MEASURING LATERAL EROSION AND DEPOSITION

UPPER OWENS RIVER, EASTERN CALIFORNIA

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Arts
in Geography

By
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May 2013
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Date

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Dr. Mario Giraldo
Date

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Dr. Amalie Orme, Chair
Date

California State University Northridge
Dedication

This thesis is dedicated to my parents and wife whose love, support, encouragements and patience have allowed me to complete this research.
Acknowledgments

I would like to acknowledge and extend my heartfelt gratitude to my committee chair, Dr. Amalie Orme, for her guidance, support and encouragements in completing this thesis, and the committee members Dr. Helen Cox and Dr. Mario Giraldo, for their help and assistance and guidance to complete this research.
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Abstract

MEASURING LATERAL EROSION AND DEPOSITION
UPPER OWENS RIVER, EASTERN CALIFORNIA

By
Mohammad Abdulrahman
Master of Arts in Geography

This research investigates the relationship between lateral erosion and deposition along the riverbanks of the Upper Owens River, eastern California. National Agriculture Imagery Program (NAIP) and Erdas Imagine were used to determine geomorphic change along the riverbank from 2005 to 2012. Remote sensing analysis technique shows that the relationship between these two processes—erosion and deposition—can be classified into two categories: wet periods, where the relationship between the two was strongly correlated, and dry periods, where no apparent relationship exists. A normalized Difference Water Index (NDWI) method was used to delineate the areas of the channel and adjacent floodplain. From there, differences between paired images were quantified to demonstrate the magnitude of erosion and deposition. The results demonstrate total lateral erosion during wet periods was higher than the amount of deposition within meanders. By contrast, during dry periods deposition along the meanders was greater than erosion. Further, the results show that the direction of river migration changed.
During wet periods the direction of migration eastwards, while during dry periods meanders shifted westwards.

Key words: Lateral erosion and deposition, meander direction, Normalized Difference Water Index, National Agriculture Imagery Program.
1. Introduction

Most rivers in nature are characterized by sinuous patterns, frequently developing into a meandering pattern associated with channel and valley gradients less than those associated with braided systems. Once a meander pattern has developed, two co-dependent processes occur along channel banks: Erosion, which is the process of removal of sediments from outer bank, and deposition, promotes the accumulation of sediment on the inner bank. As water enters the meander bend velocity along the outer bank accelerates relative to the inner bank. Leopold and Langbein (1966) suggested that the maximum meander pattern does not exceed ten times its width. This is becomes important for understanding rates of erosion and deposition and transfer of energy and sediment in areas where river engineering is planned (Blanka and Kiss 2011).

Geomorphologists study meander systems for several reasons. First, within meanders both erosion and deposition act to change the meander morphology over time. Second, the rate of erosion along the outer bank is a reasonable indicator of water stage in the channel’s history. Furthermore, historic aerial photography and satellite imagery show channel migration, channel abandonment, and the development of complex floodplain environments in response to variable hydrologic and sediment budget conditions over time.

Much research using satellite images and aerial photographs, has focused on the rate of channel migration as a surrogate for the rate of erosion, while ignoring the rate of bank deposition (Nanson, 1980; Hudson and Kesel, 2000; Blanka and Kiss, 2011; Magdaleno and Yuste, 2011). This opens a new area of research. Measuring the rate of erosion and deposition by using high-resolution (1 meter) images such as those obtained
by the National Agriculture Imagery Program NAIP provide detailed information about channel change over time.

In this research, the study area is located along the Upper Owens River, in Mono County, California. This section of the Upper Owens River flows into Lake Crowley some 30 kilometers north of Bishop. The flow pattern here is dominated by well-developed meanders that are affected by changing water levels associated with seasonal snowmelt derived from neighboring Sierra Nevada Mountain.

The purpose of this research is to examine the relationship between the rate of lateral erosion and lateral deposition using National Agriculture Imagery Program NAIP from 2005 to 2012. The relationship between these two processes is examined at 14 meanders over three time periods; 2005-2009, 2009-2012 and 2005-2012. This time frame allows evaluation not only of erosion and deposition, but also the magnitude of channel migration across the floodplain. Over the period of the imagery, this region experienced two above average precipitation and snowmelt seasons and a season of below average precipitation and resultant lower discharge.

