Water Quality in the Los Angeles River:
A Remote Sensing Based Analysis

by

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To my grandparents

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Table of Contents

List of Tables

List of Figures

Abbreviations

ANOVA	Analysis of Variance
BWRP	Burbank Water Reclamation Plant
DTCWRP	Donald C. Tillman Water Reclamation Plant
LAC	Los Angeles County
LAPIER	Los Angeles County Public Works Draft Program Environmental Impact Report
LAR	Los Angeles River
NAIP	National Agriculture Imagery Program
NDTI	Normalized Difference Turbidity Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
RS	Remote Sensing
SSI	Spatial Sciences Institute
UAVs	Unmanned aerial vehicles
USACE	United States Army Corps of Engineers
USC	University of Southern California
WQ	Water quality
WRP	Water Reclamation Plant

Abstract

Approximately 11 miles of concrete channelized Los Angeles River (LAR) are planned to be restored to natural riverbed with engineered banks by the U.S. Army Corps of Engineers (USACE) working with the City of Los Angeles. Recent studies centered on urban watersheds in Southern California focus primarily on pollutants without addressing the effects of artificial riverbed substrate on water quality (WQ). Departing from the field collection methodologies employed by previous studies in the LAR, this project is a systematic remote sensing (RS) based investigation of differences in WQ found between natural and concrete riverbed environments in the LAR. Two RS indices are applied to aerial imagery to assess relative WQ in the LAR: Normalized difference vegetation index (NDVI) and normalized difference turbidity index (NDTI). National Agriculture Imagery Program imagery is integrated with NDVI to measure chlorophyll-a concentration and NDTI to determine turbidity levels as parameters to gauge WQ. Results indicate that natural riverbed sections typically contain lower NDTI values than concrete sections, suggesting these environments abate turbidity. NDVI results detect statistically significant differences in chlorophyll-a concentration between water in concrete and natural sections that may be the product of several variables deserving further study. The RS methodology herein provides a framework for monitoring of WQ parameters in the LAR. Provision of a dense dataset of WQ parameters existing in concrete and natural riverbed zones fills a critical knowledge gap regarding the poorly studied effects of the artificial substrate. Examples of natural riverbed sections in the LAR with engineered banks harboring reduced turbidity, while providing adequate flood protection for decades, supports the argument that expanded restoration is both environmentally advantageous and safe for surrounding communities.

Chapter 1 Introduction

The goal of this project was to use remote sensing (RS) based techniques to determine fluctuations in water quality (WQ) as water travels through the highly modified Los Angeles River (LAR). A large proportion of the 51-mile long LAR is lined with concrete, providing flood protection for surrounding communities; however, some areas still contain natural riverbed sections supporting limited habitat. Currently the LAR is in the process of being restored to a more naturalized state possessing natural riverbed with engineered levees along an 11-mile stretch. Since approximately 20% of the river is slated for restoration, and much of the river is existing outside of the scope of the restoration effort, there is a need for better understanding of the benefits of restoration and consequences of the river remaining in an artificial state.

This study examined fluxes in WQ parameters where water flows from fully concrete lined sections of the LAR into natural riverbed sections. Two RS indices were chosen to carry out analysis on two specific WQ parameters: the Normalized Difference Turbidity Index (NDTI) to measure turbidity and Normalized Difference Vegetation Index (NDVI) to measure chlorophyll-a, respectively. Turbidity provides a physical WQ characteristic while chlorophyll-a provides a biological WQ characteristic. NDTI and NVDI were calculated using National Agriculture Imagery Program (NAIP) aerial imagery and the results were processed herein.

Research questions in this study focus on analyzing spectral characteristics of remotely sensed NAIP aerial imagery over each study frame in the LAR. Study frames were chosen with a focus on areas where concrete riverbed and natural riverbed sections interface. Readily available NAIP aerial imagery contains adequate spectral and spatial resolution to perform NDTI and NDVI functions and produce information on WQ. The NAIP imagery used in this study had a spatial resolution of 0.6m and 4 spectral bands: visible red, blue, green, and near infrared.

Previous investigations by the author revealed fully concrete-lined sections of the LAR had higher levels of turbidity than natural riverbed sections, with concrete sections also containing considerable variation in spectral distribution among different sample areas. These results support the assumption that water quality is relatively better in natural riverbed sections while the diversity of spectral radiances in concrete sections calls for further research and indicates the resilient behavior of the system. Substantial restoration of the LAR channel stands to increase environmental services and opportunities for recreation, while providing improved environmental conditions and positive outcomes for the Los Angeles region.

1.1. Study Area

This study is focused on the LAR which is situated entirely within Los Angeles County in California within a highly urbanized environment. The LAR as it currently exists is comprised primarily of engineered concrete flood control channel with a few exceptions where natural riverbeds persist. The modern-day LAR begins in the San Fernando Valley at the confluence of Bell Creek and Arroyo Calabasas (U.S. Corps of Army Engineers 2015). From its headwaters in the San Fernando Valley the LAR follows an easterly course along the north side of the Santa Monica Mountains until reaching their easterly edge where the river bears south at an area called the Glendale Narrows (Gumprecht 2001). The Glendale Narrows is formed by a gap between the Santa Monica Mountains and the Verdugo Mountains. Once the LAR exits the Glendale Narrows it flows into a vast coastal plain to the Pacific Ocean. The full course of the LAR is approximately 51 miles long. The full extent of the LAR and watershed boundary can be seen in Figure 1 for reference.

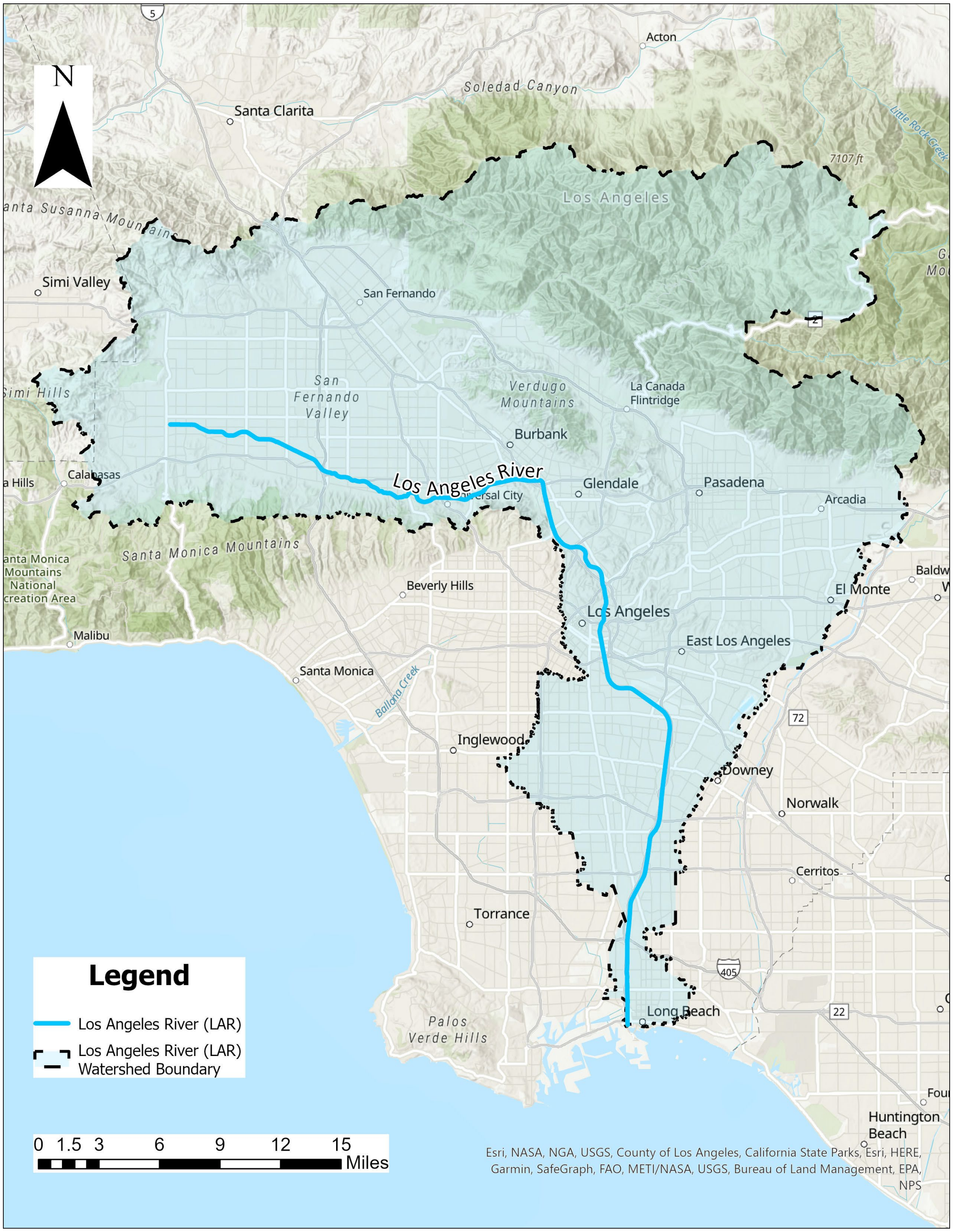

Figure 1. Los Angeles River extent and watershed

1.2. Background and Motivation

The reason the present-day LAR is functionally a flood control channel is due to a combination of rapid urban development and local geology. The eastern portion of the San Fernando Valley and the coastal plain that the LAR flows through is comprised of porous decomposed minerals with origins in the surrounding mountain ranges (Gumprecht 2001). Historically the LAR changed course often and unpredictably through the coastal plain as the river would reduce down to a trickle in dry months and become a raging torrent during the wet season. Extremely variable in nature, the LAR is prone to flooding during the rainy season from the months of October to March and capable of moving around 14 times the volume of the flow of the Hudson River in New York (U.S. Army Corps of Engineers Los Angeles District 2015).

As more people settled into Los Angeles the region shifted from an agricultural landscape to an urbanized cityscape. As development encroached into the broad floodplain of the LAR in the 19th and 20th centuries, storms produced massive flows that caused loss of life and millions of dollars in property damage (U.S. Army Corps of Engineers Los Angeles District 2015). The culminating event that spurred the mass construction project that produced the channelized version of the LAR today was the Flood of March 1938. The peak flow of the LAR during the 1938 flood was greater than the average flow of the Mississippi River at St. Louis and the flood water led to 45 deaths and $17 million dollars in damages (Gumprecht 2001). The first flood control projects began shortly after 1938 flood and continued until 1970 (Gumprecht 2001). The character of the river has changed dramatically with 94 percent of the LAR having concrete banks and three quarters of the river's course being fully concreted (Gumprecht 2001). Concrete and natural riverbed reaches of the LAR are shown with locations of sample frames used in this study in Figure 2.

