Extraction of Artificial Lakes in the *Mojos* Culture from Satellite Images

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In the *Mojos* Plain, Bolivia, artificial lakes distribute widely as remains of the *Mojos* Culture. The artificial lakes were supposed to function as fish cultivation and reservoirs for agriculture. The objective of this study was to extract artificial lakes and river systems from SAR images with image processing and to identify the distribution of the artificial lakes for the preliminary research on the *Mojos* Culture. 700 artificial lakes and 380 natural lakes were extracted from 136 scenes of SAR images, and the shape factor distinguished between natural and artificial lakes. Fractal dimensions were also used for discrimination between natural and artificial lakes, but difference of the values for mass and edge fractals was small and the discrimination was difficult. The center location of artificial lakes was at 14°25′S and 65°15′W, 60 km northwest of Trinidad, the capital of *Beni* State. Big artificial lakes distribute in upper streams of the *Beni* and *Mamore* Rivers, and they might relate with agriculture irrigation, while most of small artificial lakes distribute along the *Mamore* River and their function might be fishing and aquaculture in a small scale.

Key words: Fractal, Image Processing, *Mojos* Plain, SAR, Shape Factor

1. Introduction

In archeology, selection of a survey site for an excavation is very important. Thus, the survey site of the excavation should be determined through a careful preliminary research. When the survey site of the excavation is determined suitably, collecting samples in the excavation is developed efficiently. Then, destruction of the remains becomes the minimum and the remains are conserved enough (Iwasaki, 1998).

The remote sensing is a possible method to select the survey site of the excavation efficiently from the wide objective area. Then, the remote sensing is very effective in the preliminary research for the objective area where research access is difficult (Sakata, 2002). Especially, synthetic aperture radar, SAR is a very powerful tool to detect water body, groundwater and archeological remains (Ohuchi, 2004).

Artificial lakes distribute as the remains of the *Mojos* Culture in the *Mojos* Plain (Denevan, 2001). The *Mojos* Plain is this study's objective area. Artificial lakes had functions as fish cultivation and reservoirs for agriculture (Erickson, 2000, 2001). Therefore, the center of locations for the lakes would relate with the focus of the *Mojos* Culture. Then, this study extracted images of lakes and river systems from JERS-1/SAR and identified the center in the distribution for the ground survey. JERS-1 is Japanese earth observation satellite with SAR (Synthetic Aperture Radar), which is an active microwave sensor and reacts with water body (JAXA, 2012).

2. Materials and Method

2.1 *Mojos* culture

The *Mojos* Plain is in the Amazonia north region of *Beni* State, Bolivia as shown in Fig. 1. Mixed forests cover over 2,000 km^2 of the land, and savannas and swamps extend about 90,000 km^2 in this plain. A third of the plain becomes in a ponding state by river flooding in a rainy season.

The *Mojos* Culture, which prospered in the *Mojos* Plain, had advanced civil engineering and irrigation technology. The origin of this culture started thousands years ago. Most the remains of this culture include a *loma* (an artificial mound), a *terraplen* (a road), a canal, the cultivated field, and an artificial lake, which are still observable as land scape. Those remains distribute in the plain and inside the rain forest in the Amazonia. The *loma* is an artificial mound, which was constructed to protect people from flooding and also was estimated to use as grave because of discovery of human remains. The *terraplen* is an artificially raised road and connects each *loma* as networks.

More than 2,000 artificial lakes might exist in the plain as shown in Fig. 2. Most of the artificial lakes direct to northeast and their perimeter form is a rectangle. The depth of the lake is fixed about 2 m deep in the center of the lake. The artificial lake was estimated to be used as a reservoir and fish cultivation (Denevan, 2001; Erickson, 2000, 2001; Sanematsu, 2004; Imai, 2007).

2.2 Data used

The data used in this study is 136 images of JERS-1/SAR in total. As shown in Fig. 3, JERS-1/SAR is a gray-scale image with 18-m resolution. The path numbers are from 412 to 425, and row numbers are from 319 to 329. The objective area is about 700 km by 1000 km (Fig. 1).

Fig. 1. Objective area.

Fig. 2. Artificial lake from the airplane.