The significance of this research lies in its application to rates of sediment discharge into Lake Crowley, which used as a storage unit by the Los Angeles Department of Water and Power LADWP. The water in Lake Crowley is part of the Los Angeles Aqueduct system that provides water to Southern California. Locally, the lake is used for sport fishing. If, in theory, the rate of bank erosion is higher than the rate of bank deposition then more sediment potentially will flow into Lake Crowley. Clearly there are implications for long-term accumulation of sediment, reduction in lake size, and changes in habitat. If the rate of bank deposition is higher than the rate of bank erosion then
presumably less sediment will be transported and deposited in Lake Crowley. Further, there is the potential for sediment that is derived from the floodplain though which the channel flows, especially if channel migration is an ongoing process. Finally, if the rate of erosion is equal to deposition then the source of suspended and bed load erosion and vertical expenditure of energy.
2. **Scientific Background**

2.1 **Meander systems:**

The sinuosity of meandering rivers depends on two important processes, erosion and deposition of sediment along the channel banks, and it is clearly obvious in aerial photographs and satellite images. Leopold and Langbein (1966) showed that the sinuosity describes the intensity of the meander, which is the ratio between the length of the channel in the meander bend to the wavelength of the meander bend, where the majority of meander rivers have a ratio between 1.3 to 1 and 4 to 1.

The rate of flow, depth and width of the channel, volume of water, channel cross-section shape, and curvature of bends are considered as the main factors influencing meander (Leopold and Langbein, 1966).

Blanka and Kiss (2011) examined the relationship between water stage and rate of erosion on river banks on the river Hernad, Hungary. The study showed that the rate of erosion was 2.4-3.2 times higher during high flow than during the low stage of water. They examined the short and long term rate of bank erosion of five meanders along a short reach of the Hungarian section. In order to examine the rate of erosion in a short period (1.5 years), field measurements were taken three times to delineate the outer bank line of the five meanders within the study period. The aerial photos were used to determine the rate of erosion in 50 years to examine the long term of erosion. ErdasImagine 8.6 and ArcGis 9.3 were used to delineate the bank line and calculate the rate of erosion in m/y. Moreover, hydrographs were used to assess the relationship between the rate of erosion of outer banks and water stage. In a short-term period, the rate
of bank erosion varied between 2 and 13m. Also, it showed that when the flood occurred, the rate of erosion was 2.4-3.2 times higher than the low stage of water. Research on Mississippi River shows how high water stage cause more sediment to be eroded from river banks and flowed in the stream (Kesel et. al, 1974). When the water stage is low, sediment is deposited at the inner river bank because the rate of flow is lower than the outer river bank. It remains that while studies on larger river systems clearly demonstrate principles that are reasonable, do these same processes work in channels that are several magnitudes smaller such as the upper Owens River?

Hattingh and Rust (1993) conducted a field experiment to show the ability of high water stage to carry heavy minerals in the Swartkops River in South Africa by introducing 40,000 kg of aeolian sediment. The study showed that the distribution of heavy minerals in a meander bends channel was associated with flow velocity at the inner bank, the velocity of water was low, therefore, most of heavy minerals deposited there. Also, the concentration of heavy minerals within the swamp area was high because of plants, which further reduced flow velocity. The depositional environment is located along the inner bank of the river because the velocity of water movement is low, where suspended sediment can be deposited. At the outer bank the rate of flow is higher than the inner bank, therefore; the erosion process tend to occur on the outer bank.

