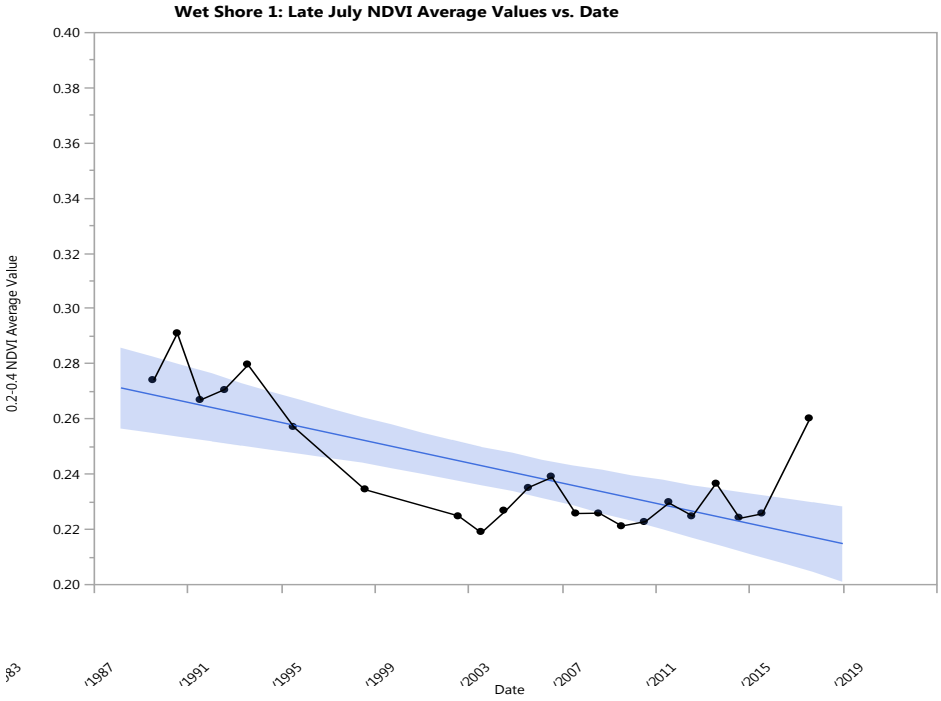

Figure C- 59 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 1 for Late July from 1984 to 2013

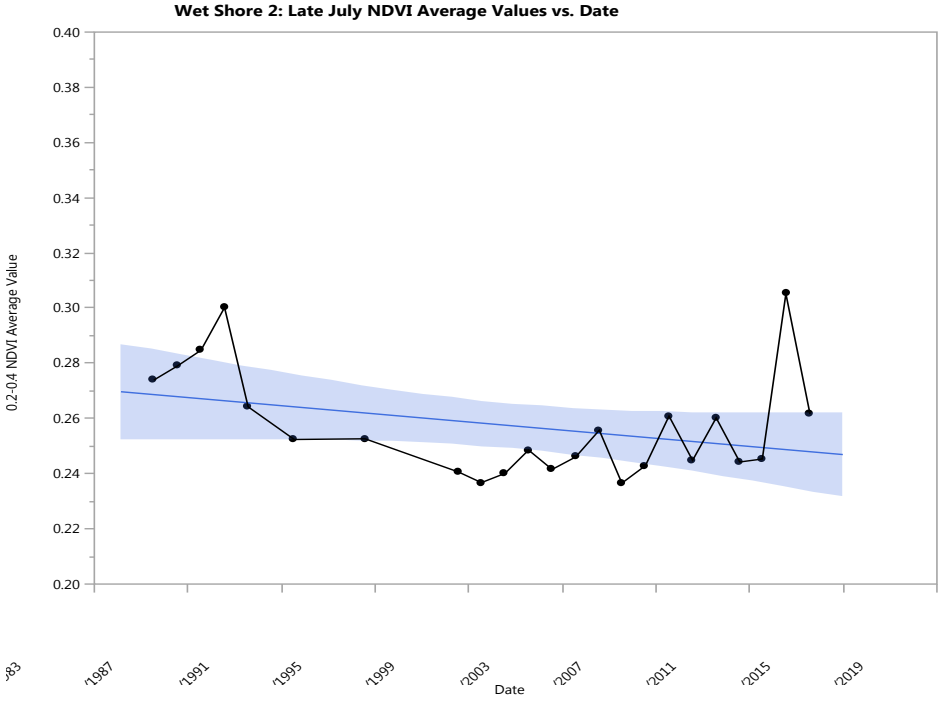

Figure C- 60 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 2 for Late July from 1984 to 2013

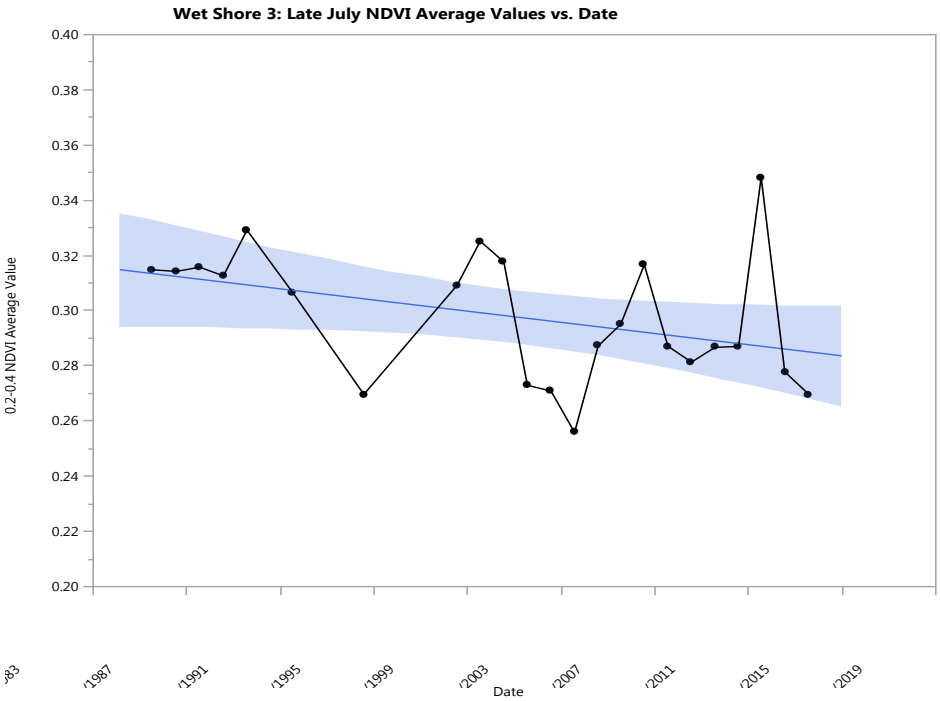

Figure C- 61 Average of 0.2-0.4 Range of NDVI Values in Wet Shore 3 for Late July from 1984 to 2013