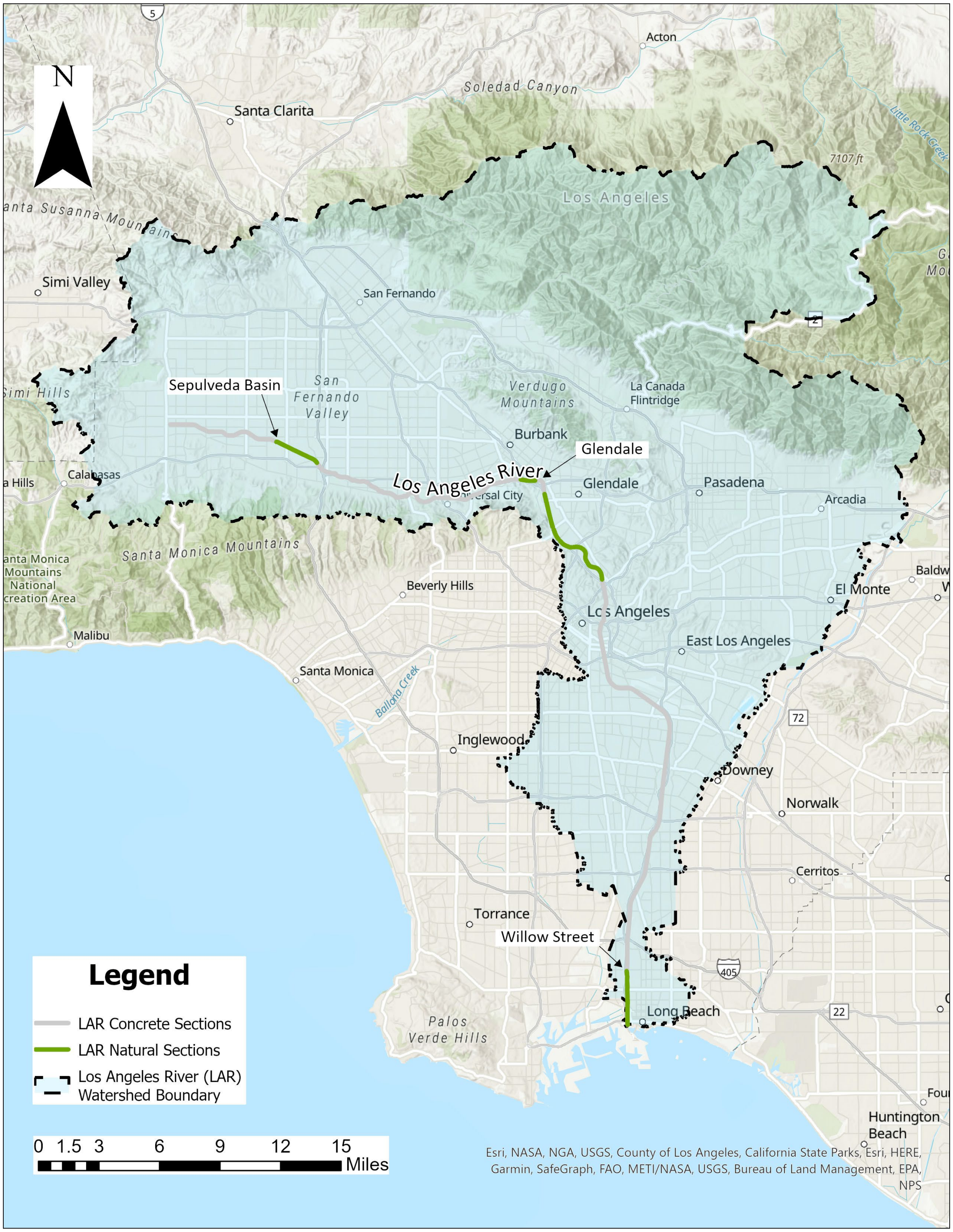

Figure 2. Concrete and natural reaches of LAR

A feasibility report completed in 2015 compressed the original 32-mile long study area into plans for an 11.5-mile long restoration effort (U.S. Army Corps of Engineers Los Angeles

District 2015). Being that the LAR is approximately 51 miles in length, a substantial portion of river corridor is not covered by the USACE-led restoration effort. The USACE work to be conducted is substantial; however, the example set by the partial restoration can serve as a proof that further naturalization of the LAR is feasible. The City and County of Los Angeles can observe the USACE restoration and consider expanding restoration to other portions of the river channel in years to come. Proposed work over the 11.5 mile stretch in the study may return that portion of river to relative normalcy although the remainder of the river will remain in a fully channelized state. Moreover, communities downstream of the USACE restoration area will not reap the same environmental benefits of restoration as their neighbors upstream. Large-scale restoration of the LAR can revive the river system to a more natural ecological state while improving the quality of life for people living in adjacent communities.

Past studies on the LAR and other urban watersheds in the vicinity of the study area focused mainly on pollutants in the corridor (Ackerman 2003; Ackerman and Schiff 2003; Stein and Tiefenthaler 2005; Stein and Ackerman 2007; Stein and Yoon 2007; Boroon and Coo 2015). Alternatively, reports conducted by Los Angeles County focus on civil engineering perspectives and leave out assessments of the benefits from semi-natural sections of the river. Environmental consequences due to full channelization are accepted as the price of flood protection. Ultimately, there is not much known about the effects of the LAR’s channel substrate on the hydrochemistry of the water that flows though it (Boroon and Coo 2015). Moreover, previous studies fail to evaluate the environmental benefits and costs of both the semi-natural and fully channelized states of river sections. Observation of water quality can serve as a litmus test linking the environmental effects imposed by a concrete riverbed versus a natural riverbed. A focused chain of analysis using remotely sensed data in the LAR can provide data rich insights. Using ArcGIS

Pro to identify and analyze the spectral radiance of the environment at specific dates can provide temporal snapshots of water quality in the LAR through time.

1.3. Augmentation of Data through Remote Sensing

Since imagery sources for this project encompass the natural riverbed and concrete riverbed sections in the same temporal frame, comparison of the two environments is direct. These analyses are sufficient to augment previous studies and provide a more complete understanding of the river system at present. A remote sensing-based approach to analysis of the LAR can capture the spectral characteristics of the river channel prior to, during, and after restoration efforts have concluded. The temporal resolution of the aerial imagery provides for monitoring and investigation of the LAR unlike other temporally sporadic methods of investigation which require field work.

For the LAR downstream of the spatial limits of the USACE study and restoration area, a Draft Program Environmental Impact Report (LAPIER) was prepared by ICF International Inc. for Los Angeles County Public Works. This report concluded that a restoration alternative of implementing a natural riverbed while maintaining the current engineered channel configuration would increase flood risk and not improve water quality and therefore was eliminated from project plans (ICF International Inc. 2021). This assertion appears to contradict the USACE-conducted study upstream which is used sections of semi-natural LAR in Glendale as an example for future restoration efforts. Portions of the Glendale reaches of the river are composed of a natural riverbed within an engineered channel in which natural hydrologic processes persist and flooding events are controlled. The USACE expects similarly designed future restoration areas to have the same behavior (U.S. Army Corps of Engineers Los Angeles District 2015). An example of this area can be seen in Figure 3.

Figure 3. Section of natural bottom riverbed adjacent to the Glendale Narrows Riverwalk. Author January 2022.

The Glendale Narrows is a working example of a hybrid natural/engineered river channel providing adequate flood protection while maintaining a functioning riparian habitat (U.S. Army Corps of Engineers Los Angeles District 2015 ES-4). A remote sensing-based approach to observe this area and several other study sites along the LAR can provide evidence to test the conclusion found in the LAPIER report from 2021 regarding any naturalized channel restoration efforts being unfeasible. Specifically, a remote sensing-based methodology which focuses on comparing water quality in natural and concrete riverbed reaches of the LAR can illustrate the benefits of environment services provided in the semi-natural stretches of the river.

Utilizing remote sensing technology to determine water quality in the LAR serves significant purposes closely linked with restoration efforts. Critically, as stated previously, Los

Angeles County Public Works has arrived at the conclusion that restoration alternatives which include naturalizing the riverbed while maintaining engineered levees do not improve water quality. Remote sensing derived water quality data can provide evidence that natural riverbed portions of the LAR contain better water quality than concrete lined sections. The observation of better water quality in natural riverbed sections coupled with the USACE assertion that natural riverbed-engineered levee sections are flood safe can serve as support for policy makers to encourage a pro-restoration position on the LAR.

Furthermore, as restoration efforts are conducted observation of water quality can be monitored at all stages of construction. USACE anticipates increased turbidity during restoration therefore remote sensing based observation could provide an oversight function during the construction process. Additionally, beyond the link to restoration efforts, the LAR is heavily affected by effluent discharges (U.S. Army Corps of Engineers Los Angeles District 2015, 3-24). The remote sensing workflow developed within this study can also be focused on areas where effluent enters the LAR to provide monitoring of potential pollutant loads affecting water quality. The dense datasets that imagery provides can serve myriad use cases. Lastly, the image-based analysis of water quality in the LAR serves to bolster the scientific literature related to remotely sensed water quality observation in urban environments.

1.4. Thesis Structure

The remainder of thesis consists of four chapters. In Chapter 2 focuses on related works investigation and provides information on the behavior of electromagnetic radiation in relation to hydrospheric science, characteristics of remote sensing-based hydrologic observations and the corresponding validity, as well as information on current local restoration efforts on the LAR. Chapter 3 describes research questions, the data, the sample sites, and the research design.

Chapter 4 summarizes the results of the study for all of the sample sites. Lastly, Chapter 5 discusses the utility and limitations of the current work and suggests future work.

Chapter 2 Related Work

This includes sections providing a foundation for a remote sensing-based proof of concept for investigating water quality in the LAR. The first section provides background information on the behavior of electromagnetic radiation and the integral aspects of hydrospheric science in relation to the study. The second section provides a basis for exploring the hypothesis that water quality is better in natural riverbed sections compared to fully concrete riverbed sections. This section also provides background on remote sensing-based techniques for measuring chlorophyll-a and turbidity levels in water bodies. Lastly, the third section focuses on municipal reports outlining planned and potential restoration efforts in the LAR corridor.

2.1. Electromagnetic Radiation and Hydrospheric Science

Owing to the nuanced nature of applying remote sensing techniques to extract information from water bodies, it is appropriate to provide some background related to the methodology used in this study. Remote sensing-based observation of hydrologic features fundamentally differs from observation of the Earth’s surface. In observing land remotely, the electromagnetic radiation received at the sensor is the product of reflection from the surface. Alternatively, in water body observations the majority of the electromagnetic radiation that reaches the sensor is produced from volume reflection which is a composite of the spectral properties of the full water column (Campbell 2011). As illustrated in Figure 4, additional sources of electromagnetic radiation that reach the sensor include atmospheric scattering, surface reflection and bottom reflection (Campbell 2011). These additional sources can distort the true spectral profile of the observed water column and its constituents (Yu et al. 2020).

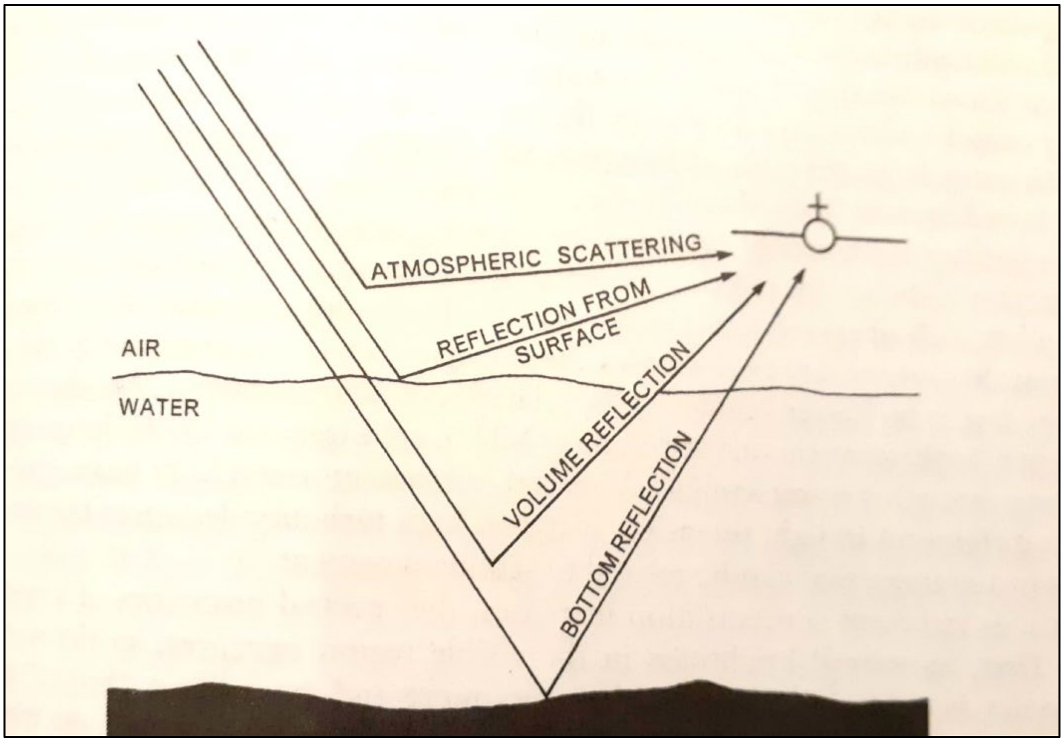

Figure 4. Electromagnetic radiation behavior in water bodies and atmosphere (Campbell 2011, 551 as modified from Alföldi 1982, 318)

A common phenomenon that alters the spectral profile of light entering a remote sensor is atmospheric scattering. Atmospheric scattering can be defined as disruption of the original path of electromagnetic radiation by the contents of the atmosphere, with this effect being exacerbated by the distance traveled through the atmosphere (Campbell 2011). For remote sensors fixed to aircraft and Unmanned Aerial Vehicles (UAVs), atmospheric effects are not as significant as with satellite mounted sensors which may contend with light traveling through the full width of Earth's atmosphere (Campbell 2011). The metadata accompanying the 2020 NAIP imagery applied in this study indicates that atmospheric effects were rectified by Leica XPro software prior to being made available to the public for download (U.S. Geologic Survey 2021).