The relationship between geomorphic parameters of the meander and the rate of erosion and deposition of materials on river banks are examined in a study conducted along the Ebro River in Spain by Magdaleno and Yuste (2011). They found that when the ratio between radius and width of the meander is between two and four, the migration rate of the meander and rate of erosion, was high. Moreover, Crosato (2009) conducted
experimental tests to evaluate the relationship between rate of erosion and the ratio between radius and width of the meander. He compared between two physics-based models, which are the Ikeda model and the Crosato model. The differences between those models were that the Crosato model included the topography of the meander because the depth of water at the outer bank is deeper than inner bank. The Ikeda model and the Crosato model showed strong relationship between migration rate and bend sharpness. They showed that the migration rate increases with increasing the ratio of curvature until it reached a critical value, which is between 1.8 to 3. Also, both models showed a good relationship between migration rate and river sinuosity, which depends on river curvature. Other studies showed that the rate of erosion increased with increasing bend sharpness when the ratio is between 2 and 4 (Crosato, 2009; Magdaleno and Yuste, 2011).

Factors that control the dynamics of meander are highly interconnected with each other. As the water flow increases, the rate of erosion at the outer bank increases, which causes the radius of meanders to increase. The interaction between those factors and river banks creates an erosion environment along the outer bank because the rate of flow is high and also creates a deposition environment along the inner bank because the rate of flow is low along the inner bank (Hattingh and Rust, 1993).

### 2.2 Remote Sensing Method applications in geomorphology:

Remote sensing is defined as a science of collecting information about an object or area on the ground without being in physical contact with the object (Jensen, 2006),
and in geomorphology it is useful to collect information about river systems including water quality, temperature, sediment load, and water level. Imagery also permits the evaluation of river shifts through time (Muller et. al, 1993). A variety of techniques are used to delineate channel patterns to determine the rate of erosion or migration and to map the overbank areas (Mcfeeters 1996; Frazier and Page, 2000; Jain et. al, 2005; Ji et. al, 2009 and Lu et. al, 2011). The most widely used methods in these researches are Density slicing single band, Tasseled Cap Transformation, Maximum Likelihood Classification and Normalized Difference Water Index (NDWI).

Density Slicing technique has been used with satellite data obtained from SPOT, IRS LISS III, and Landsat (MSS, TM) (Jain et. al, 2005). This type of technique looks at a single band of the image and displays the light intensity in different colors according to its value (akin to using classified symbology in GIS). Frazier and Page (2000) used Density Slicing to delineate different water bodies such as sub channels, lagoons and small pools in the Murrumbidgee River, Australia. They applied the technique on six bands in Landsat 5TM. Another study used the same technique to delineate flood area by using two different satellite data, Landsat TM and IRS LISS III (Jain et. al, 2005). This study used six bands in Landsat TM and three bands of IRS LISS III data to delineate flood areas at the river Koa, in Bihar, India. Both studies showed that the infrared band had a good identification of water bodies and the accuracy level was more than 90%. This method had some limitations in delineating water bodies because it mixed between water bodies and other land cover like vegetation (Frazier and Page, 2000 and Jain et. al, 2005).

Tasseled Cap Transformation uses a linear combination of bands of the image to generate new bands of information called greenness, brightness and wetness. Crist and
Cicone (1984) developed the Tasseled Cap Transformation coefficient data for Landsat TM and used the wetness band to delineate water bodies. The Tasseled Cap Transformation method was used to map flood prone area at the river Koa, India (Jain et. al, 2005). They found that the wetness band in Landsat TM had a better identification of water bodies than the Density Slicing method. Mixing between moist soil surface and water surface, and the shadow effect on images are the main limitations of Tasseled Cap Transformation (Jain et. al, 2005).

Both Minimum distance classification and Maximum Likelihood classification depend on statistical decision in which each pixel in the image will be classified into a corresponding class (Myung, 2003). Minimum distance classification classifies pixels on the image based on the distance of the pixel from the mean of the class, while the Maximum likelihood classification classifies each pixel based on the distance from the mean and the standard deviation of each class. Maximum Likelihood Classification was used to delineate water bodies in Murrumbidgee River, Australia (Frazier and Page, 2000). They found that this type of method showed a high level of accuracy when they compared it with raw data. Study of the Maximum Likelihood classification algorithm shows that misclassification is unavoidable because each pixel is classified by using the deviation of pixels from the mean and standard deviation of each class (Susaki and Asaki, 2000).