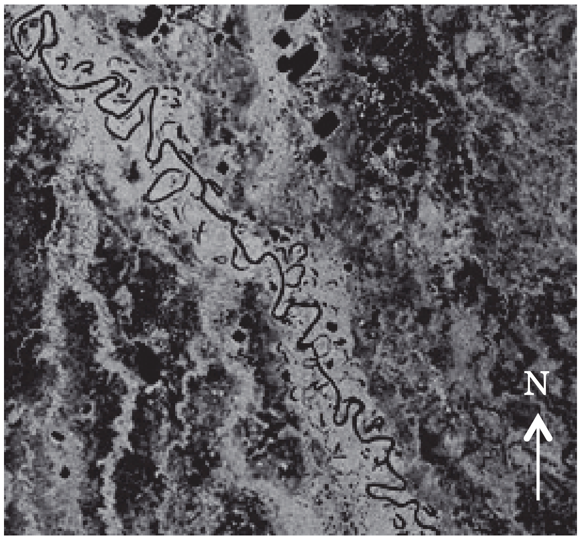

Fig. 3. SAR image for the objective area.

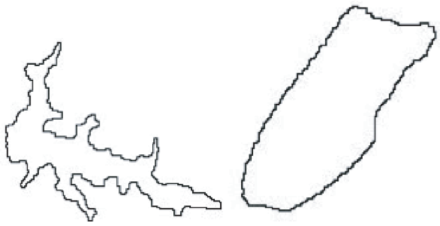

Fig. 4. Natural lake (left) and artificial lake (right).

2.3 Extraction of artificial lakes

First, SAR images were resized in 1/2, and then the speckle noise was reduced (Takagi and Shimoda, 2004). Next, binarization was processed with thresholds (Takagi and Shimoda, 2004) and lakes were extracted. A threshold value for binarization was determined by 0.4 to 0.6 times of the mean of pixel digital values in the image with visual judgment. Next, noises in the binary image were removed with the reduction and expansion processes. Finally the shape factor each object in the image was obtained on the labeling process (Takagi and Shimoda, 2004).

The shapes of natural and artificial lakes are obviously different as shown in Fig. 4. Therefore, the objects with more than 1000 pixels and less than 5 of shape factor value were extracted as an artificial lake. The lakes with less than 1000 pixels are difficult to distinguish between artificial and natural lakes because of resolution in the image.

The shape factor φ is a coefficient indicating the object's irregularity and expressed by the following equation (Takagi and Shimoda, 2004).

$$\varphi = \frac{P^2}{4\pi S} \geq 1 \tag{1}$$

where the S is the area and the P is the perimeter. If the object is a circle, φ becomes 1.

Finally, the artificial lakes were discriminated from natural lakes with their characteristic rectangle form.

2.4 Center location of the artificial lakes

After extraction of the artificial lakes, the geometric correction and mosaic process (Takagi and Shimoda, 2004) were performed with UTM values of four corners each image. Finally, the center location of artificial lakes was determined by averaging their coordinates with weights of the area.

2.5 Extraction of river

River systems were divided into the main river and tributary river systems, and extracted respectively, because the meandering features are quite different depending on the width of rivers. Then, the river systems were composed of two different types of images.

In extraction of the main river systems, first, the binarization was performed for images resized in 1/2. The threshold was 0.65 times of the mean of digital values in the image. Next, noises in the image were removed with reduction and expansion processes (Takagi and Shimoda, 2004). Finally, the density was calculated with labeling (Takagi and Shimoda, 2004), and the objects with less than 0.12 of the density value were extracted as the big river systems. The density is defined by the ratio of connecting black pixels in each rectangle image surrounding the connecting black pixels (Takagi and Shimoda, 2004).

In the tributary river systems, the binarization was per-

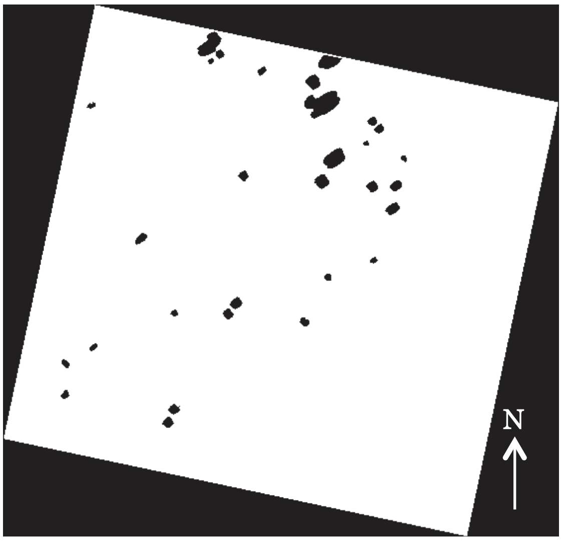

Fig. 5. Extraction image of artificial lakes.