A key challenge to account for in remote sensing of water is surface reflection. Surface reflection, also known as sun glint, is caused by water body surfaces being uneven and sun light not entering the water medium but changing direction back into the atmosphere (McKim et al. 1984). Surface reflected electromagnetic energy collected by remote sensors skews data since the spectral strength is higher than volume reflected light (McKim et al. 1984). Effective solutions for removing sun glint from imagery have been developed. Notably, a study published in 2005 by Hedley provides an elegant regression equation based on manual pixel sampling and using visible and NIR wavelengths to eliminate glint successfully.

Water depth in the LAR is relatively shallow in the concrete sections with the submerged riverbed being visible in the NAIP aerial imagery making bottom reflectance a factor that must be considered. Bottom reflectance is electromagnetic radiation reflected off the terrestrial bottom of a water body and contributes to distortion of the observed spectral character of the water column (Tolk, Han and Rundquist 2000; Katlane et al. 2020; Yu et al. 2020). It is possible the bottom reflectance from the concrete riverbed sections is spectrally significant in shallow water. To accurately measure chlorophyll-a and turbidity levels in the water column, imagery containing the deepest possible water in each sample frame was selected to mitigate spectral distortion from bottom reflectance prior to NDVI and NDTI function deployment.

2.2. Remote Sensing Based Hydrologic Observation

Anthropogenic caused upward nutrient fluxes impacting water systems can lead to negative consequences on environments (Carpenter et al. 1998). It has been documented in the past that the LAR has elevated nutrient (nitrogen) levels beyond the acceptable threshold as determined by the Clean Water Act and that these nutrient loads can lead to algal growth (U.S. Army Corps of Engineers Los Angeles District 2015). Algal blooms have the effect of removing oxygen from the water body they occupy as they decompose, effectively producing an environment in which many organisms cannot survive (Chislock et al. 2013). Algal growth in the

LAR beyond a typical baseline have the potential to cause harm to water quality and the ecosystem as a whole.

Living plant matter contains pigments integral in the process of photosynthesis, with the most common being chlorophyll-a (Campbell 2011). The specific spectral character of chlorophyll-a provides a linkage for the detection of algae in water bodies (Richardson 1996). Previous studies have successfully detected chlorophyll-a concentrations in aquatic environments (Avdan et al. 2019; Kuhn et al. 2019). Vegetation indices such as NDVI are designed to identify vegetation in digital imagery data by exploiting inherent spectral properties in plant tissue using ratios of light wavelengths to produce a relative intensity value (Campbell 2011). NDVI is attractive for use in this study since it requires visible red and near infrared wavelengths which are included in available NAIP imagery. NDVI specifically has been shown to be effective in measuring chlorophyll-a in streams when utilized with high spatial resolution imagery containing visible blue, green, red, and near infrared bands (Kim et al. 2021).

Turbidity can be summarized as the level of sediment immersed in a body of water (Campbell 2011). Measurement of turbidity has direct significance to the USACE restoration of the LAR since construction activities will cause elevated sediment concentration in the river during restoration efforts and afterwards as the water channel returns to normal suspended sediment levels (U.S. Army Corps of Engineers Los Angeles District 2015

). Remotely sensed detection of turbidity has potential advantages of efficiency and low-cost over analysis of field collected water samples (McKim et al. 1984).

It was hypothesized that natural riverbed portions of the LAR possess the behavior of having lower turbidity levels than concrete-lined portions of the river. On a macroscopic scale, it has been observed that natural watershed catchments contain lower levels of WQ parameters such as nitrates and total suspended solids than developed watershed catchments (Stein and Yoon 2007). By extension, on a smaller scale, it can be surmised that natural riverbed sections contain better water quality than artificial sections. Natural riverbed sections contain riparian vegetation whereas concrete reaches of the LAR are barren. Vegetation has the behavior of reducing turbidity in waterbodies (Austin et al. 2017; U.S. Army Corps of Engineers Los Angeles District 2015). In addition, higher velocity water allows for higher turbidity thresholds and concrete lined sections of the LAR are designed to convey water through the channel as efficiently as possible. Natural riverbed portions of the LAR contain heterogenous fluvial morphology that has an effect of reducing flow velocity and by extension the turbidity threshold.

Lacaux et al. (2007) produced the Normalized Difference Turbidity Index (NDTI) for measuring turbidity in ponds in West Africa. The NDTI requires the visible green and red spectral bands to function and the available NAIP imagery includes these bands. This index was applied in a study published by Chen et al. (2022) to measure the effects of the Covid-19 lockdowns on water quality in the Haihe River Basin in China, effectively documenting significant drops in turbidity after the Covid-19 outbreak. The spatial resolution of the imagery used in many remote sensing based-water quality studies is sourced from satellites and is coarse when compared to the resolution available from aerial sensors. The studies by Lacaux et al. (2007) and Chen et al. (2022) relied on imagery with a maximum spatial resolution of 10m which is relatively coarse in comparison to the 0.6m resolution utilized in this study. The NAIP imagery available in the study areas allows for analysis of water quality phenomena at a fine spatial resolution.

2.3. Validity of Remote Sensing Derived Measurements

Another consideration is the strength of correlation between remote sensing-based measurements with measurements derived from field collected samples. Numerous studies have explored the efficacy of remote sensing as a means to determine various water quality parameters. Within the literature, strong correlations have been demonstrated between remote sensing-based measurements and measurements derived from in-situ water samples of turbidity and chlorophyll-a concentration. Bid and Siddique (2019) derived NDTI values from LANDSAT 5 and 8 satellite images then validated them against laboratory tested water samples and yielded an average correlation coefficient value (R^2) of 0.90. Kim et al. (2021) achieved a strong correlation between NDVI and chlorophyll-a of $R^2 = 0.88$ using an UAV to collect imagery and unmanned surface vehicle (USV) equipped with a fluorometer to collect water samples. Studies specific to validating remote sensing derived NDTI and NDVI values with in-situ water samples tested for actual turbidity and chlorophyll-a are listed in Table 1. Water quality assessment by remote means has been established as a reliable technique in lieu of in-situ water quality measurements. For the scope of studying how the concrete lined and natural riverbed sections of the LAR may impact water quality in distinct aspects, the remote sensing indices NDTI and NDVI are suitable. Additionally, imagery offer the advantage of capturing the spectral reflectance of a relatively large spatial area at one simultaneous moment in time whereas in-situ samples are collected as data points. Any portion of an image can be analyzed. Alternatively, each in-situ data point is confined to a minute extent.

Table 1 Correlation strength of RS indices and in-situ samples

Study	RS Index	RS Data	In-Situ Data	R^2
Kaplan et al. 2020	NDTI	RapidEye-3 satellite images (5m spatial resolution)	Water samples laboratory tested for actual turbidity level	0.82
Elhag et al. 2019	NDTI	Sentinel-2 satellite images (10m spatial resolution)	Water samples laboratory tested for actual turbidity level	0.94
Bid and Siddique 2019	NDTI	LANDSAT 5 and 8 satellite images (30m spatial resolution)	Water samples laboratory tested for actual turbidity level	0.90
Rodríguez-López et al. 2020	NDVI	LANDSAT 5, 7 and 8 satellite images (30m spatial resolution)	Water samples laboratory tested for chlorophyll-a using fluorometric technique	0.78
Kim et al. 2021	NDVI	Parrot Sequoia UAV images (11cm spatial resolution at 120m flight altitude) Pix4D. 2022.	Water samples collected by an unmanned surface vehicle and tested for chlorophyll-a using an on board fluorometer	0.88

2.4. Municipal and Federal Reports Focusing on the Los Angeles River

The Los Angeles County Public Works Draft Program Environmental Impact Report contains the most recent released Environmental Impact Report and is critical to planning and development of the LAR corridor within Los Angeles County (LAC) for the next 25 years (ICF International Inc. 2021). This expansive text will serve as a foundational reference related to municipal planning of the LAR in LAC. The 2015 USACE produced report (Feasibility Report) centers on an approximately 11-mile stretch of the LAR and serves as the guiding document for restoration efforts over that study area. This report has a wealth of information related to flood control, local ecology, and the history of the LAR. Each of the reports conducted for local municipalities offer a window into the future of policy making revolving around the LAR.

A remote sensing-based focus on water quality in the LAR corridor has the potential to fill knowledge gaps that are either under studied or not studied at all. In addition, a richer knowledge of the implications of natural riverbed versus concrete riverbed sections on WQ may encourage LAC to revise its position that a natural channel will not improve water quality (ICF International Inc. 2021). The conclusions reached in the reports produced by the City of Los Angeles (working with USACE) and Los Angeles County are fundamentally different and possibly contradictory. Whereas the USACE report has elected to go forward with restoration efforts of the LAR that include unearthing natural riverbed while maintaining engineered levees, the Los Angeles County draft report has decided that such alternatives do not meet their criteria. Remote sensing focused on the true spectral character of the LAR has the potential to illuminate the water quality dynamics along one of the most infamous stretches of river in the United States.

Chapter 3 Methods

The following research questions inform the subsequent research within the LAR. What is the extent of the differences in chlorophyll-a and turbidity concentrations when comparing natural riverbed sections with concrete riverbed sections of the Los Angeles River? What negative consequences on WQ, if any, can be attributed to sections of concrete river channel? What benefits on WQ, if any, can be observed in natural riverbed sections? Two indices will be used to determine different aspects of WQ. NDVI will provide reflectance values corresponding to chlorophyll-a mostly associated with algae within the LAR channel. NDTI will provide turbidity levels in the LAR. Each index delivers information correlated with WQ metrics that will provide a deeper understanding of the environmental effect of river channelization.

The results of the image data processed through RS indices in this study serve to preserve a window into baseline environmental behavior prior to river restoration. Availability of water quality metrics available at adjustable locations along the full length of the LAR during specific temporal windows offer benchmarks for post-restoration LAR water quality to be compared against. In addition, with the availability of relatively low cost of UAVs the workflow presented within this experiment can easily be adapted for concurrent and post-restoration observation of aquatic environmental metrics. Furthermore, using the same methodology, effluent discharge zones along the LAR can be readily monitored aerially.

3.1. Data Description

In order to carry out precise remote sensing-based water quality analysis in the LAR, there are some specific resolution requirements. High spatial resolution is crucial since parts of the river channel contract to relatively narrow widths. For example, in the Glendale concrete sample area the width of channel containing flowing water is roughly 3.7m wide. The raster imagery needs a spatial resolution capable of resolving the highly variable water surface extents within the LAR. Within the vicinity of the LAR, NAIP aerial imagery is available from 2005 at a lower resolution and available roughly biennially with some larger gaps in availability. Starting in 2016 imagery was made available at a 0.6 meter spatial resolution.

Each of the indices employed in the methodology, NDVI and NDTI, need differing combinations of electromagnetic wavelengths to function. NDVI measures relative vegetative vigor and requires visible red and near infrared spectral bands. NDTI is used to measure turbidity in water and requires visible red and visible green spectral bands. NAIP imagery is adequate for the purposes of the study as it consists of the following four spectral band: visible red 619-651nm, visible green 525-585 nm, visible blue 435-495 nm and near infrared 808-882 nm. Table 2 lists the resolution information for NAIP aerial imagery.