Normalized Difference Water Index (NDWI) technique, developed by Macfeeters (1996) depends on band ratio between the green and near infrared bands. Those two bands were chosen because they represent the maximum reflection of water, which is the green band, and the minimum reflection of water, which is the near infrared band.
Different studies showed high accuracy levels of NDWI when it was compared with raw data and other methods.

Jain et. al (2005) found that Normalized Difference Water Index (NDWI) presents more accurate data than the Density Slicing and Tasseled Cap Transformation methods when mapping flood areas. This type of method has been applied to many different satellite images including Landsat TM, IRS LISS III and HJ-1A/B, which is new Chinese satellite imagery, used to map water bodies in Beijing, China (Lu et. al, 2011).

One study compared between different Normalized Difference Water Index methods which have been used in several studies (Ji et. al, 2009). It compared between Mcfeeters, Roger and Kearney, Xu and Lacaux et equations. It showed that Modified Normalized Difference Water Index MNDWI was the most successful technique to map the water bodies when they compared between all NDWI methods.

Research shows that the Normalized Difference Water Index is the most widely used technique when applied to different satellite data like Landsat, SPOT, ASTER and MODIS (Je et. al, 2009), and the most accurate one when it is compared with the raw data.
3. Methods

3.1. Study Area:

The study area is located on a 1 km reach of the Upper Owens River, in Mono County, California. The meander section that was evaluated just flows into Crowley Lake some 30-kilometer north of Bishop. Los Angeles Department of Water and Power (LADWP) uses Crowley Lake as a storage unit that provides water to Southern California. The flow of Upper Owens River in this section is dominated by well-developed meanders that are affected by changing water levels associated with seasonal snowmelt derived from the neighboring Sierra Nevada Mountain (Fig.1). The length of the meander belt at the study area is 2393.10 m. The channel system here is characterized by a dominant single channel, with several smaller meandering channels plus many abandoned channels or oxbow lakes (Fig.2).

3.2. Data and Methods:

The main source of data was from National Agriculture Imagery Program NAIP, which was downloaded from the California Atlas website (State of California, 2010). NAIP imagery is high-resolution (1-meter ground sample distance) (GSD). Weather data were collected from Mammoth Lakes R S weather station at 2379m (weather source, 2005). The study site is located at 2210 m. Mammoth Lakes R S provides historical monthly precipitation and snowfall. The sum of these values produces the annual precipitation and snowfall (Table.1).

National Agriculture Imagery Program NAIP collects data during agricultural seasons in the United States. It begins with three bands blue, green and red. In 2007, some NAIP images had one more band that is the near infrared, but 2010 all NAIP
images four bands; blue, green, red and near infrared. Though the spatial resolution of NAIP originally was 2 meter ground sample distance (GSD), in 2008 all NAIP imagery was collected with a 1 meter GSD (USDA- FSA, 2012).

In this research, three NAIP images were used to determine the changes along the channel banks of the Owens River: 2005, 2009 and 2012, where the 2009 and 2012 NAIP had four bands, while 2005 had only three. Therefore, Normalized Difference Water Index (NDWI) of 2005 was not able to be calculated because it used near infrared band in the analysis. Unlike the Landsat which has long term record of image collection, NAIP imagery was limited to only most recent acquisitions.

The images were downloaded from Cal-Atlas in a tiff format. Using Erdas Imagine software, the images were converted from the tiff format into .img format. To focus only on the changes that occurred within the study area, the subset function was used. Although the study area was located at the corner on the NAIP images, where the lenses of the aircraft camera was not perpendicular to the ground thereby introducing some distortion, the geo-referencing objects function initially was used to ensure all images lined up correctly (Fig.3,4). This process was done by using the swipe tool to verify the alignment of images, where the intersections of the roads were used as ground control point (Fig.5).

Each image was classified by defining each class in the signature editor on the image by using Area Of Interest (AOI) tools. This type of classification is called supervised classification, where the user defines signatures for each class. The main goal of the classification is to distinguish the water bodies from other land covers like vegetation, wet areas, sand and roads. Therefore, defining many signatures for water
bodies in the signature file provides more accurate classification of the river. Training samples were selected on the 14 meanders and on each meander three training samples were selected, two on the edges of the river and one in center. After the signature definition of each image was completed, maximum likelihood classification was used to classify each pixel on the images to a class, based on the distance from the mean and standard deviation of the class (Fig.6). Because the river is the only feature to be evaluated, a recoding technique was used to change all the pixels in water classes to the same single value and the other pixels to a single “no water” class (Fig. 7).