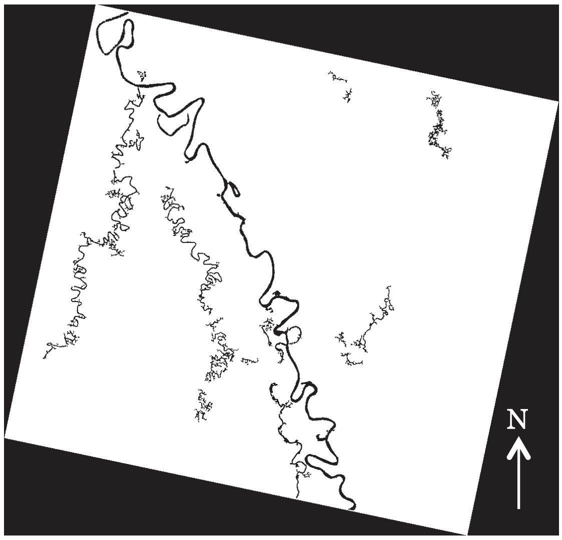

Fig. 6. Extraction image of river systems.

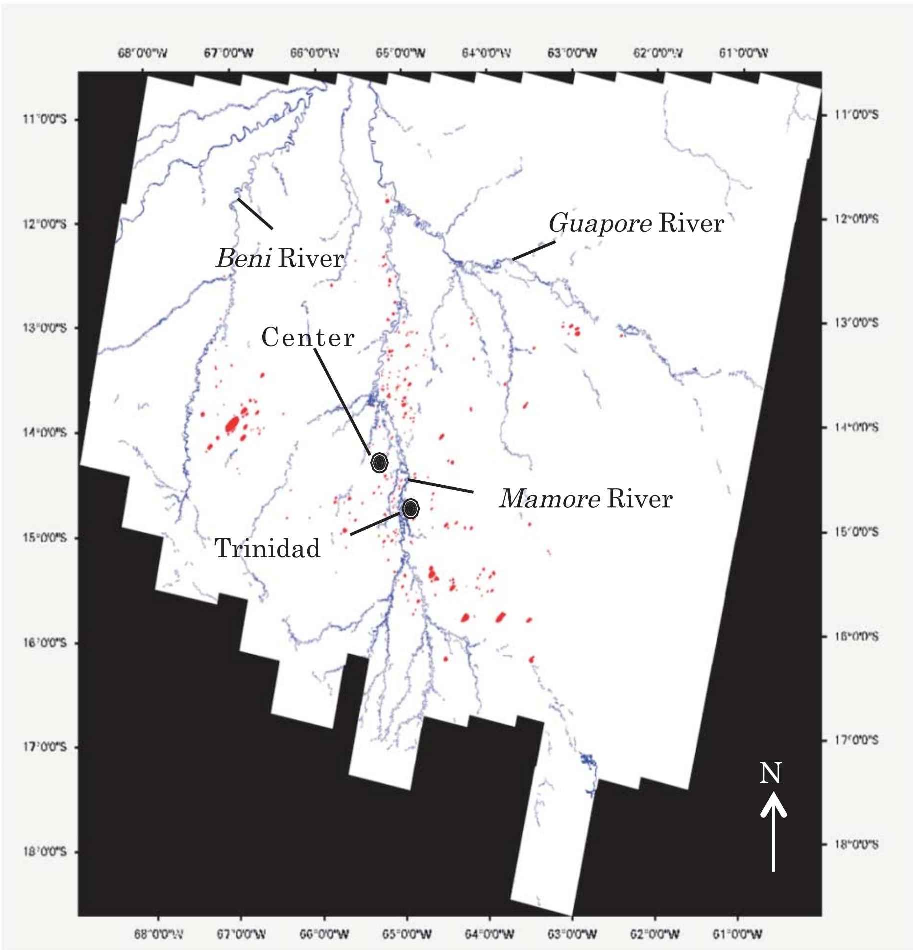

Fig. 7. Center location of the artificial lakes. It was at 14°25′S and 65°15′W, 60 km northwest of Trinidad, the capital of *Beni* State. Red objects are artificial lakes and blue lines are extracted rivers.