Table 2 Required data.

Required Data	**Spatial Resolution**	**Spectral Resolution**	**Temporal Resolution**	**Data Availability**
NAIP aerial imagery	*0.6 meter	*Four spectral bands: visible red 619-651 nm visible green 525-585 nm visible blue 435-495 nm near infrared 808-882 nm	Imagery dataset available annually to biennially. *Image tiles captured 2018 and 2020.	Freely available for download from USGS Earth Explorer. Coverage is available over full extent of the LAR.

*Data resolutions are reported in metadata file of NAIP imagery download (U.S. Geologic Survey Earth Explorer 2021)

The spatial scope of NAIP imagery covers the full extent of the approximately 51-mile long LAR allowing for manually extracted samples to be taken anywhere along the channel. The image tiles used in the study were collected in the spring summer months of 2018 and 2020.

Fortunately, NAIP image tiles are available at no cost to the public. Image collection dates for each sample frame in each year are recorded in Table 3.

Table 3 Image acquisition dates

Sample Frame	**Date**
Sepulveda Basin 2018	July 22, 2018
Sepulveda Basin 2020	April 25, 2020
Glendale 2018	July 23, 2018
Glendale 2020	May 05, 2020
Willow Street 2018	July 23, 2018
Willow Street 2020	May 05, 2020

3.2. Sample Sites

The central component under review within this study is identifying variations in water quality between concrete and natural riverbed sections within the LAR system. Areas where these two differing environments transition are a key requirement in sample site selection. The sole examples of where concrete to natural riverbed transitions currently occur in the LAR are the Sepulveda Basin, Glendale, and at West Willow Street in Long Beach. Each of these locations was selected as sample locations and each location holds unique characteristics that set them apart from each other.

Within each sample site, equally sized polygons were chosen from natural and concrete-lined sections for study. These polygons were chosen visually to ensure an unobscured water surface for study. Another method for extracting the water surface in an image relies of Equation 1:

Normalized Difference Water Index (NDWI) which is the result of the equation:

$$\text{NDWI} = (\text{Visible Green} - \text{Near Infrared}) / (\text{Visible Green} + \text{Near Infrared}) \quad (1)$$

Theoretically, placing NDWI into the methodology would be advantageous over manually creating polygons to extract areas of interest. However, shadows prevented accurate results with an NDWI analysis, so this method was deemed insufficient.

3.2.1. Sepulveda Basin

The Sepulveda Basin sample frame lies within the San Fernando Valley in a flood control basin enclosed by the Sepulveda Dam which was completed in 1941 by the USACE in response to the extensive flooding in the Los Angeles region in 1938 (U.S. Army Corps of Engineers Los Angeles District 2011). Being one of the last remaining natural corridors along the LAR, there is a continuous stretch of natural riverbed through the basin of approximately 2.3 miles. This semi-natural stretch of the LAR contains several confluences with other surface water sources that have downstream proximity to sample sites. Approximate measurements taken in ArcGIS Pro beginning from the concrete to natural riverbed transition marking the beginning of the Sepulveda Basin indicate Bull Creek enters the river 4145 ft downstream, treated discharge originating from the Donald C. Tillman Water Reclamation Plant (DTCWRP) enters 5180 ft downstream, and Woodley Creek enters the channel 8875 ft downstream.

In the Sepulveda Basin sample area, a shallow trapezoidal concrete channel approximately 14 feet wide containing water transitions into a natural riverbed containing relatively deep slow moving water surrounded at its banks with thick vegetation. All sample sites occur upstream of any major surface water confluences in the Sepulveda Basin; however, the final natural sample site (SN4) lies 600 ft upstream of Bull Creek within a stretch of water bounded by dam-like structures. Relative locations of all concrete and natural sample sites are listed in Table 4. and Figure 5 specifies the complete Sepulveda Basin sample frame.

Table 4 Sepulveda Basin Sample Distribution

Sample Polygon and Key Features	**Distance (ft)**
SC1	0
SC2	84
SC3	166
SC4	250
Concrete to Natural Riverbed Transition	615
SN1	1330
SN2	1703
SN3	3292
SN4	4128

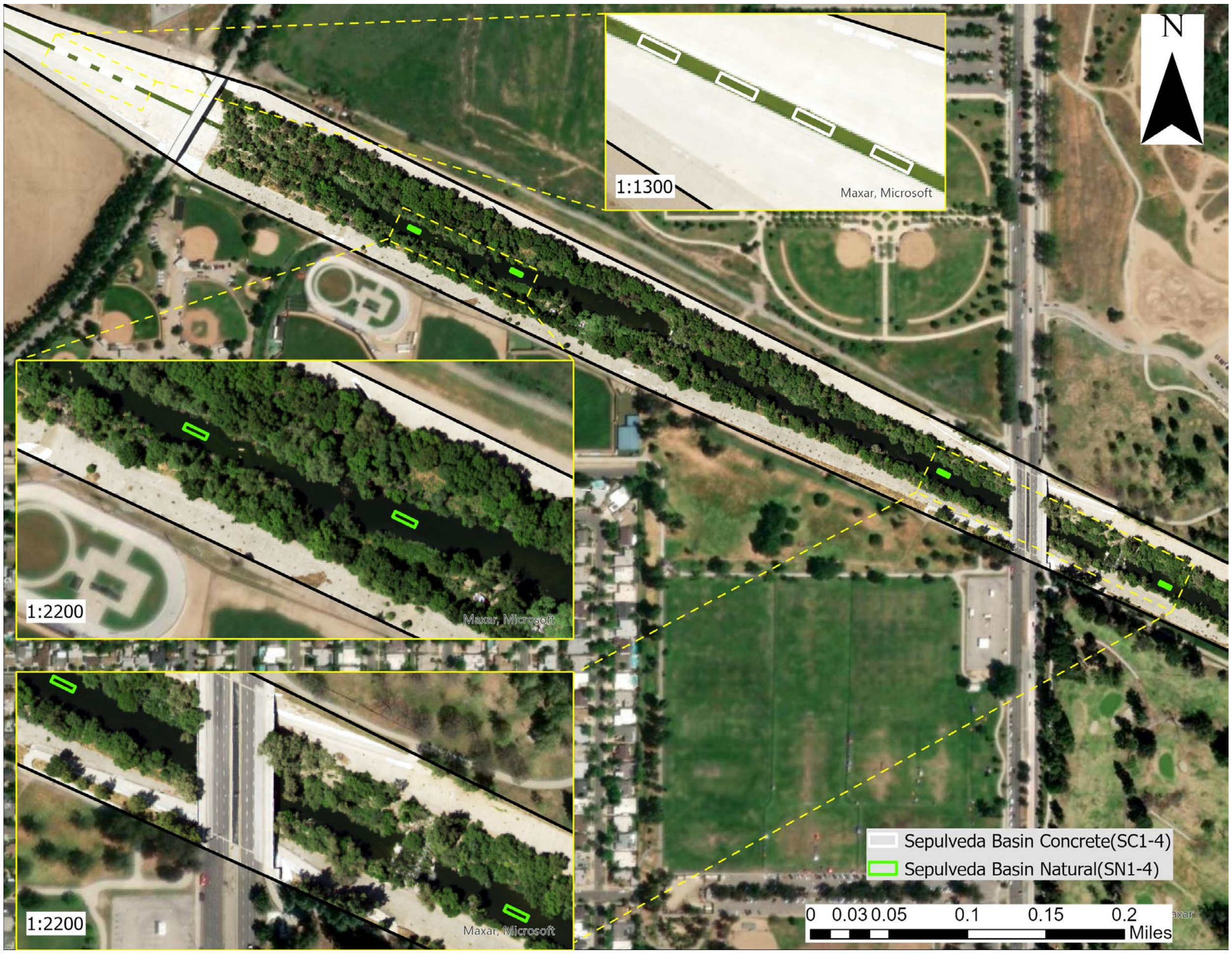

Figure 5. Sepulveda Basin sample frame

3.2.2. Glendale

The Glendale sample frame is located on a stretch of the LAR situated along the boundary of Griffith Park where the cities of Burbank, Glendale and Los Angeles converge. The water table in portions of this zone exist too close to the land surface to allow for paving and accordingly, the current iteration of the LAR here contains stretches of natural riverbed with engineered concrete banks (Gumprecht 1999). The concrete stretches were sampled 2.6 miles upstream from the samples collected in the natural riverbed area within this sample area due to the physical characteristics of the channel in this location. There is an approximately 12 ft wide rectangular concrete channel conveying relatively deep water ideal for RS analysis that abruptly transitions into a roughly 105 ft wide concrete channel with water too shallow to permit capture of genuine spectral characteristics.

The structure of the LAR maintains a wide concrete channel containing shallow water for 1.7 miles before reaching a confluence with another concrete lined waterway, known as the West Burbank Channel, and then travels 550 ft to a concrete to natural riverbed transition. This stretch of natural riverbed bed runs for 1700 ft, changes to a 330 ft concrete strip before another transition to a 1511 ft run of natural riverbed where the natural samples were collected for this sample area. Cobble stones and sediment with trees and vegetation have taken hold in the soft bottom stretches of this zone. Also, another notable factor related to this sample frame is the Burbank Water Reclamation Plant (BWRP), which discharges treated wastewater into the West Burbank Channel before the confluence with the LAR. Specific locations of sample polygons and key features for the Glendale sample area are listed in Table 5 and Figure 6 encapsulates the extent of the sample frame.

Table 5 Glendale Sample Distribution

Sample Polygon and Key Features	**Distance (ft)**
GC1	0
GC2	119
GC3	242
GC4	355
West Burbank Channel Confluence	9792
Concrete to Natural Riverbed Transition	10342
Natural to Concrete Riverbed Transition	12038
Concrete to Natural Riverbed Transition	12368
GN1	13884
GN2	13948
GN3	14003
GN4	14011

