Beyond modern landscape features: New insights in the archaeological area of Tiwanaku in Bolivia from satellite data

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ABSTRACT

The aim of this paper is to investigate the cultural landscape of the archaeological area of Tiwanaku (Bolivia) using multiscale, multispectral and multitemporal satellite data. Geospatial analysis techniques were applied to the satellite data sets in order to enhance and map traces of past human activities and perform a spatial characterization of environmental and cultural patterns.

In particular, in the Tiwanaku area, the approach based on local indicators of spatial autocorrelation (LISA) applied to ASTER data allowed us to identify traces of a possible ancient hydrographic network with a clear spatial relation with the well-known moat surrounding the core of the monumental area. The same approach applied to QuickBird data allowed us to identify numerous traces of archaeological interest, in Mollo Kontu mound, less investigated than the monumental area. Some of these traces were in perfect accordance with the results of independent studies, other were completely unknown. As a whole, the detected features, composing a geometric pattern with roughly North–South orientation, closely match those of the other residential contexts at Tiwanaku.

These new insights, captured from ASTER and QuickBird data processing, suggested new questions on the ancient landscape and provided important information for planning future field surveys and archaeological investigations.

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1. Introduction

The investigation of ancient land-use patterns represents an important issue in a number of disciplines ranging from archaeology, botany, forestry, soil science and hydrology, etc. Information on the impacts of human actions upon the environment can be widely used to address issues in human settlement, to better understand environmental interaction, climate change, the Earth’s system, etc.

The term cultural landscape is frequently used by archeologists to indicate the human action on environment and the subsequent modifications occurred over the following centuries and millennia. Although traces of human impact may still today be fossilized in the modern landscape, their identification and interpretation is one of the most complex archaeological and historical issues.

Remote sensing technologies offer a synoptic view and reliable data sources which are very useful to extract information about the contemporary landscape and make possible, in some conditions and to some extent, to infer changes in the former environment.

Since the thirties of the last century (Lasaponara and Masini, 2011), aerial photography has been the first remote sensing technique employed to reveal lost landscape. Beginning from the eighties, early studies on palaeo-environment and archaeological landscapes were conducted using satellite data acquired from both active and passive sensors.

In the last decade, the availability of very high resolution (VHR) satellite images (Ikonos in 1999, QuickBird in 2001, WorldView1 in 2007 and GeoEye in 2008) opened new perspectives in archaeology. These data sets appeared particularly effective in recording archaeological spatial features (Lasaponara and Masini, 2011) because human activity leaves distinctive marks on the surface. These are generally called damp, soil and crop marks (Masini and Lasaponara, 2007) and are due to the differences in moisture content, porosity, vegetation phenology and/or status caused by the presence of buried archaeological remains. In particular, the presence of stones or buried walls determines a limitation on moisture and nutrient content, thus causing an increase in the rate of germination and differences in vegetation growth patterns. Vice versa pits and ditches induces an increase in the rate of vegetation growth being that they are characterized by a greater depth of soil, major concentration of water and nutrient compared to the surroundings. Crop marks are most easily visible during specific periods of the year according to the specific plant phenology and meteorological conditions.

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For bare soil the presence of buried walls or pits and ditches may be visible due to the diverse characteristics and surface conditions of topsoil, such as, diverse grain sizes and/or different colors compared to the surrounding topsoil. Therefore, soil marks are most easily visible from space or aerial view in low light conditions, or after raining due to the diverse spatial patterns of moisture content.

Nevertheless, it is worth to note that as for other applications also in archaeology, features of interest are generally not isolated, but mixed with others and may also appear quite different within the same image due to their diverse physical characteristics.

Moreover, archaeological features generally do not exhibit clear and clean patterns and/or edges even in high-resolution data sets acquired from both active and passive sensors. This is due to the fact that archaeological marks are characterized by subtle spatial/spectral signals. In addition, it must be considered that there are numerous factors, such as noise, atmospheric contaminations, etc. that tend to further distort subtle edges and features. To face these challenges and collect as much information as possible, the use of robust data processing techniques is required.

In this paper, geospatial analysis techniques were applied to the satellite data in order to enhance and map trace of past human activities in the archaeological area of Tiwanaku (Bolivia).

Investigations based on ASTER and very high-resolution satellite data (QuickBird) were conducted mainly in a sector located at south of the monumental core area, less investigated compared to other sector of Tiwanaku.

2. Study area

2.1. Geographical and geological setting

Tiwanaku is located on a valley at 3880 m above sea level, near the southern shoreline of the Titicaca Lake (Fig. 1). It is geologically characterized by 10–20 m of Quaternary lacustrine and fluvial deposits laid on a bedrock composed of andesites and basalts. The valley is bordered by the Cordillera Real and Cordillera Blanca, and it is composed of Paleozoic andesites, sandstones, and red mustones (Argollo et al., 1996; Knudson, 2008)
2.2. Historical and archaeological context

Tiwanaku was the center of a prehispanic civilization which influenced large territories of south-central Andes for more than six centuries, from AD 500 to AD 1150 (Kolata, 1993; Janusek, 2004).

Concerning the archaeological interpretation related to the type and function of Tiwanaku, there are currently three intellectual traditions (Janusek, 2004):

(i) the symbolic and ritual significance was emphasized by an old tradition of archeologists who considered Tiwanaku an uninhabited ceremonial center;
(ii) according to a later and dominant intellectual tradition, Tiwanaku was the densely inhabited capital of a centralized state which aggressively conquered large regions at South and North of the Titicaca Lake. In this way the Tiwanaku civilization was able to build an empire which controlled much of the south-central Andes;
(iii) finally, a more recent line of thought argues that Tiwanaku was a federation of autonomous groups.

Archaeological records attest a long history traditionally divided in three chronological periods: (I) Late Formative (100 BC to AD 500), when Tiwanaku emerged as major regional center along with Lukurmata; (II) Tiwanaku period (AD 500–1150), during which the site became a densely inhabited center of a pan-regional state. Its political and economic leading role in the southern-central Andean context ended between 1000 and 1150 due to environmental factors (long-term drought) and social-cultural-political dynamics.

The III period (AD 1150–1450) was characterized by the resurgence of regional identities and polities.

Fig. 2 shows three multitemporal satellite scenes of the monumental area from QuickBird (June 2003), in Fig. 2(a), and Google Earth (July 2009 and July 2012), in Fig. 2(b) and (c), respectively. The most remarkable monuments are indicated in Fig. 2 and are Akapana (1), Kalasasaya (2), Templete (3), Kantatalita (4), Putuni (5), Mollo Kontu mound (6), and Puma Punku (7).

The multitemporal images put in evidence some changes, among them, (i) the urbanization at west of the monumental area and (ii) the dynamics and enlargement of the excavation in the Akapana area.

3. Satellite data processing

Satellite data can provide invaluable information for archaeology and palaeo-environmental studies, nevertheless, the identification and extraction of the features of interest may pose serious challenges related both to data processing and interpretation. The use of robust data processing techniques is required to identify, extract and collect as much information as possible. The data processing rationale and methods used for QuickBird (Sections 3.1 and 3.2) and ASTER (Section 3.2) data are described below.

3.1. Data fusion

The use of data fusion techniques can fruitfully improve the enhancement of archaeological marks and make their detection easier by exploiting both the higher spatial resolution of the panchromatic image and the multispectral properties of the spectral channels (Aiazzi et al., 2007). Moreover, another advantage of
using data fusion products is that the increased spatial resolution can fruitfully provide a more accurate localization of the archaeological features. This more accurate localization, from the initial spatial resolution of multispectral data around meter (2.4 m for QuickBird, 2 m for GeoEye) to the sub-meters spatial resolution of panchromatic (0.6m for QuickBird or 0.5 m for GeoEye) can be very helpful during in situ survey, such as GPS (Global Position System) campaigns, geophysical prospection or excavation trials.

Over the years, a number of algorithms have been developed for data fusion, among them we selected the Gram Schmidt (GS) panchromatic sharpening (Brower and Laben, 2000), because it was successfully applied in a number of archaeological data analysis (Lasaponara and Masini, 2012).

It is based on the Gram Schmidt transformation using the following steps:

(i) panchromatic simulation by averaging the multispectral bands;
(ii) GS transformation using simulated panchromatic scene, assumed as the first band, and the MS bands;
(iii) panchromatic replaces the first GS component;
(iv) the inverse GS transform to obtain the pan-sharpened products.

In this study, this approach was only applied to QuickBird satellite images, being that it is based on the joint elaboration of panchromatic and multispectral channels.

3.2. Spatial autocorrelation

In the analysis of satellite image, spatial autocorrelation is a very useful tool since it enables us to jointly consider the value of the pixel (reflectance, temperature, and spectral index) and its spatial relationships with its surrounding pixels in a given window size.

Global measures of spatial autocorrelation provide a single value that indicates the level of spatial autocorrelation within the variable distribution, namely the homogeneity of a given values within the image under investigation.

The Global indicators of autocorrelation utilize distance to define the neighborhood of a region and measure if and how much the dataset is autocorrelated in the entire image.

One of the principal global indicator of autocorrelation is the Moran’s index I (Moran, 1948), defined in formula (1)

\[
I = \frac{N}{\sum_{i,j} w_{ij}(X_i - \bar{X})(X_j - \bar{X})}{\left(\sum_{i,j} w_{ij}\right) \left(\sum_{i} (X_i - \bar{X})^2\right)}
\]

where, \(N\) is the total pixel number, \(X_i\) and \(X_j\) are intensity in points \(i\) and \(j\) (with \(i \neq j\)), \(\bar{X}\) is the average value, \(w_{ij}\) is an element of the weight matrix.

\(I \in [-1; 1]\); if \(I \in [-1; 0]\) there’s negative autocorrelation; if \(I \in (0; 1]\) there’s positive autocorrelation.

Theoretically, if \(I\) converges to 0 there’s null autocorrelation, in most of the cases, instead of 0, the value used to affirm the presence of null autocorrelation is given by Eq. (2):

\[
E(I) = -\frac{1}{N - 1}
\]

where \(N\) is the number of events in the whole distribution.

The second global indicator of spatial autocorrelation is the Geary’s C (Geary, 1954), expressed by formula (3):

\[
C = \frac{(N - 1)}{2w_{ij}} \frac{\sum_{i,j} w_{ij}(X_i - X_j)^2}{\left(\sum_{i} (X_i - \bar{X})^2\right)}
\]

where symbols have the same meaning than expression (1).
that typically range from approximately +1, representing complete positive spatial autocorrelation, to approximately −1, representing complete negative spatial autocorrelation.

(iii) Local Geary’s C index allows us to identify edges and areas characterized by a high variability between a pixel value and its neighboring pixels.

These geostatistical analysis tools are available in several commercial software, ranging from Geographic Information System (GIS) and image processing as well as in open source codes (GRASS).

Finally, to further improve edges and features linked to subsurface archaeological remains some convolution filters. In particular, the best results in terms of edge enhancement have been obtained by using convolution directional filter angle (Lillesand and Kiefer, 2000) based on first derivative that selectively enhances image features having specific direction components (gradients).

4. Results and discussion

The above described methodological approach was applied to QuickBird (Sections 3.1 and 3.2) and ASTER (Section 3.2) data set. In particular, we focused on VNIR and SWIR bands in order to extract multitemporal spatial and spectral patterns of vegetation and moisture content, and therefore, to identify anomalies referable to remains of past human activities.

Using ASTER data (see white box in Fig. 3), we investigated the entire monumental area including a tributary of the Tiwanaku river, the moat in front of the east side of the monumental area and other hydrographic features.

Using QuickBird imagery, we mainly focused on the anomalies previous detected using ASTER data along with the southern part of Tiwanaku.

Fig. 4a and b show the RGB compositions of three VNIR (V3B, V2 and V1) and SWIR (S6, S5 and S4) bands, respectively. Image 4a

Fig. 5. The features detected from VNIR bands of Aster in Fig. 4(a) have been emphasized by applying Moran index to V3b band (a) and the convolution filtering (b).
puts in evidence high values of near infrared bands (mainly V3b channel) which enable the identification of two distinct patterns:

(1) the first pattern exhibits a quadrangular shape and borders Akapana and Kalasasaya complexes (indicated by the orange arrows in Fig. 4(a) linked to the presence of the moat which is also clear visible in the QuickBird false color image (Fig. 3)

(2) the second pattern is located in the southern part of the monumental area (see black arrows in Fig. 4(a)) and also exhibits a quadrangular shape.

Both of these patterns are enhanced by LISA. In particular, the best results were provided by the Moran index (as showed in
Fig. 5(a), which was further emphasized by using convolution direction filtering (Fig. 5(b)).

What is undoubtedly evident (also by Fig. 5(a) and (b)) is the alignment of the eastern sides of these two patterns. This suggests the fascinating question: is this signal referable to a buried ditch which is perfectly aligned with the east side of the known moat?

The spectral behavior exhibited by the ASTER VNIR band typically characterizes crop marks and well fits with the anomalies visible in the RGB composition of SWIR bands (in Fig. 4(b)). This also suggests the presence of high moisture content. In Fig. 4(a) and (b) additional features are also evident, such as: a tributary of the Tiwanaku river (indicated by white arrows) and a canal connecting the above said tributary with the moat (see green arrows). Finally, the blue arrows indicate another possible canal connecting the moat with the above said southern pattern. This canal is more evident from the QuickBird false color composite shown in Fig. 6(a). As previously obtained in the case of ASTER data processing (Fig. 5(a)), the Geary index applied to NIR band better enhanced, compared to the other local indices, the spatial features and allowed an accurate mapping of the canal (Fig. 6(b)).

One more question arises: which is/was the function of this canal? In recent times this and other similar canals may be used for water drainage during wet seasons to mitigate flooding especially during intense rainfall.

What was its function in the past? Maybe the same, to protect from flooding an important area as it was due to the presence of Mollo Kontu mound and area around, where surveys and excavations revealed materials related to Middle Formative settlements and a Late Formative occupation (Blom et al., 2003). Moreover, probably the canal was connected with a system of ditches and canals as the ovoidal one which surrounded and still surrounds Mollo Kontu mound (see Fig. 3).

In order to obtain additional information we focused on QuickBird images which were processed using pan-sharpening and LISA. Interesting results have been obtained just on Mollo Kontu mound which we focused because previously less investigated than to its surrounding area.

Satellite data emphasizes external features of the mound related to terraced platforms. On the top of Mollo Kontu, results obtained from Moran and Geary indices applied to panchromatic and NIR band show interesting archaeological features (Fig. 7 shows) which seems to be part of perimeter walls. These feature indicated by the orange arrows in Fig. 7 have been successful compared with the results of independent studies based on geophysical investigations (Spence-Morrow, 2009). These spatial anomalies are linked to excavations proof which unearthed buried walls later back-filled after the exact proof.

Fig. 7 also shows additional spatial anomalies, indicated with green arrows, which support the hypothesis made by Spence-Morrow (2009) on the basis of his magnetic survey. The presence of these anomalies is now confirmed by our satellite based analysis which also provides further additional features. In particular, on the top of the Mollo Kontu mound satellite data processing enable us to find unknown archaeological features indicated by both orange and green arrows), which were not visible from the geophysical prospecting carried out by Spence-Morrow (2009). These internal features are indicated by green dashed lines in Fig. 7(d). Other features shown in Fig. 7(e) composed a geometric pattern with roughly North–South orientation which closely matched those of the other residential contexts at Tiwanaku.

From the computational point of view, the visual comparison of Fig. 7 suggests that Moran enables us to enhance the external feature linked to the perimetal walls, whereas Geary index better emphasizes the internal geometric pattern of anomalies.

Finally, in Fig. 8, all the anomalies already detected from ASTER data (denoted by dashed red lines) have been overlaid on the

QuickBird scene in order to assess the correspondence between results obtained from the two satellite data sets. It is worth to note that ASTER anomalies partially correspond to the traces identified by QuickBird: in particular, the moat and a sector of the eastern side of the southern pattern (inside the elliptical blue box shown in Fig. 8(b)). This is due to different acquisition time and spatial resolution of the two satellite images.

QuickBird imagery confirm the orientation of the moat in the cardinal directions according to the architectural planning of the Kasalasaya, Templete. The orthorectified images enable us to measure the extension of the moat: It is 0.65 km against 0.90 hypothesized by archeologists (Kolata, 1993, 2003) and its width ranging 15–40 m.

As a whole, our satellite investigations based on multiscale and multispectral approach enable us to detect unknown cultural
features which provided new insights in the archaeological area of Tiwanaku.

5. Final remarks

The satellite based investigations conducted using mainly spatial autocorrelation provided useful results to study the modern and ancient landscape of Tiwanaku ceremonial center.

The LISA method significantly enhanced spatial and spectral anomalies for both ASTER and Quickbird satellite data sets. The data processing we adopted made easier the identification and extraction of spatial patterns linked to past cultural landscape. Traces of past human activities were clearly identified. Unknown features were detected along with other already known and in perfect accordance with independent studies. The unknown features we detected in this study provided new insights and suggested new questions on the ancient landscape.

In particular, in the Tiwanaku area, LISA approach applied to ASTER data allowed us to identify traces of a possible system of moats and canals which exhibited a clear spatial relation with the well-known moat surrounding the monumental area; thus suggesting the hypothesis of their temporal and functional relation.

In Mollo Kontu LISA approach applied to Quickbird data allowed us to identify traces of archaeological interest completely unknown before our investigations. These anomalies composed a geometric pattern with roughly North–South orientation which closely matched those of the other residential contexts at Tiwanaku; thus suggesting the presence of buried structures, linked to urban and/or ceremonial function.

References