formed in images resized in 1/2. In this case, the threshold was determined by subtracting the standard deviation from the average. For the purpose of removal of noises, isolated points were removed. Next, the reduction and expansion processes (Takagi and Shimoda, 2004) were performed for connection of the divided objects. The labeling was performed in the picture and the object with over 13000-pixel area and over 30 of the shape factor was extracted. Finally left noises were deleted visually. The threshold used for extraction in the main and tributary river systems was cal-

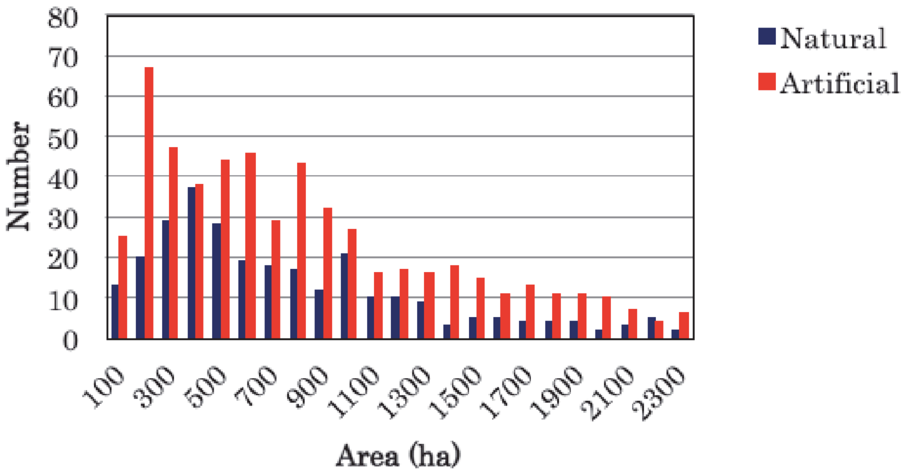

Fig. 8. Histogram of natural and artificial lake area (ha).

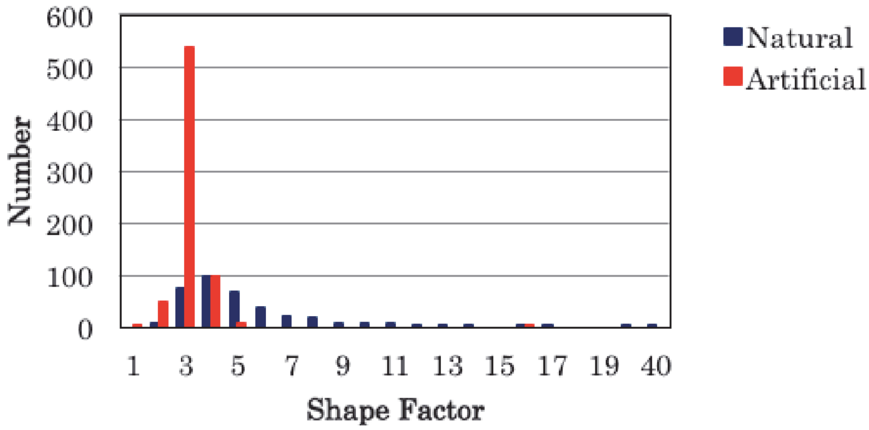

Fig. 9. Histogram of shape factors for artificial and natural lakes.

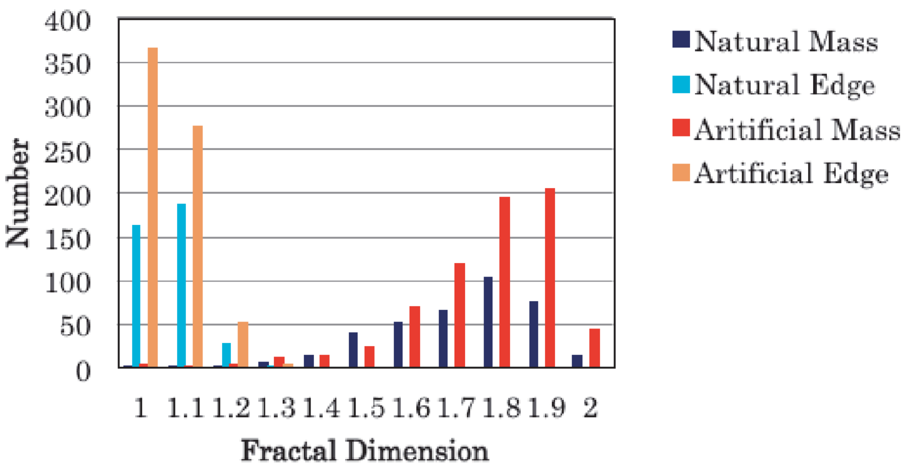

Fig. 10. Histogram of fractal dimensions for artificial and natural lakes.