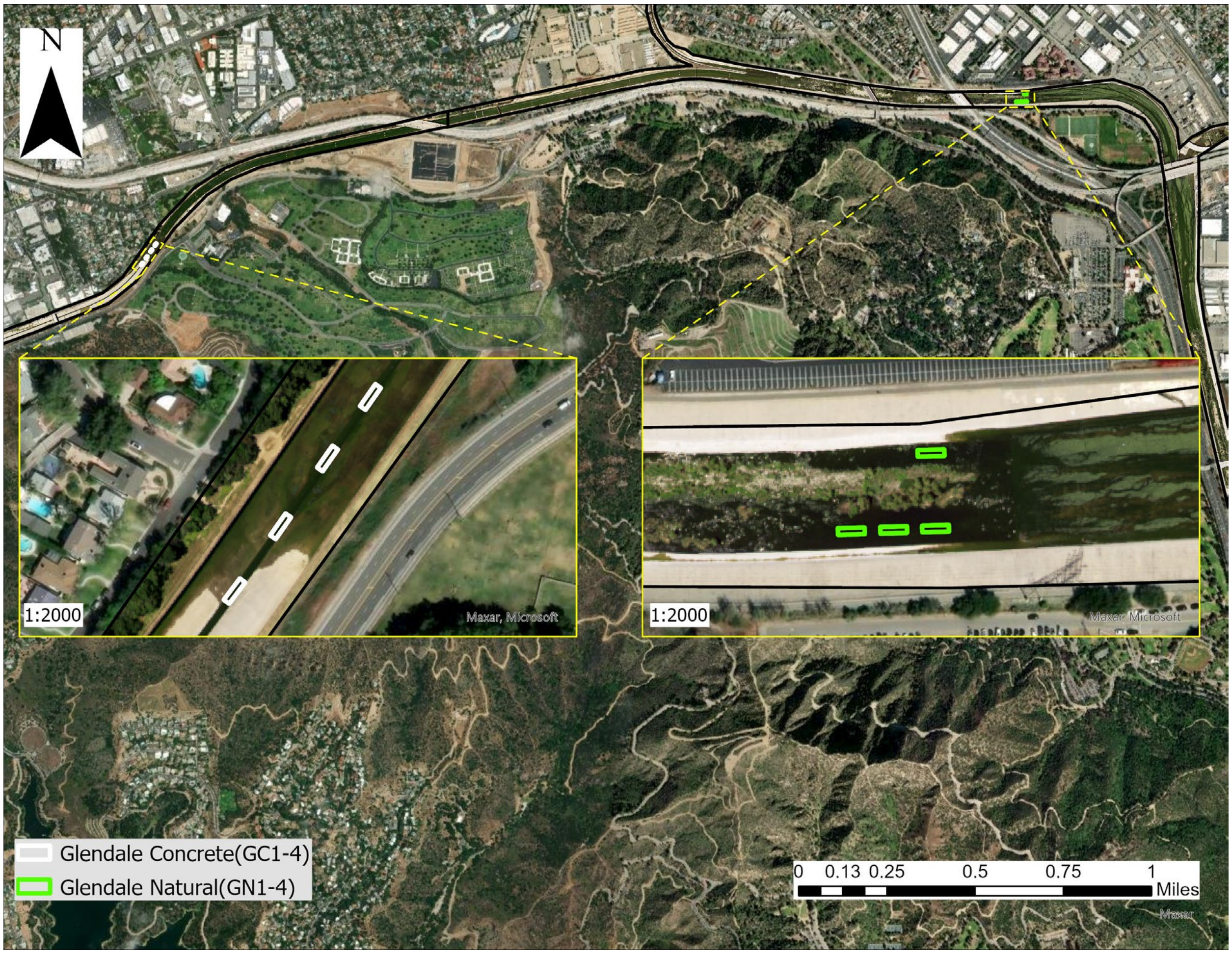

Figure 6. Glendale sample frame

3.2.3. Willow Street

Located in Long Beach the Willow Street sample area occurs near the end of the course of the LAR. Similar to Glendale the water table in this area occurs too close to the ground surface for the bottom of the LAR to be paved. For approximately 2.5 miles the river consists of an earthen bottom before reaching its mouth and exchanging water with the Pacific Ocean (Gumprecht 1999). The river in this zone consists of a wide sediment laden concrete channel with a roughly 25 foot wide rectangular depression situated at its centerline containing relatively deep flowing water. Abruptly after the LAR passes under the Willow Street bridge concrete channel transitions to a natural riverbed area with slow moving water.

In comparison to the other sample frames the natural samples sites at Willow Street occur far closer to their upstream concrete sample counterparts. Natural sample sites were chosen close to the upstream concrete sample sites in this case in an effort to avoid river water subject to tidal mixing. The surface elevation of the LAR drops shortly after the concrete to natural riverbed transition following the Willow Street bridge and becomes continuous with estuarine waters that have a higher likelihood of being brackish. Freshwater in the LAR is the subject of this study thus the natural riverbed sample site placements in this sample frame are chosen using this additional selection criterion to avoid river water mixed with ocean water. Sample site locations are indicated per Table 6, and Figure 7 details the complete Willow Street sample frame.

Table 6 Willow Street sample distribution

Sample Polygon and Key Features	**Distance (ft)**
WC1	0
WC2	59
WC3	117
WC4	172
Concrete to Natural Riverbed Transition	686
WN1	746
WN2	789
WN3	810
WN4	861

Figure 7. Willow Street sample frame

3.3. Research Design

The image analysis workflow begins with acquisition of image tiles covering the sample sites. The full workflow is summarized in Figure 8. Raster images are generally relatively large files and NAIP tiles are quite expansive measuring approximately 6.27 km x 7.4 km, thus it is necessary to remove the portions of image that are outside of the river channel to improve processing speed in ArcGIS Pro. To make the image tiles containing the study areas of interest more manageable a raster clip function was performed. The significance of isolating the river channel from the remainder of the image tile was also central to the WQ analysis conducted as part of this research project. The aim was to isolate spectrally consistent portions of water surface that represent the spectral character of the water column.

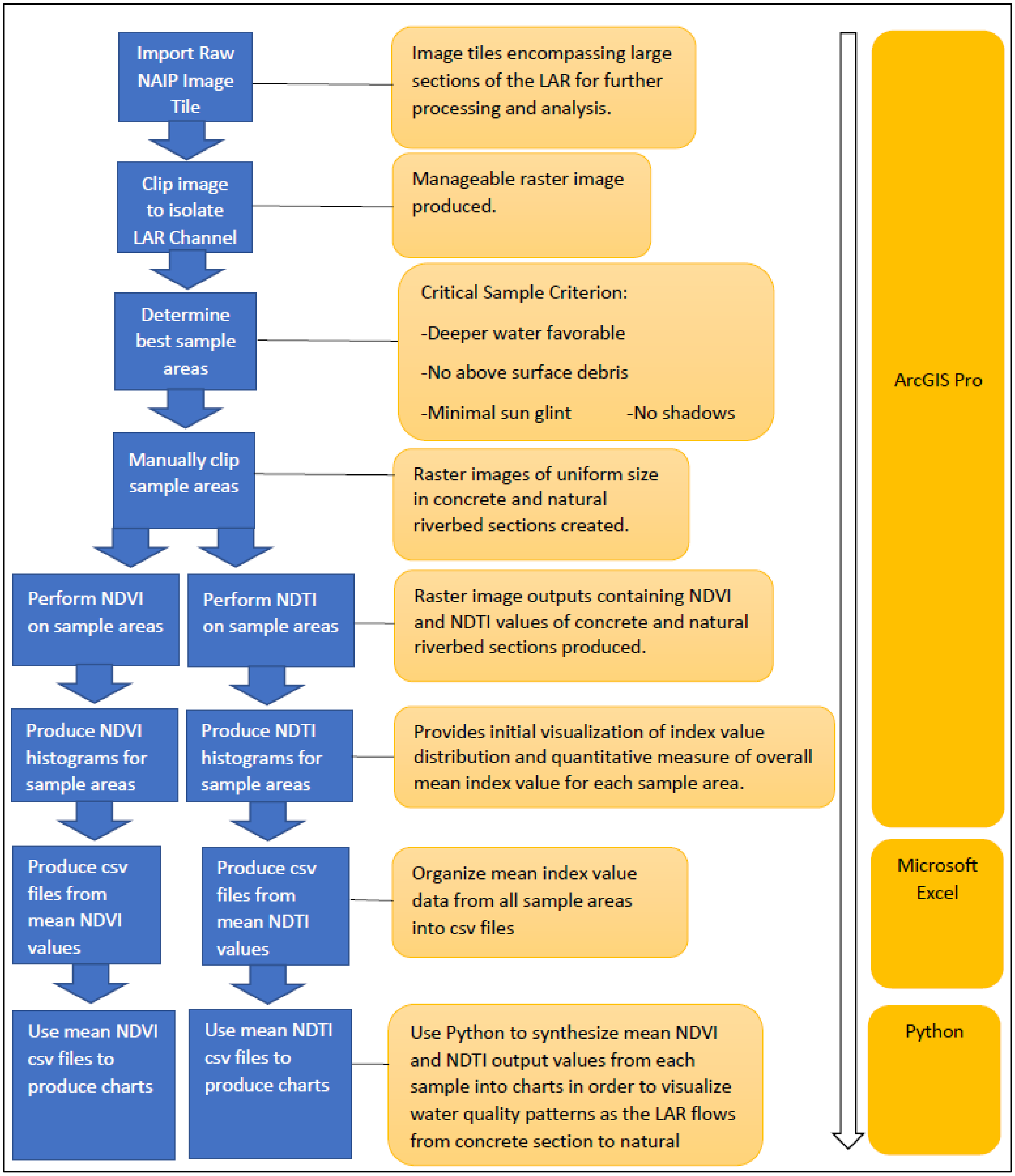

Figure 8. Image analysis workflow

The clip function isolating the LAR channel is conducted by manually creating a polygon feature that closely outlines the outer edge of the engineered banks of the river. This polygon is then used to clip the preferred section of the raster image for further processing. Moving forward in the chain of analysis, the best sample areas are determined in concrete riverbed and natural riverbed sections using visual image interpretation. Criteria employed for selecting ideal sample areas included deeper water devoid of surface debris, no shadows and minimal sun glint. All of these factors are in keeping with the goal of collecting genuine volume reflectance of the water column with little or no spectral noise.

In targeting deeper water, the assumption is bottom reflectance will be minimized, as it has been observed in laboratory testing that bottom reflectance is minimal in turbid water at a depth of 80 cm (Tolk, Han and Rundquist 2000). When water surfaces become uneven, they can produce sun glint by reflecting the sun and producing brighter reflectance values than calm water (Campbell 2011). The LAR is structurally dynamic containing areas that cause some relatively significant water surface disturbance. Therefore, manual imagery interpretation will be administered prior to imagery analysis to rule out pixels that are spectral outliers containing sun glint. Acquiring a sample as close to spectral truth as possible from the LAR is crucial in developing a clear understanding of the state of water quality. The surface debris and shadows observable in the LAR also contain spectral characteristics that diverge from the volume reflectance of smooth water.

When areas containing the aforementioned criteria were located, manually created polygons were produced in ArcGIS Pro using the Create Features tool to isolate and clip the raster image samples. Efforts were made to place sample polygons at uniform distances from each other however placement is largely dictated by the availability of samples meeting the criteria determined by manual image interpretation techniques. Each clip polygon measured 10 ft by 40 ft. The reasoning for these specific sample polygon dimensions is threefold. First the 10 ft polygon width is necessary since certain concrete stretches of the LAR containing water condense to a width of approximately 12 ft wide. The second consideration is obtaining an adequate number of pixels in each raster image sample to capture statistically archetypal information which is spectrally consistent with the target samples. Third, in observing phenomenon in a feature such as a river, the phenomena occur over a continuous field; however, it is necessary to organize samples into discrete objects due to finite thresholds in sampling precision (Montello and Sutton 2013). Breaking samples into standardized discrete objects within the study is especially significant owing to the multiple criteria used a viable image raster to calculate the RS indices.

It is suggested to use 10 x n pixels for developing training sites for supervised classification with n representing the number of raster image bands (Green, Congalton, and Tukman 2017). This method has been extrapolated here to set a minimum pixel count for input rasters being processed to produce the RS indices used in this study. The imagery used in the workflow contains four spectral bands and a pixel resolution of 0.6 m thus the clip polygons exceed the minimum pixel counts per the 10 x n pixels benchmark while retrieving spectrally precise samples.

At each sample frame, four image samples are taken in the concrete section and four samples are taken in the natural section downstream of the concrete to natural riverbed interface. After image raster samples have been extracted for each riverbed type in each study area for all image tile years, NDVI and NDTI functions are applied to them using the Band Arithmetic tool in ArcGIS Pro:

NDVI = (Near Infrared - Visible Red) / (Near Infrared + Visible Red) (2)

NDTI = (Visible Red- Visible Green) / (Visible Red + Visible Green) (3)

Raster images clipped with uniform polygons can be seen below in Figure 9.

Figure 9. Glendale sample frame. Left: concrete riverbed sample. Right: natural riverbed sample. NAIP Imagery (U.S. Geologic Survey 2021). Sample area rasters produced in ArcGIS Pro.

Following NDVI and NDTI outputs for each sample area, histograms were produced for initial statistical visualization. Histograms are effective in identifying patterns in NDVI and NDTI value distributions as well as the overall means. Next, mean index values produced by the histograms from each sample site index result were organized into .csv files for further analysis. The .csv files containing mean RS index values are then inputted into Python and charts are created with Matplotlib in order to better visualize the chlorophyll-a and turbidity levels as they pass downstream through the LAR and crucially as water transitions from concrete to natural riverbed environments.

Chapter 4 Results

This chapter documents the NDTI and NDVI results for each sample site in each sample frame within the LAR. The mean index values derived from pixels confined in each image raster clip are represented in charts produced for each sample frame. RS index result charts are produced using Pandas and Matplotlib library commands in a Python environment. For each sample frame location, charts represent results in the direction of flow in the LAR traveling downstream beginning with concrete lined sample sites and then transitioning to natural riverbed sites. As noted in Chapter 2, the distances between each sample site within each sample location was not uniform and placement was dictated by availability of samples meeting various criteria.