The change detection technique was used on the recoded images. Change detection determines the nature and magnitude of change between images of different times. The change detection was used to calculate the difference from 2005 to 2009, 2009 to 2012 and from 2005 to 2012. The rational between grouping the images in this manner was to capture events over shorter and longer terms. Longer-term geomorphic events (2005-2012) potentially mask small changes that may happen in the intervening years for a fluvial system that experiences change and quickly masks the change. Because the changes of each pixel on the image were calculated, it was important to distinguish the main meander bodies of the river from other neighboring water bodies such as abandoned meanders or water-occupied oxbow lakes. This was done by defining the main river using a polygon to define an Area Of Interest (AOI) around only the river (Fig. 8). Finally, 14 meanders were defined and delineated to calculate the lateral erosion and deposition on riverbanks.
The Normalized Difference Water Index (NDWI) technique was used to evaluate the wetness of the river area in 2009 and 2012. The technique was done in Model Maker in the software, where NDWI =

\[
\frac{\text{Band4} - \text{Band2}}{\text{Band4} + \text{Band2}},
\]

(Fig.9). The values of NDWI range from -1 to 1, where values close to 1 show wet areas, while values close to -1 show dry areas. The histogram of NDWI of 2009 and 2012 show the values of pixels in 2012 were closer to 1 than 2009. In 2009, the values range from -0.505 to 0.29, while in 2012 was from -0.559 to 0.737, which indicates that the wetness areas of 2012 was higher than 2009 (Fig.20,21). The weather data shows that before 2009 it was a dry period especially in 2007 where the amount of precipitation and snowfall was 13.13 inches and 121.9 inches respectively. After 2009 it considered as wet period where the amount of precipitation and snowfall in 2010 was 34.65 inches and 369.8 inches respectively.
Figure 1. Study area at Upper Owens River

Figure 2. The length of meander system at the study area, Upper Owens River
<table>
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<th>Year</th>
<th>Precipitation (In)</th>
<th>Snowfall (In)</th>
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<td>2004</td>
<td>20.8</td>
<td>222.3</td>
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<tr>
<td>2005</td>
<td>28.96</td>
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</tr>
<tr>
<td>2008</td>
<td>21.74</td>
<td>202.4</td>
</tr>
<tr>
<td>2009</td>
<td>22.38</td>
<td>171.4</td>
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<tr>
<td>2010</td>
<td>34.65</td>
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<tr>
<td>2011</td>
<td>17.89</td>
<td>217.6</td>
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<tr>
<td>2012</td>
<td>19</td>
<td>173</td>
</tr>
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Table 1. Precipitation and snowfall at Mammoth weather station

Figure 3. NAIP image of Upper Owens River, study area is located in the blue box.
Figure 4. The study area at Upper Owens River, NAIP

Figure 5. Swipe technique to compare between two images.
Figure 6. Maximum likelihood classification of Upper Owens River

Figure 7. Recode of classes as water / no water
Figure 8. Defining the meanders from other water bodies by using AOI.

Figure 9. Model for Normalized Difference Water Index (NDWI).
4. Results

4.1 Change Detection

The change detection technique showed the difference between two images at different time. Change detection method was done on the recode images, which values range from 0 to 1. Therefore, the possible pixel values in different image are -1,0,1. (Fig 10,11) shows the results of the change detection. Purple color is used to show pixels that decreased in values, while turquoise color is used to show pixels that increased in values.

In order to evaluate the changes along the riverbanks, which are the rate of erosion and the rate of deposition, the change detection technique was used to produce three images. The first change detection showed the difference between 2005 and 2009, the second one showed the difference between 2009 and 2012, and the third one showed the difference between 2005 and 2012.