Table 1. Means and the standard deviations of shape factor.

Natural lakes	Artificial lakes
4.18 (1.21)*	2.54 (0.54)

*The mean of shape factors for natural lakes is in a logarithmic normal distribution. Values in the parentheses indicate the standard deviations.

Table 2. Fractal dimensions.

Natural lakes		Artificial lakes	
Mass	Edge	Mass	Edge
1.66 (0.18)	1.02 (0.06)	1.71 (0.17)	1.01 (0.07)

*Values in the parentheses indicate the standard deviations.

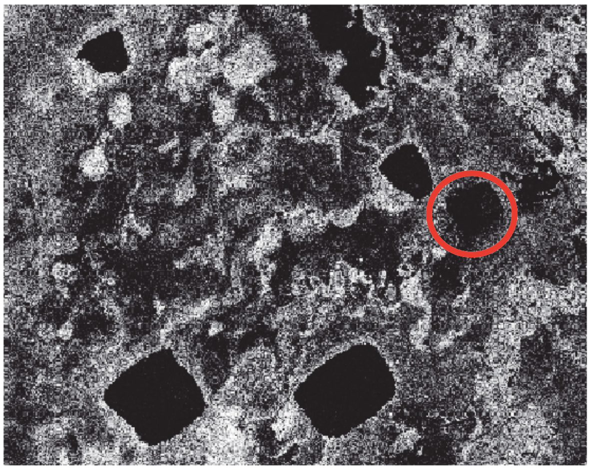

Fig. 11. Image of artificial lakes. Red circle shows gray lake image.

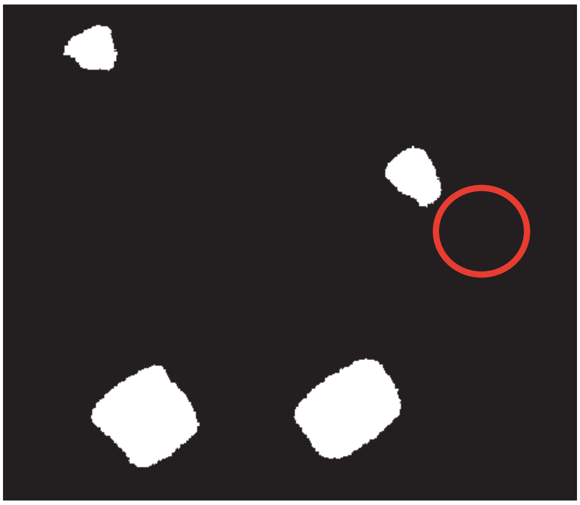

Fig. 12. Extracted image of artificial lakes. The gray lake image disappears.

culated from an empirical rule (Sakurai *et al*., 2005).

2.6 Fractal dimensions

Fractal is irregular shape figures with self-similarity, indicated by fractal dimensions (Mandelbrot, 1982). Rivers are typical fractal. In lake figures, two kinds of fractals exist, mass fractal and edge fractal. Fractal dimensions are calculated with a box counting method (Mandelbrot, 1982). The box counting is a practical method to calculate fractal dimensions by the slopes of log-log plots for the resolution and numbers of pixels in the object with coarse graining.

Relationship between the perimeter and the area for lakes is expressed as next.

$$P = aS^{D/2} \tag{2}$$

where a is a coefficient and D is a fractal dimension.

Substituting (2) into (1),

$$\varphi = \frac{a^2}{4\pi} S^{D-1}. \tag{3}$$

This equation is relationship between a shape factor and a fractal dimension.

3. Results

3.1 Extraction of artificial lakes and river systems

Figure 5 shows the result of extraction for artificial lakes. From 136 images, 700 artificial lakes and 380 natural lakes were extracted. Figure 6 shows the result of extraction for river systems. The main river systems were extracted accurately.