4.1. Sepulveda Basin

This section summarizes the results for the Sepulveda Basin sample frame, the NDTI-turbidity results, and finishing with the NDVI-chlorophyll-a results.

4.1.1. NDTI-Turbidity

Within the Sepulveda Basin turbidity was observed to be of lower concentration in natural sample sites as opposed to concrete sample sites for all data points collected. In comparing physical characteristics of the other sample frames in the study, Sepulveda Basin contains the longest stretch of natural riverbed, is heavily vegetated, and contains slow moving water. Vegetation has an attenuating effect on turbidity intensity in waterbodies. Moreover, there are no WRPs upstream of the sample sites at this location that would influence hydrochemistry. The DTCWRP discharges treated water into the LAR downstream of the sample sites and is separated by a rudimentary dam. The features of the Sepulveda Basin make it the most ideal sample frame in this study for comparing turbidity in concrete and natural riverbed stretches.

The final sample site (SN4 in Figure 10) in the natural riverbed section is close to the confluence with Bull Creek. SN4 is isolated on a stretch of the LAR between two dam like structures and Bull Creek discharges into the same stretch. It is possible the creek could influence the NDTI levels near the SN4 sample site. Bull Creek has been observed to exceed water quality objectives for turbidity set by the California Department of Water Quality Control Board in wet and dry seasons (Weston Solutions, Inc. 2005). In the 2020 NDTI results the highest natural riverbed turbidity value was located at the SN4 sample site whereas the 2018 NDTI result at the same site recorded the lowest turbidity which is indicative of the highly dynamic nature of turbidity within a river system.

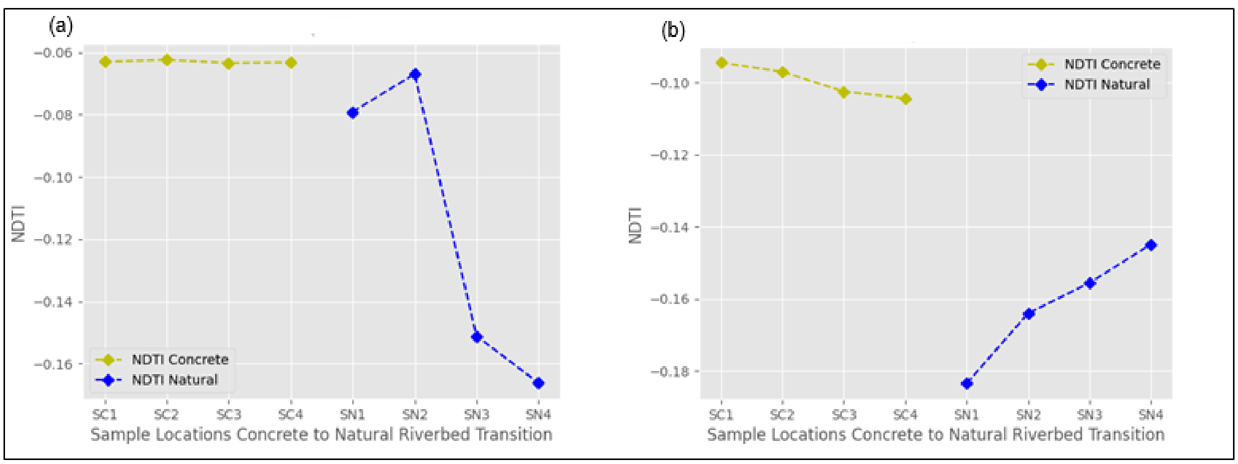

Figure 10 Sepulveda Basin NDTI: (a) 2018 and (b) 2020.

4.1.2. NDVI-Chlorophyll-a

NDVI results in the Sepulveda Basin for the 2018 imagery indicate a rise in chlorophyll-a levels as water travels from the concrete to natural riverbed. In the 2020 imagery, the chlorophyll-a levels decline as water transitioned from concrete to natural riverbed (Figure 11). The 2018 results pointing to increased chlorophyll-a levels in the natural stretch of the LAR in the Sepulveda Basin conflict with the original hypothesis that chlorophyll-a levels should decrease as water flows through the natural riverbed section. Nonetheless, chlorophyll-a levels are a biological indicator driven by environmental inputs such as hydrochemistry and seasonality.

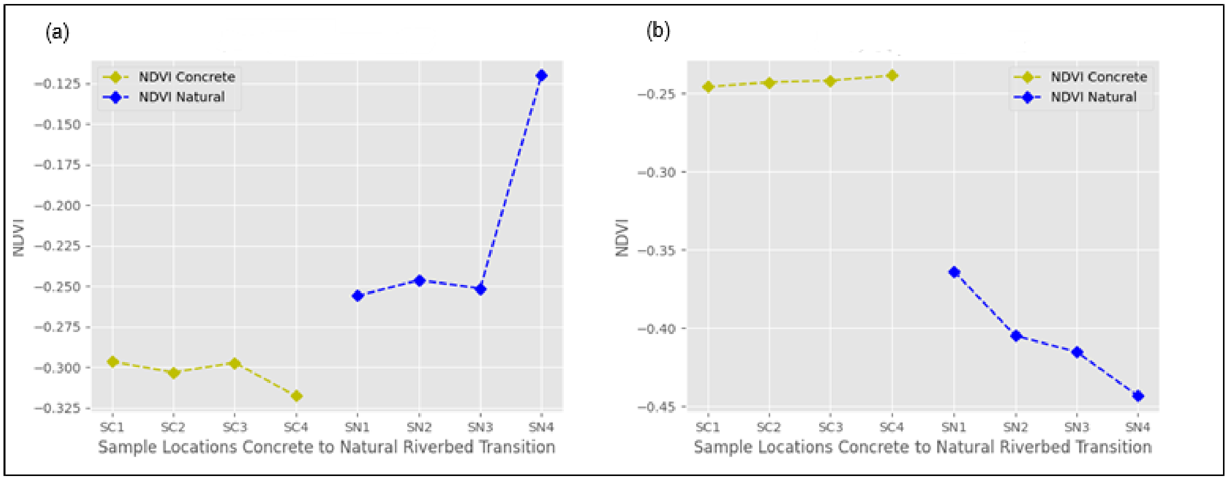

Figure 11 Sepulveda Basin NDVI: (a) 2018 and (b) 2020.

One significant factor when interpreting NDVI results in this study is the relationship between algal growth and nitrate levels in the LAR. Elevated nitrate levels increase algal growth which can lead to eutrophication and poor water quality (Boroon and Coo 2015). It has been observed in the LAR that nitrate levels are highest during the dry periods and mainly originate from runoff in the Sepulveda Basin and runoff from surface streets in highly urbanized areas of Los Angeles (Boroon and Coo 2015). Within the Sepulveda Basin sample frame, the natural riverbed sample sites are surrounded by several sports fields with maintained grass. The concrete sample sites in Sepulveda Basin are upstream of any runoff that would flow from these manicured sports fields thus less nitrate would be expected to enter the concrete section ultimately leading to reduced algal growth and lower chlorophyll-a levels detected by NDVI.

Another factor to consider is the time of year each image tile was collected. The 2018 images for Sepulveda Basin were collected in late July while the 2020 images were collected in late April. A spring season algal spike is not apparent in the Sepulveda Basin sample frame although elevated NDVI values were observed in the 2020 results at the Glendale and Willow Street sample frames. Each of the natural riverbed sample locations are isolated by concrete sections of river and have specific physical characteristics that may produce site-specific results.

4.2. Glendale

This section summarizes the results for the Glendale sample site, starting with the NDTI-turbidity results, and finishing with the NDVI-chlorophyll-a results.

4.2.1. NDTI-Turbidity

The NDTI results for the Glendale sample frame were not as uniform as expected. The 2018 NDTI results shown in Figure 12 show that the turbidity levels in the natural riverbed sample sites were all higher than any of the turbidity levels in the upstream concrete sample sites. The elevated turbidity values in the natural riverbed samples in 2018 could be attributed to the unique characteristics the Glendale sample frame. The BWRP discharges treated wastewater into the West Burbank Channel roughly two miles upstream, and constituents discharged by the BWRP may contaminate the river by adding partially treated effluent into the system (Boroon & Coo 2015). The concrete sample sites in the Glendale sample frame were collected upstream of the West Burbank Channel and LAR confluence and therefore the hydrochemistry was affected by this source. The 2020 NDTI results for Glendale indicate the turbidity was lowest in the natural riverbed sample sites (Figure 12b).

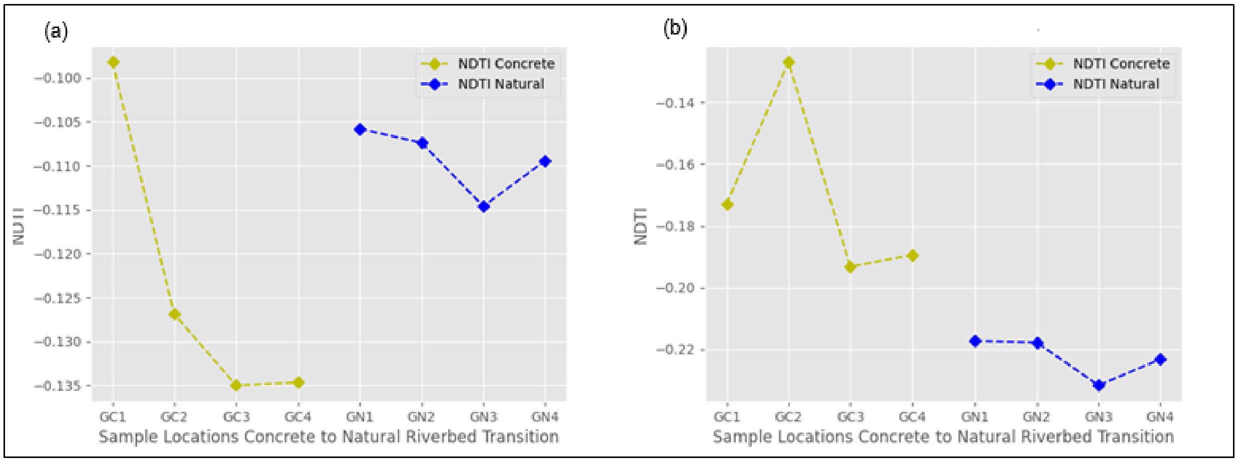

Figure 12. Glendale NDTI: (a) 2018 and (b) 2020.

4.2.2. NDVI-Chlorophyll-a

Similar to the NDVI results in Sepulveda Basin, the results for the Glendale sample frame are split. At Glendale chlorophyll-a concentrations declined in the concrete to natural riverbed transition in 2018 but increased in 2020. Unlike the Sepulveda Basin sample frame, the natural riverbed section sampled at Glendale is influenced by an upstream WRP. The highest nutrient levels in the LAR have been observed downstream of WRPs (Stein and Ackerman 2007). Since the concrete sample sites at Glendale occur upstream of the inlet channel connected to the BWRP, they are not influenced by the same constituents as the natural rived bed sites. In addition, the intermittent nature of WRP discharges creates fluctuating hydrochemistry downstream of any outlet. In any circumstance however, mean NDVI values derived from individual pixel values in each sample polygon and charted in Figure 13 indicate a clear shift in chlorophyll-a concentration at concrete to natural riverbed transitions.

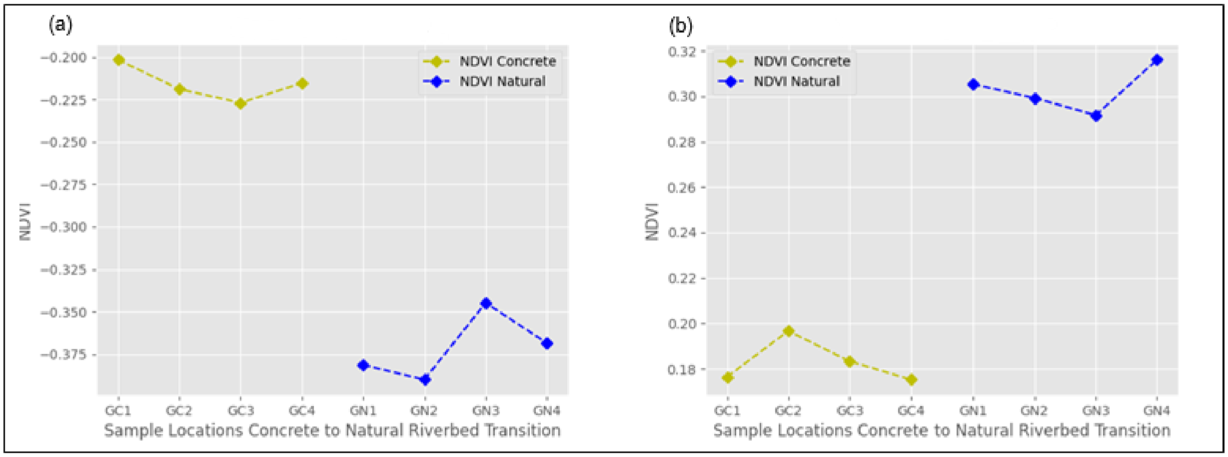

Figure 13. Glendale NDVI: (a) 2018 and (b) 2020.

4.3. Willow Street

This section summarizes the results for the Willow Street sample site, starting with the NDTI-turbidity results, and finishing with the NDVI-chlorophyll-a results.

4.3.1. NDTI-Turbidity

The Willow Street sample site signifies the end of the freshwater run of the LAR before meeting and mixing with the saline water in the Pacific Ocean. River water at this site passes the Willow Street bridge and abruptly shifts from flowing over a concrete channel into a wide soft bottom pool where water velocity was observed to be reduced before traveling down grade through a series of small rapids into the broader soft bottom estuarine stretch of the LAR. The concrete sample sites are the closest in proximity to the natural sample sites of any of the sample frames in this study. Additionally, there are no major surface water inlets that mix with the LAR in the vicinity of the sample sites at Willow Street which means this site may prove to provide a true view of how turbidity varies in transitions between concrete lined and natural riverbed lined LAR sections. The 2018 and 2020 NDTI results both indicate lower turbidity in natural sample sites than concrete sample sits at Willow Street (Figure 14).

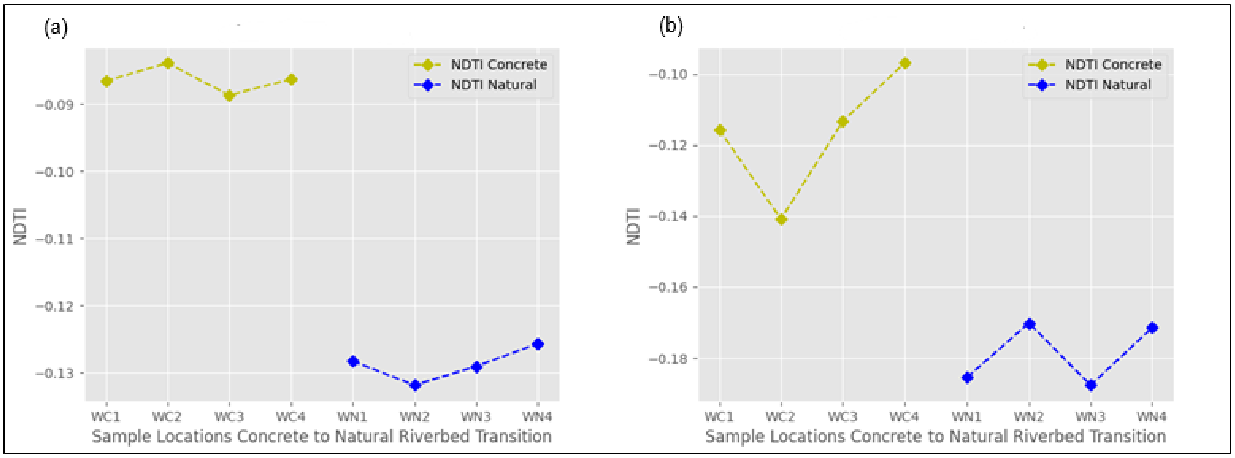

Figure 14. Willow Street NDTI: (a) 2018 and (b) 2020.

4.3.2. NDVI-Chlorophyll-a

Mirroring the Glendale sample frame, the NDVI results at Willow Street pointed to lower algal concentrations in the natural section for 2018 while algal concentrations were higher for the natural section in 2020 (Figure 15). It should also be noted that the highest observed NDVI values in the study occurred in the Glendale and Willow Street 2020 imagery. Glendale is downstream of the DTCWRP and BWRP while Willow Street is downstream of all WRPs on the river and nearly all urban runoff inlets contributing to the LAR. Different from Sepulveda Basin and Glendale, the concrete and natural riverbed sections at Willow Street have the same inputs meaning there are no waterway confluences affecting the sample sites, and similar to other sample frames, the natural riverbed section at Willow Street contains lower velocity water and a higher residency time than the concrete section.

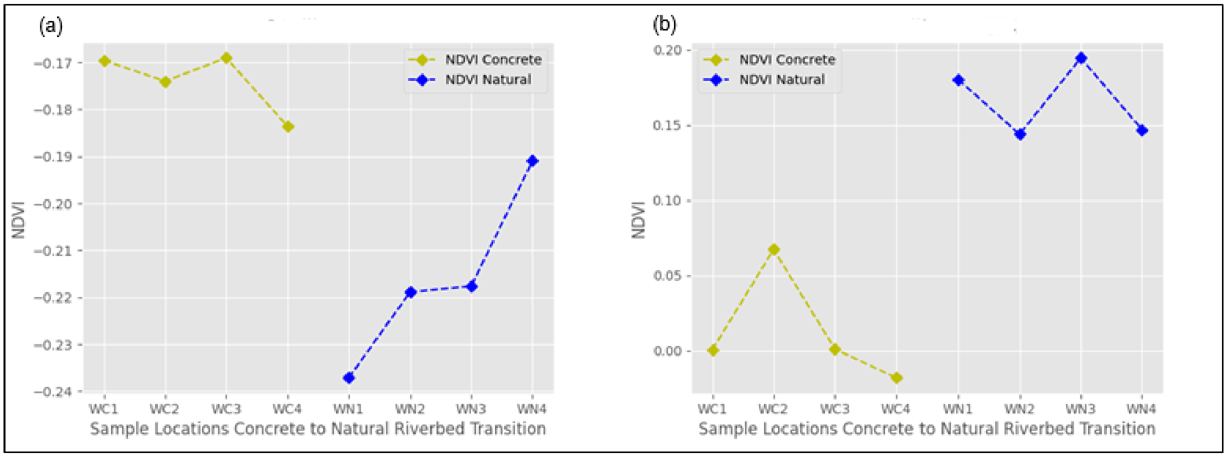

Figure 15. Willow Street NDVI: (a) 2018 and (b) 2020

4.4. ANOVA

The methodology utilized in this study consists of uniform polygon clip boundaries used to created raster images of the same size for calculation and analysis of RS indices. Index results within this study therefore are the outcome of a deliberate, balanced experimental design. The RS index histogram value distributions yielded a mean index value for each sample site and represent continuous values which are dependent on the execution of each RS index ratio. In order to determine whether the variation the results of the RS indices used in this study are statistically significant analysis of variance (ANOVA) was executed. RS index results for concrete and natural sample sites are compared using a one-way ANOVA. This approach is appropriate for comparing two or more datasets beholden to one dependent variable (Ross and Willson 2017). Microsoft Excel was used to apply one-way ANOVA to .csv files containing NDTI and NDVI index means for each sample site in each sample frame in the study. A check was also performed running ANOVA on index values in polygon sample sites at the individual pixel level and it was determined that using the mean index values at the concrete to natural transition yields conservative p-values in comparison.

ANOVA results for four of six NDTI results indicate p-values below the 0.05 threshold which is widely used as a benchmark for determining statistical significance. The two p-values above the 0.05 figure were both from 2018 imagery and occurred at Sepulveda Basin and Glendale with values of 0.08 and 0.16, respectively. Both Sepulveda and Glendale are sites influenced by several unique factors that may influence the natural riverbed section water chemistry in ways that are different from the preceding concrete riverbed sections. Constituents present in the LAR are variable and unpredictable and fluctuate on time scales from hours to months due to several sources (Stein and Ackerman 2007). The two NDTI ANOVA results above the p-value threshold could have been the product of turbidity fluctuations local to the natural riverbed sections that skewed the variance.

Table 7 NDTI ANOVA p-values

Sample Frame	p-value 2018	p-value 2020
Sepulveda Basin	0.079202	0.000325
Glendale	0.1575	0.01581
Willow Street	2.01×10^{-7}	0.000891

The ANOVA results for NDVI produced statistically p-values for all outputs considered in terms of 0.05 standard (Table 8). The least statistically significant NDVI p-value output (0.04) was recorded at the Sepulveda 2018 sample frame. Relying solely on the 0.05 p-value for determining whether a claim is correct or false can be reckless when study design, measurement accuracy and external variables are not also considered (Wasserstein and Lazar 2016). Despite NDVI results being split, indicating three sample frames having higher algal concentrations in concrete sections and three sample frames having higher algal concentrations in natural sections, all the ANOVA outputs represent significant variation in RS index values through the concrete to natural riverbed transitions.

Table 8 NDVI ANOVA p-values

Sample Frame	2018	2020
Sepulveda Basin	0.042524	6.02×10^{-5}
Glendale	8.56×10^{-6}	2.78×10^{-6}
Willow Street	0.005859	0.000485

Chapter 5 Conclusions

The main objective of this study was to determine the effects of concrete and natural riverbed substrates on WQ as water flows through the LAR. More precisely, the extent in variation of turbidity and chlorophyll-a concentration within the artificial and semi-natural channels of the LAR were examined by processing imagery data with RS indices. Lastly, the validity of benefits of natural riverbed sections on WQ was investigated by confirming statistical significance with ANOVA.

This chapter considers the implications of the results produced in this project as well as their utility and the limitations associated with the applied methodology. Finally, an alternative methodology is proposed which expands upon the findings in this study may be used in real world use cases.

5.1. Discussion

A pattern of turbidity level decrease was observed in five out of six sample sites at concrete to natural riverbed transitions despite the variations in the physical conditions present at the three sample frames. The one NDTI result for which there was not a decrease in turbidity in the natural riverbed zone occurred at Glendale in 2018. The natural section of LAR at the Glendale sample frame is influenced by discharge from the BWRP, and this may have caused a turbidity spike in the natural section in 2018. The NDTI result for the 2018 Sepulveda Basin sample frame showed a decrease in turbidity in the natural sample sites; however, ANOVA produced a p-value of 0.08 which exceeded the 0.05 p-value benchmark used in this study to denote statistical significance. Nonetheless, when compared to the NDTI results of imagery acquired in different years and other sample frames, while bearing in mind the variable nature of constituents present within the LAR at brief temporal scales, it can be observed that turbidity in the LAR reliably decreases as water flows from the artificial reaches into natural reaches.

With respect to chlorophyll-a concentrations in the LAR, results were split with half the low chlorophyll-a levels occurring in the concrete sections and half in the natural sections. Chlorophyll-a in the LAR is a biological indicator subject to delayed response times given several factors such as water velocity, water temperature and nutrient concentration. All of the chlorophyll-a results were statistically significant, but it is likely that the prediction of chlorophyll-a levels in the LAR would be better if additional variables beyond riverbed type were included.

The cumulative results of each RS index in this study serves as an impetus for continued attention, study, and action on the LAR. Policy makers in the Los Angeles area can use the NDTI results in this study as a basis to advocate for expanded restoration of the LAR outside the scope of the ongoing USACE project. This study suggests naturalized sections of the LAR provide environmental services that reduce the turbidity of water traveling through them. Additionally, the NDVI results indicate significant fluxes in chlorophyll-a concentration at concrete to natural riverbed transition zones which have dangerous potential when associated with algal blooms and the associated die-offs that cause anoxic conditions. Comprehension of the factors leading up to sharp shifts in WQ are possible since each of the RS indices used in the study have proven themselves as promising detection and monitoring tools for turbidity and chlorophyll-a concentration levels in the LAR. Modifying the methodology in this study to increase temporal resolution and field validation of the turbidity and chlorophyll-a concentrations will further increase utility.

The current purpose of the LAR is mainly to transport water as efficiently as possible through the system to protect surrounding areas from floods. Environmental services that a natural system would typically perform are traded for flood protection. Study frame locations in this study such as Glendale and Willow Street are working examples of natural riverbed sections with engineered banks providing flood protection and environmental services simultaneously. The observed reduction in turbidity in natural sections of river in this study is consistent with the 2015 USACE feasibility report and undermines the assumption by the 2021 LAC draft environmental impact report that natural sections of the LAR do not contribute to improved WQ. With knowledge that sections of the LAR possessing natural riverbeds with engineered levees have increased WQ over fully concrete sections, a more aggressive might be taken by USACE to restore longer stretches of this river moving forward.

5.2. Limitations

One factor that would improve the practicality of this study would be to increase the temporal resolution of imagery acquisition. In the workflow of the current study the temporal resolution of image capture is once every two years, which represents a key limitation. In a methodology where images are captured at a higher temporal frequency WQ fluctuations could be more closely studied and better understood.

Another data limitation to consider in this study is related to bottom reflectance in the LAR. There was considerable effort exerted in searching for ideal areas of the LAR to sample which contained minimal bottom reflectance. Some areas of the LAR, particularly concrete sections containing shallow water which may have spectral characteristics influenced by the bottom reflectance of the concrete riverbed. In order to truly validate the quality of imagery data, in-situ sampling of WQ should be conducted simultaneously with image capture.

Moreover, the present RS methodology provides a qualitative measure of the WQ parameters of turbidity and chlorophyll-a in the LAR. The results derived from this project are valuable in the sense that they detect a reduction in turbidity in natural sections of river while effectively detecting differences in chlorophyll-a in concrete and natural portions of the LAR. While the results provided by this study constitute relative intensities of turbidity and chlorophyll-a in the LAR they are not interchangeable with field collected samples of these WQ parameters. Future work is necessary in order to reliably correlate RS index values with field collected WQ samples.

5.3. Future Work

In reviewing the results and limitations of the study there are some key components in the methodology that can be modified or augmented to increase reliability and practicality. Looking forward and expanding upon the findings in this study, increasing the temporal resolution of imagery and collecting in-situ WQ samples for validation are of high value. In order to develop a dependable template that relates RS index values to physical parameters, in-situ WQ sampling can be conducted concurrently with UAV flight missions. UAVs with adequate spatial and spectral resolution to collect imagery are available for purchase by the public. Utilization of UAVs increases the temporal resolution of imagery capture manyfold over the biennially captured NAIP aerial imagery used in this project. With greatly increased temporal resolution, WQ patterns can be monitored on a daily or weekly basis.

In-situ field collected WQ results can be compared with the RS index results derived from simultaneously collected UAV imagery to determine correlation strength. Once correlation is firmly established between field collected WQ data and RS index results, WQ in-situ sampling can be relegated to occasional data quality checks of RS data captured by UAVs. This proposed future work is essential in enabling remote monitoring of WQ that can be compared against local water quality standards for compliance. WQ parameters can be determined at daily intervals and used to alert local agencies WQ in the LAR in near real time. This work could provide great benefit to the residents of Los Angeles and the communities that reside in the Los Angeles River Basin.

References

Ackerman, D. and Schiff, K. 2003. “Modeling storm water mass emissions to the Southern California Bight.” *Journal of Environmental Engineering*, Vol. 129 No. 4. 308-317.

Ackerman, D., Schiff, K., Trim, H., and Mullin, M. 2003. "Characterization of water quality in the Los Angeles River." *Bulletin of the Southern California Academy of Sciences* 102, No. 1

Alföldi, T.T. 1982. “Remote sensing for water quality monitoring”. In Remote Sensing for Resource Management, Johannsen, C.J. & Sanders, J.L., (Eds), *Soil Conservation Society of America*, 317-328.

Avdan, Z.Y., Kaplan, G., Goncu, S., and Avdan, U. 2019. "Monitoring the water quality of small water bodies using high-resolution remote sensing data." *ISPRS International Journal of Geo-Information* 8, no. 12: 553.

Austin, Å. N., Hansen, J. P., Donadi, S., and Eklöf, J. S. 2017. "Relationships between aquatic vegetation and water turbidity: A field survey across seasons and spatial scales." *PLOS one 12*, no. 8: e0181419.

Bid, S., Siddique, G. 2019. Identification of seasonal variation of water turbidity using NDTI method in Panchet Hill Dam, India. Model. Earth Syst. Environ. 5, 1179–1200. https://doi.org/10.1007/s40808-019-00609-8

Boroon, M. and Coo, C. 2015. “Water quality assessment of the Los Angeles river watershed, California, USA in wet and dry weather periods.” *Journal of Geography, Environment and Earth Science International* 4(3) 1–17.

Campbell, J.B. 2011. *Introduction to Remote Sensing.* 5th edition. New York: Guilford Press.

Weston Solutions, Inc. 2005. California Department of Water Quality Control Board, Final Report.

Carpenter, S., Caraco, N.F., Correll, D.L., Howarth, R., Sharpley, A.N., and Smith, V.H. 1998. “Non-Point Pollution of Surface Waters with Phosphorus and Nitrogen.” *Ecological Applications*. Vol. 8, No. 3 559-68

County of Los Angeles. 2022. Accessed April 4, 2022. https://urldefense.com/v3/__https://geohub.lacity.org/datasets/lacounty::streams-and-rivers/explore?location=33.824213*2C-118.226184*2C8.99__;JSU!!LIr3w8kk_Xxm!9pWOVH3D4AxGhL1K-eD4S97LlBUSxu0ZFs9IhP6cbnwrqDol1Bs2eV6fzdofapQ$

Chen, X., Chen, W., Bai, Y., and Wen, X. 2022. "Changes in turbidity and human activities along Haihe River Basin during lockdown of COVID-19 using satellite data." *Environmental Science and Pollution Research* 29, no. 3: 3702-3717.

Chislock, M. F., Doster, E., Zitomer, R. A. & Wilson, A. E. 2013. “Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems.” *Nature Education Knowledge* 4(4):10

Elhag, M., Gitas, I., Othman, A., Bahrawi, J., and Gikas P. 2019. "Assessment of Water Quality Parameters Using Temporal Remote Sensing Spectral Reflectance in Arid Environments, Saudi Arabia" Water 11, no. 3: 556. https://doi.org/10.3390/w11030556

Gumprecht, B. 1999. *The Los Angeles River: Its Life, Death and Possible Rebirth.* Baltimore: The Johns Hopkins University Press.

Congalton, R. G. and Green. K. 1999. *Assessing the accuracy of remotely sensed data: principles and practices.* Boca Raton, FL: Lewis Publishers.

Hedley, J. D., Harborne, A. R., and Mumby, P. J. 2005. "Simple and robust removal of sun glint for mapping shallow‐water benthos." *International Journal of Remote Sensing 26*, no. 10: 2107-2112.

ICF International Inc. 2021. “2020 LA River Master Plan Draft Program Environmental Impact Report.” Los Angeles County Public Works.

Kaplan, G., Avdan, Z. Y., Goncu, S., and Avdan, U. 2020. "Evaluation of RapidEye-3 Satellite Data for Assessing Water Turbidity of Lake Borabey" Proceedings 48, no. 1: 14. https://doi.org/10.3390/ECWS-4-06424

Katlane, R., Dupouy, C., El Kilani, B., Berges, J. C. 2020. “Estimation of chlorophyll and turbidity using sentinel 2A and EO1 data in Kneiss Archipelago Gulf of Gabes, Tunisia.” *International Journal of Geosciences, Scientific Research 11*, p. 708-728.

Kim, E., Sook-Hyun, N., Koo, J., and Hwang, T. 2021. "Hybrid Approach of Unmanned Aerial Vehicle and Unmanned Surface Vehicle for Assessment of Chlorophyll-a Imagery Using Spectral Indices in Stream, South Korea." *Water 13*, no. 14: 1930.

Kuhn, C., Valerio, A., Ward, N., Loken, L., Sawakuchi, H. O., Kampel, M., Richey, J., et al. 2019. "Performance of Landsat-8 and Sentinel-2 surface reflectance products for river remote sensing retrievals of chlorophyll-a and turbidity." *Remote Sensing of Environment* 224.104-118.

Lacaux, J. P., Tourre, Y. M., Vignolles, C., Ndione, J. A., and Lafaye, M. 2007. "Classification of ponds from high-spatial resolution remote sensing: Application to Rift Valley Fever epidemics in Senegal." *Remote Sensing of Environment* 106, no. 1: 66-74.

McKim, H. L., Merry, C. J., and Layman, R.W. 1984. "Water quality monitoring using an airborne spectroradiometer." *Photogrammetric Engineering and Remote Sensing* 50, no. 3: 353-360.

Montello, D. and Sutton, P. 2012. *An Introduction io Scientific Research Methods in Geography and Environmental Studies*. Vol. 1. Sage.

Pix4D. 2022. “Learn more about Sequoia+.” Accessed September 11, 2022. https://www.pix4d.com/product/sequoia/faq.

Rodríguez-López, L., Duran-Llacer, I., González-Rodríguez, L., Abarca-del-Rio, R., Cárdenas, R., Parra, O., Martínez-Retureta, R., and Urrutia, R. 2020. "Spectral analysis using LANDSAT images to monitor the chlorophyll-a concentration in Lake Laja in Chile." *Ecological Informatics* 60: 101183.

Ross, A. and Wilson, V. 2017. *Basic and Advanced Statistical Tests Writing Results Sections and Creating Tables and Figures*. Sense Publishers.

Saberioon, M., Brom, J., Nedbal, V., Souček, P., and Císař, P. 2020. "Chlorophyll-a and total suspended solids retrieval and mapping using Sentinel-2A and machine learning for inland waters." Ecological Indicators 113: 106236.

Stein, E. D., and Ackerman, D. 2007. “Dry weather water quality loadings in arid, urban watersheds of the Los Angeles Basin, California, USA.” *JAWRA Journal of the American Water Resources Association*. Vol. 43 No. 2. 398– 413.

Stein, E.D. and Yoon, V.K. 2007. “Dry weather flow contribution of metals, nutrients, and solids from natural catchments.” *Water, Air, and Soil Pollution.* Vol. 190 No1.183-195.

Tolk, B. L., Han, L. and Rundquist. D. C. 2000. "The impact of bottom brightness on spectral reflectance of suspended sediments." *International Journal of Remote Sensing* 21, no. 11: 2259-2268

U.S. Army Corps of Engineers Los Angeles District. 2011. Sepulveda Dam Basin Master Plan and Draft Environmental Assessment.

U.S. Army Corps of Engineers Los Angeles District. 2015. Los Angeles River Ecosystem Restoration Integrated Feasibility Report. FINAL Feasibility Report and Environmental Impact Statement/Environmental Impact Report. Volume 1: Integrated Feasibility Report.

U.S. Geologic Survey. 2021. Accessed November 7, 2021. https://earthexplorer.usgs.gov/

Wasserstein R. L. and Lazar N. A. 2016. “The ASA’s statement on p-values: Context, process, and purpose.” *The American Statistician*. 70. No. 2: 129-133.

Yu, Y., Chen, S., Qin, W., Lu, T., Li, J. and Cao, Y. 2020. “A Semi-Empirical Chlorophyll-a Retrieval Algorithm Considering the Effects of Sun Glint, Bottom Reflectance, and Non-Algal Particles in the Optically Shallow Water Zones of Sanya Bay Using SPOT6 Data." *Remote Sensing* 12, no. 17: 2765.