Figures 12, 13, 14 show the total erosion and deposition on the riverbanks, where the purple represents deposition, and the turquoise represents erosion. The total erosion areas of the riverbanks from 2005 to 2009 was 4164 m², while the deposition was 7317 m², and from 2009 to 2012 the total erosion was 6024 m², while the deposition was 4704 m². Finally, the total erosion from 2005 to 2012 was 5037 m², while the deposition total was 7372 m².

Fourteen meanders were selected to determine the rate of lateral erosion and deposition on the riverbanks of Upper Owens River. Figure 15 shows the location of the
14 meanders. These meanders were subsetted to calculate the amount of deposition and erosion along riverbanks, (Fig.16).

Table 2 shows areas of erosion and deposition of the fourteen meanders from 2005 to 2009. The total deposition areas between these years were 3726 m², while the erosion areas were 1701 m². The erosion area of the meander (1) was 91 m², while the deposition area was 193 m². The largest erosion area occurred on meander (7), which was 247 m², while the largest deposition area was occurred on meander (11), which was 528 m².

Table 3 shows areas of erosion and deposition of meanders from 2009 to 2012. During this period the total erosion areas were higher than deposition areas, 2843 m² and 1956 m² respectively. The largest erosion and deposition areas were occurred on meander (7), while the smallest erosion and deposition areas were occurred on meander (4).

Table 4 shows areas of erosion and deposition of meanders from 2005 to 2012. The total deposition areas were higher than erosion areas, 3311 m² and 2151 m² respectively. Also, the largest erosion area was on meander (7) 373 m², while the smallest erosion area was on meanders (6&11), which was 85 m².

Linear regression analysis was used to determine the relationship between lateral erosion and deposition on the riverbanks. Also, Linear regression can be used to predict the change in deposition when erosion occurs. The relationship between erosion and deposition can be evaluated by R squared value, which ranges from 0 to 1 as positive relationship and 0 to -1 as negative relationship. Figures 17, 18 and 19 show the relationship between erosion and deposition, at three periods; 2005-2009, 2009-2012 and 2005-2012, respectively. The linear regression from 2005 to 2009 does not show any relationship between erosion and deposition of sediment along the riverbanks, where the
R squared value is 0.08812. While from 2009 to 2012 R squared value is 0.5698, which is a high relationship. Finally, the relationship between erosion and deposition areas from 2005 to 2012 is weak, where $R^2 = 0.31963$. The correlation coefficient (R) value, which measures the strength and direction of data, shows high and moderate correlation with positive direction between 2009-2012 and 2005-2012 respectively. Correlation coefficient from 2009-2012 was 0.754 and from 2005-2012 was 0.565, while from 2005-2009 the correlation coefficient was -0.296, which is weak with negative direction.
Figure 10. Image difference file from 2005 to 2009

Figure 11. Highlight change file from 2005 to 2009.
Figure 12. Total erosion and deposition areas from 2005 to 2009.
Figure 13. Total erosion and deposition areas from 2009 to 2012.

Figure 14. Total erosion and deposition areas from 2005 to 2012.
Figure 15. The location of the 14 meanders at Upper Owens River.
Figure 16. Erosion and deposition areas on meander 1 from 2009 to 2012.

Table 2. Erosion and deposition areas of meanders from 2005 to 2009

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Table 2. Erosion and deposition areas of meanders from 2005 to 2009
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<td>Erosion (m²)</td>
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<td>14</td>
<td>223</td>
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<tr>
<td>Total</td>
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</tr>
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Table 3. Erosion and deposition areas of meanders from 2009 to 2012
<table>
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<th>Meanders</th>
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<td>Deposition (m²)</td>
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<tr>
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</tr>
<tr>
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<tr>
<td>Total</td>
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</table>

Table 4. Erosion and deposition areas of meanders from 2005 to 2012
Figure 17. Linear regression analysis of meanders from 2005 to 2009

R² = 0.08812
Figure 18. Linear regression analysis of meanders from 2009 to 2012

Figure 19. Linear regression analysis of meanders from 2005 to 2012
Figure 20. Normalized Difference Water Index NDWI of 2009
Figure 21. Normalized Difference Water Index NDWI of 2012
5. Discussion and Conclusion

Measurements of the lateral erosion and deposition areas of the fourteen meanders at three different times, 42 measurements, indicate that the relationship between lateral erosion and deposition can be classified into two categories. The first result does not show any relationship between the two processes, which was during dry periods. The second result shows a strong relationship between lateral erosion and deposition, which was during wet periods. Total erosion areas of the 14 meanders were higher than deposition areas during wet periods, while during dry periods the deposition areas were higher.