Most of artificial lakes were extracted as a black feature. However, some lakes were not extracted. In the case of tributary river systems, pixels of intricately serpentine rivers were connected each other and then these pixels were not extracted as tributary river systems accurately. The pixel intensity of tributary rivers was weaker than the main rivers.

Figure 7 shows the extracted image of artificial lakes and river systems in the total objective area. Most of artificial lakes direct to northeast along the *Mamore* River, which flows north in the center of the *Mojos* Plain. Large artificial lakes distributed along the upper *Mamore* River and the upper *Beni* River. Artificial lakes did not distribute along the western *Beni* River or the northern *Guapore* River, Brazil.

3.2 Center location of artificial lakes

Figure 7 shows also the center location of artificial lakes. The center location of artificial lakes was at 14°25′S and 65°15′W, 60-km northwest of Trinidad, the capital of *Beni* State.

3.3 Shape factor and fractal dimensions

Figure 8 shows a histogram of the area for natural and artificial lakes. Natural lake areas are a logarithmic normal distribution with the mean of 250 ha in a logarithmic normal distribution, while artificial lake areas are also a logarithmic normal distribution with the mean of 215 ha in a logarithmic normal distribution. Table 1 shows the results of shape factor for natural and artificial lakes and Fig. 9 shows a histogram of the shape factor. The shape factor for natural lakes is a logarithmic normal distribution with the mean of 4.18 in a logarithmic normal distribution, while the shape factor for artificial lakes is a normal distribution with the average of 2.54. Table 2 shows fractal dimensions calculated for natural and artificial lakes and Fig. 10 shows a histogram of the fractal dimensions. The mass and edge fractal dimensions for natural lakes are 1.66 and 1.02, respectively, while the mass and edge fractal dimensions for artificial lakes are 1.71 and 1.01, respectively. They are very near each other.

4. Discussion

The center of the artificial lakes is near Trinidad where many people live at present. The Amazon brings flooding every year. However, in a dry season people have a little rainfall and small amount of discharge in the Amazon River, therefore people need also irrigation for agriculture from the lakes in the dry season. Development of big artificial lakes might relate with agriculture irrigation. No artificial lake is in the flooding area and few people live there still today.

On the other hand, most of small artificial lakes distribute along the *Mamore* River. Obviously the function of these small lakes is different from the big lakes. Probably they were used for fishing and aquaculture.

Most of artificial lakes were extracted as a black feature in Fig. 11. However, some lakes were not extracted. When the lake water becomes dry, the SAR image becomes gray. Such a lake could not be extracted as shown in Figs. 11 and 12. On the process of extracting, the gray image became the background.

If the lake size is less than 1000 pixels with 18-m resolution, these lakes also disappear in the binary image for this algorithm. In total, among about 2000 lakes, 1080 lakes were extracted. Disappearing lakes size should be less than 324000 m^2, which could function for fishing, aquaculture and the daily life, out of big scale water control.

5. Conclusions

This paper described that the preliminary research by remote sensing should be carried out to determine the optimum remains among many archaeological remains distributing widely at shortest and most efficiently. This paper calculated the center location for the artificial lake distribution in the *Mojos* Plain from satellite data. Our conclusions were the next.

1. 700 artificial lakes and 380 natural lakes were extracted by judging their features from SAR images. The center location of artificial lakes was at 14°25′S and 65°15′W, 60 km northwest of Trinidad, the capital of *Beni* State.
2. The shape factor for natural lakes was a logarithmic normal distribution with the average of 4.18, while the shape factor for artificial lakes was a normal distribution with the average of 2.54. The mass and edge fractal dimensions for natural lakes were 1.66 and 1.02, respectively, while the mass and edge fractal dimensions for artificial lakes were 1.71 and 1.01, respectively.
3. In a dry season people have a little rainfall and small amount of discharge in the Amazon River, therefore people need also irrigation for agriculture from the lakes. Development of big artificial lakes might relate with agriculture irrigation. On the other hand, most of small artificial lakes distribute along the *Mamore* River. Obviously the function of these small lakes might be different from the big lakes. Probably they were used for fishing and aquaculture in a small scale. But most of the lakes in the *Mojos* Plain were in a small size.

As a future assignment, the objective research site should be selected by extracting *lomas* and *terraplens* using satellite data and evaluating the total culture as public construction networks. Therefore, the comprehensive algorithm to evaluate topographic maps, DEM, ALOS/visible, infrared, and SAR will be required as the next step.

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