Change detection technique shows the existence of erosion and deposition processes along the riverbanks at Upper Owens River, at three periods; 2005-2009, 2009-2012, and 2005-2012. Also, it shows that the river has an obvious direction of migration, where the erosion occurred on one side of the riverbanks; east during wet periods and west during dry periods.

Change detection technique from 2005 to 2009 shows that the total deposition areas were higher than erosion areas; it was more than twice the erosion areas. The deposition areas for each meander were higher than deposition areas except meander 2 (Table.2), but the difference between deposition and erosion is 8 m². This result is consistent with the weather data during the test periods, especially during 2007, where the total snowfall was 121.9 inches (Table.1). Also, Normalized Difference Water Index (NDWI) showed that the maximum value of water body pixels in 2009 was 0.29 which is lower than 2012 which was 0.737.
Erosion processes in a fluvial environment depend on discharge as the main factor to erode sediment from riverbanks. When the amount of discharge decreases the erosion process decreases too. During a dry season there is no erosion so the relationship between erosion and deposition does not exist. This is reflected by the linear regression analysis which shows an R squared value of 0.0881. Erosion process from 2005 to 2009 occurred on the west side of the river, while the deposition occurred on the east. It was clear from the change detection image that the river has west direction of migration.

Change detection from 2009 to 2012 shows that the total erosion areas were higher than deposition areas. And as weather data shows that during this period the amount of snowfall was high, especially in 2010, which was 369.8 inches (Table 2). Moreover, Normalized Difference Water Index (NDWI) of 2012 shows that the maximum water bodies pixels reached 0.737, which is closer to 1. Because the discharge was high during the test period, the erosion areas were larger than the deposition areas. The linear regression analysis shows that the relationship between erosion and deposition was strong, where R squared value = 0.5698 because the erosion was driving the deposition. Change detection image from 2009 to 2012 shows that the river has an eastward direction of migration where the erosion process occurred on the east side of the riverbank.

The test period from 2005 to 2012 includes the two categories, which are dry and wet periods; therefore, linear regression analysis shows only a weak relationship between erosion and deposition areas, where R squared value = 0.31963. Although the dry period affects on the linear regression, but the river preserve the direction of migration during the wet period, which was to the east.
During the dry period, the amount of water in Crowley Lake dropped because the amount of discharge from the Upper Owens River that flows to the lake decreased. This is a good indicator regarding the hydrological control on the meander system. Reid (1993) showed that there is evidence for long term change of the river direction, through the explanation for this phenomenon may be related to overall valley deformation associated with periods of resurgence of the Long Valley Caldera.

The study area shows that the river is dynamic, where the processes of lateral erosion and deposition fluctuate in the short term along the riverbanks. The amount of lateral deposition areas from 2005 to 2009 was higher than erosion by 2025 m², while from 2009 to 2012 the erosion areas was higher than deposition by 887 m², also, from 2005 to 2012 it was higher by 1196 m². This larger implication of this lies in the pulses of sediment that are being introduced into Crowley Lake.

There remains the question of what processes are responsible for the channel shift during dry versus wet years. Complicating the picture is the observation from the imagery that abandoned oxbows show water occupation during dry years. The redistribution of flow in meanders intrinsically should be a function of deflection by sediment accumulation along the channel bed and banks and variability in discharge. Is there a critical volume of sediment that gradually or episodically shifts flow? If so, this question may be answered by field measurement and more continuous acquisition of imagery. An even broader area of investigation would be to detail the actual transport of sediment down channel. There is some evidence that downstream changes do not necessarily result from the movement of bars across the channel or moving progressively from reach-
to-reach (Hooke, 2007). However, in the case of the upper Owens River, meanders showing sharply curving bends reflect more change during the study period.
Reference:


