Geomorphological map of the Tiwanaku River watershed in Bolivia: implications for past and present human occupation

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Abstract

The Altiplano and more specifically the Titicaca circum-lake sector have recorded several major landscape transformations. In particular, changes in the lake water level lead to a significant vulnerability and contributed to the development of flexible and diverse agropastoral activities of the pre-Columbian and current populations to climate change. The Tiwanaku River, particularly because of the presence of the pre-Columbian Tiwanaku site, has been the subject of several research studies aimed at characterizing the environment of the archaeological site. Here we propose a new synthesis of the geomorphology of the Tiwanaku River watershed based on an interdisciplinary approach (Historical geography and remote sensing, cross combined with field survey). Our results show that the general organization of the drainage system is influenced by lake level and climatic changes. However several watercourses of the Tiwanaku River might be related to pre-Columbian agricultural or proto-urban structures. Our work allowed to estimate the regressive pattern of the coastline of Lake Titicaca and to identify major changes of the terminal and medium watercourse of the Tiwanaku River over the last 70 years.

Keyword: Geomorphological map, remote sensing, historical aerial photography, Titicaca Lake, Tiwanaku River, Bolivia.

1. Introduction

The Altiplano is a high plateau (between 3600 and 4200 m asl (Above Sea Level)) of about 190 000 km^2, surrounded by peaks rising to over 6000 m altitude (Fig. 1A). The Altiplano lacustrine system (Titicaca-Desaguadero-Poopó-Coipasa Salt Lake) is the result of early Pleistocene evolution that induces considerable variations in the lake level (Argollo and Mouguiart 2000, Baker et al. 2001a, Delclaux et al. 2007, Guerin et al. 2001, Revollo 2001, Talbi et al. 1999).

Holocene climatic evolution, identified from the study of lacustrine sediments, shows that Lake Titicaca (7131 km^2, mean depth 100 m, max depth 285 m) and its southern sub basin (Lake Wiñaymarka, 1428 km^2, mean depth 9 m, max depth 40 m) has undergone several major fluctuations (up to 15 m) (Abbott et al. 2003, Abbott et al. 1997, Baker et al. 2001b, Dejoux and Iltis 1992, Delaere 2019, Mourguiart et al. 1998, Rowe et al. 2004, Servant et al. 1995, Weide et al. 2017). Although some sedimentary formations have been described and mapped in the lake's vicinity, few conclusions about the influence of lake level variations on the local sediment routing system or the stratigraphic organization have been proposed (Baucom and Rigsby 1999, Farabaugh and Rigsby 2005, Rigsby al. 2003, Servant and Servant-Vildary 2003). On the other hand, long term archaeological occupation have been found in most valley systems surround Lake Titicaca (Capriles et al. 2014, Craig et al. 2010, Erickson 2000, Hastorf et al. 2005, Silverman and Isbell 2008, Stanish 2003). The valleys located in the southern part of the Lake Wiñaymarka (Tiwanaku, Katari and Desaguadero River), are one example among other that highlight this continuity (Albarracin-Jordan and Mathews 1990, Bandy 2006, Hastorf 1999, Isbell and Silverman 2002, Janusek 2008, Kolata 2003). It has been shown that during Holocene times, some pre-Columbian civilizations emblematic of the central Andean sector have developed, then disappeared possibly related to the lacustrine landscape evolution and prolonged drought (Arnold et al. 2021, Binford et al. 1997, Kolata and Ortloff 1996, Ortloff and Kolata 1992). There is still a strong controversy about the chronology and a lot of critique of the environmentally-driven view of pre-Columbian cultures collapse in Lake Titicaca area (Erickson 1999, Graffam 1992, Bandy 2005, Stanish 2003, Janusek 2004). Taking into account the complex relationship between ancient civilization and their environment, it is needed to understand the interactions between allogenic forcing of the natural system and human adaptations. As such, this paper proposes to establish a reliable cartography of the superficial sedimentary formations at the scale of the watershed of the Tiwanaku River.

Many superficial geological data are available in the Tiwanaku area, but to our knowledge, no attempts have been made to propose a regional geomorphological synthesis at the scale of the watershed. The realization of a new geomorphological map in the Tiwanaku valley aims to better constrain the pattern of geomorphic entities in regards of climatic and anthropogenic evolutions. This work also allows to better define and represent the relationships between the Holocene variations of the lake level and the response of the geomorphological system including the morphologic evolution of the valley. We show that the dynamics of the landscape are still active until recent times attested by the high mobility of the lake coastline and river positions over the last 70 years.

Finally, the occurrence of remnant canals, *sukka kollus* and *kochas* attest that the Tiwanaku valley can be considered as an ancient agricultural landscape as suggested by previous studies (Erikson 2003, Kolata 2003).

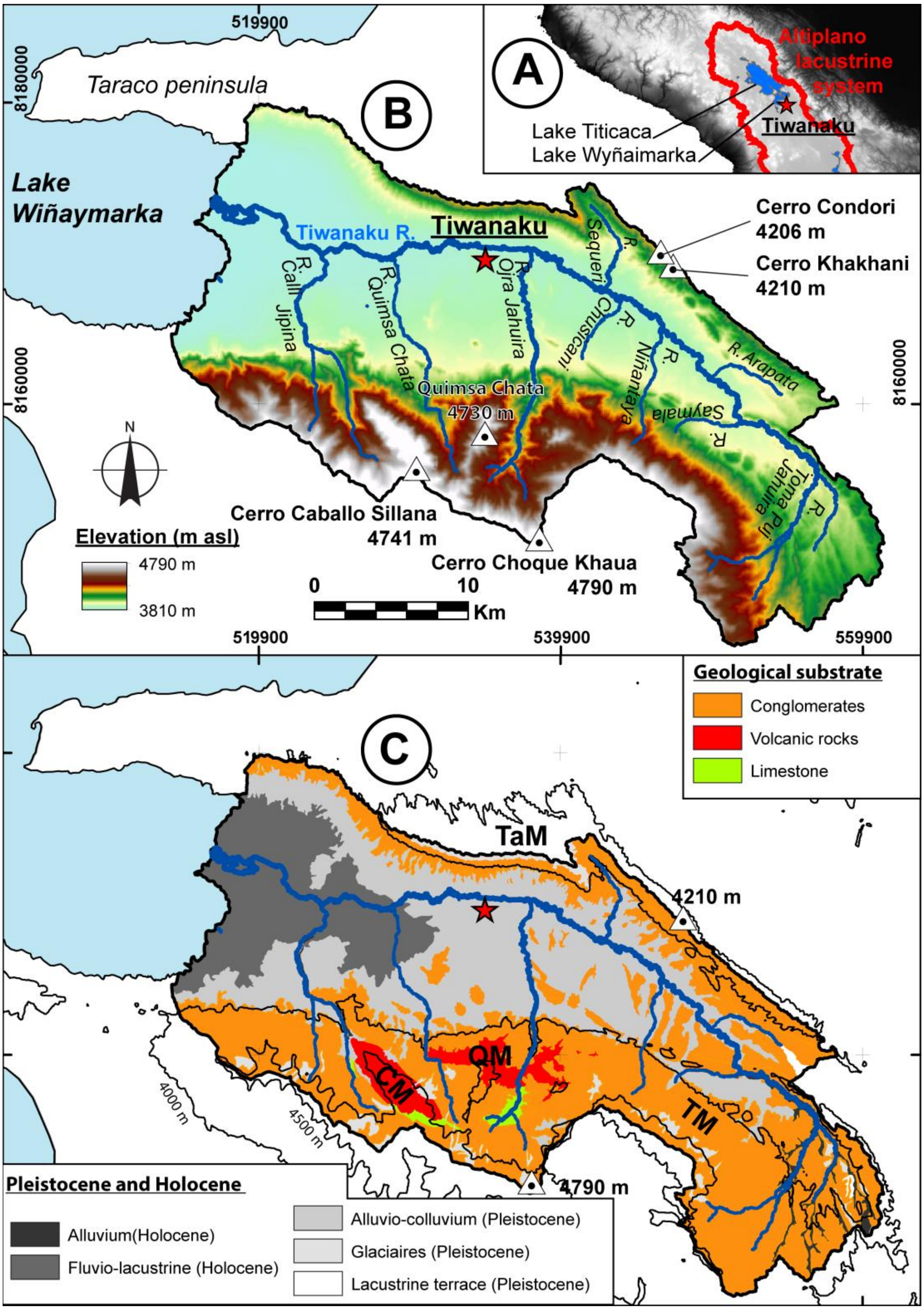

Fig. 1: Geomorphological characteristics of the Tiwanaku watershed. A: Location of the study area in South America. B: Geographical features and main rivers (topography: ASTER GDEM; Coord. System UTM WGS 1984 zone 19S Lat., Long. in meters). **C: Simplified lithology** (after GEOBOL 1994, modified). Tiwanaku mountain range (TM); Chilla mountain range (CM); Quimsa Chata mountain range (QM); Taraco mountain range (TaM).

2. Background

2.1 Geographical context

The Tiwanaku River, east-west oriented, is located 75 km northeast of La Paz. This river, about 64 km long, flows into Lake Wiñaymarka (southern sub lake of the Lake Titicaca) located in the south of the Taraco peninsula (Fig. 1B). The topography of the watershed (~820 km^2) is flanked by the Taraco mountain range on the northern side and the Tiwanaku mountain range on the southern side. The northern flank reaches a maximum altitude of about 4200 m asl (Cerro Condori 4206 m asl, Cerro Khakhani 4210 m asl), the southern slope reaches almost 4800 m asl (Cerro Choque Khaua 4790 m asl, Cerro Caballo Sillana 4741 m asl, Cerro Quimsa Chata 4730 m asl) while the alluvial plain is located at ~3815m asl. The Tiwanaku watershed shows a strong asymmetry with large southern tributaries (from upstream to downstream: Toma Puj Jahuira River, Saymala River, Niñantaya River, Chusicani River, Ojra Jahuira River, Quimsa Chata River, Calli Jipina River) and short northern tributaries (from upstream to downstream: Arapata River, Sequeri River). The pattern of the Tiwanaku River presents a braided morphology in the upstream part evolving to a meandering system in the middle and lower valley. It finally flows in Lake Wiñaymarka by forming a lacustrine delta (3810 m asl).

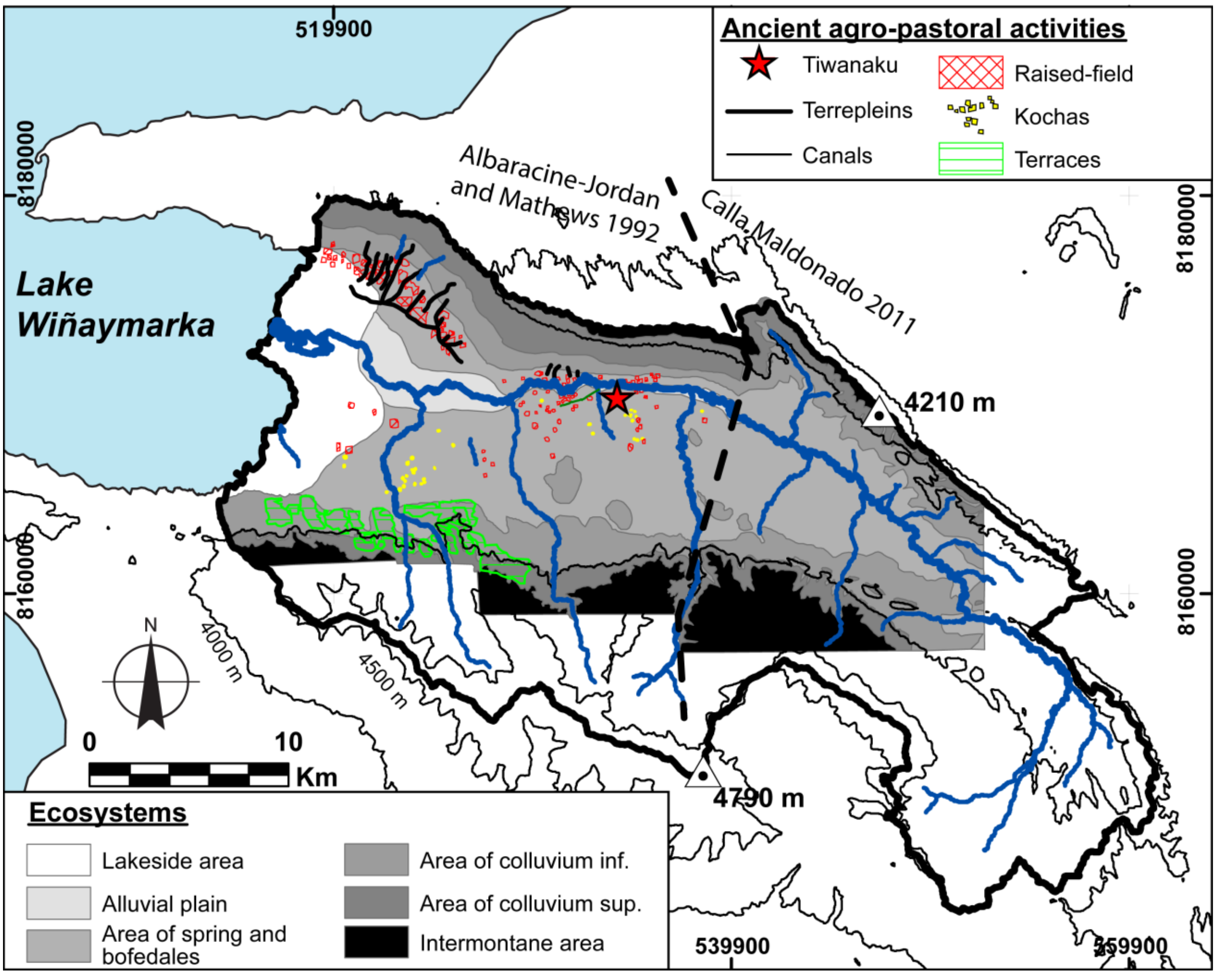

Fig. 2: Geoarchaeological map of the Tiwanaku valley (modified after Albaracine-Jordan and Matthews 1992, Calla Maldonado 2011).

2.2 Geological context

The Tiwanaku watershed is located on the Altiplano that represents a low-relief, internally-drained basin flanked between the Eastern Cordillera (uplifted core of the central Andean fold and thrust belt) and the Western Cordillera (modern volcanic arc) (Baucom and Rigsby 1999). The Altiplano basin is mainly filled with Cenozoic sedimentary and volcanic rocks. The Tiwanaku area is composed of several geological formations roughly linked to the late geological evolution of Atliplano.

The southern part of the Tiwanaku valley is flanked by the Tiwanaku mountain range oriented SE-NW, and composed of highly folded sandstone and argillite dating from the Tertiary (Fig. 1C). This range is connected eastward with the Quimsa Chata massif mainly composed by volcanic rocks and dated from the Upper Miocene. Glacial formations dated from Pleistocene can be mainly observed on this southern flank. The northern flank is characterized by the Taraco mountain range. It is composed of conglomerates of the Coniri, Kollu Kollu (Oligo-Miocene) and Taraco (Pliocene) formations, organized in a NW-SE folded structure (Argollo 2003, GEOBOL 1994). Paleolimnological studies on Lake Titicaca identified large and rapid lake-level fluctuations during the Quaternary (Abbott et al. 1997, Abbott et al. 2003, Delaere 2017, Fritz et al. 2004, Mourguiart et al. 1998, Rowe et al. 2003, Servant and Servant-Vildary 2003, Theissen et al. 2008, Weide et al. 2017). Some lacustrine terraces can be observed in the lower parts of the Tiwanaku valley (between 3815 and 3940 m asl) and are related to Pleistocene high lake stands (Argollo 2003). The Bolivian Altiplano is a tectonically quiescent plateau situated between the fold-and-thrust belt of the eastern Cordillera and the active arc of the western Cordillera (Baucom and Rigsby 1999). The occurrence of tilted paleo shorelines associated to the Pleistocene Lake Minchin and located above the current Titicaca’s shoreline, indicated some large scale tilting processes over the last 17 ky in the central Altiplano (Bills et al. 1994).

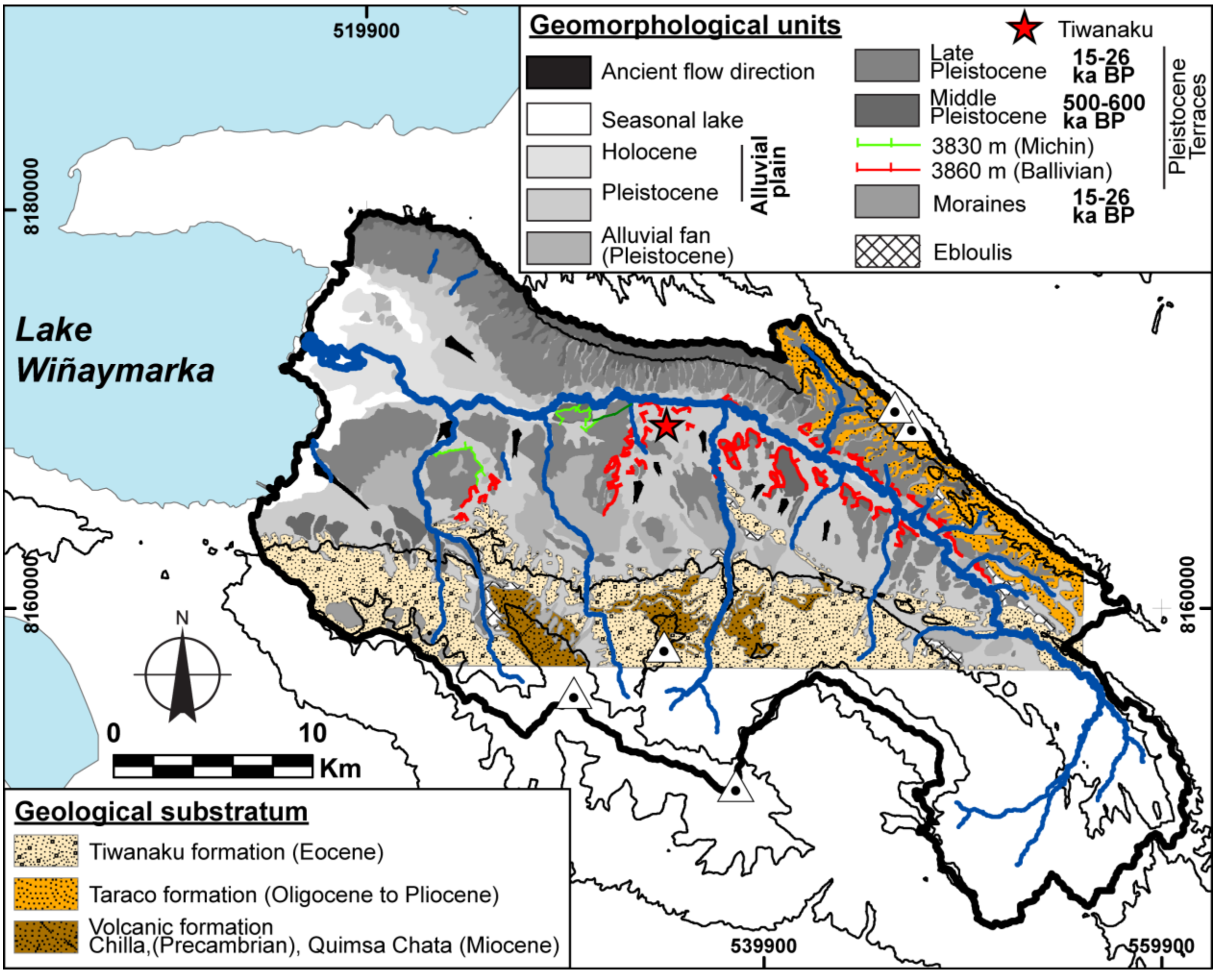

Fig. 3: Geomorphological map of the Tiwanaku valley (after Argollo 2003).

2.3 Holocene alluvial and lake level variations

The fluvial and lacustrine terraces as well as incision features of the Tiwanaku River can be linked to Lake Titicaca variations (Abbott et al. 1997, Baker and Fritz 2015, Delaere 2017, Martin et al. 1993, Mourguiart et al. 1998, Roche et al. 1992, Rowe et al. 2003, Weide et al. 2017).). Annual variations can be correlated to the tropical Andean South American Summer Monsoon rainfall (SASM) (Bird et al. 2011). At a decadal time scale, these variations are linked in response to events such as El Niño-Southern Oscillation (ENSO) (events often associated with a prolonged dry season on the Altiplano and/or a lake-level drops) (Martin et al. 1993, Vuille and Werner, 2005). Records from lacustrine sediments (Abbott et al. 2003, Arnold et al. 2021, Bird et al., 2011), speleothems (Apaestegui et al., 2014), and ice cores (Thompson et al. 2006, Thompson et al 2000, Thompson et al., 1998), suggest that at centennial to millennial timescales precipitation levels in the Altiplano are linked to shifts in the Intertropical Convergence Zone (ICTZ) over the tropical Atlantic and Pacific (Abbott et al. 2003, Arnold et al. 2021).

Lake Titicaca experienced long phases of drought with lake levels sometimes much lower than the current one, in particular around 8 000 BP (Abbott et al. 1997, Abbott et al. 2003, Fritz et al. 2004, Weide et al. 2017, Wirrman et al., 1992).The Late Holocene water-level fluctuations in Lake Wiñaymarka evolved with (i) a minor lake-level rise (6–8 m) around 4000 BP (Wirrmann and Mourguiart 1995), (ii) a rapid 15–20 m lake-level rise around 3500 BP and (iii) 4 major cycles of lake-level transgression and regression during this global high-level stage (3200-2800 cal yr BP, 2200-2000 cal yr BP, 1650-1450 cal yr BP, 900-700 cal yr BP; Abbott et al. 2003, Abbott et al. 1997, Binford et al. 1997). Studies from the main basin of Lake Titicaca (Baker et al. 2001a, Seltzer et al. 1998) indicate that Lake Titicaca was below the modern spill level until at least 3000 BP. The current period reached a maximum lake level in the 17th and 18th centuries (Wirrmann 1988) and can be correlated to the wet period of the Little Ice Age (LIA, Mourguiard et al. 1997, Rabatel et al. 2008, Thompson et al. 1986).The lake water level fluctuated more than six meters during the 20th century (Roche et al. 1992).

Holocene sedimentary formations of fluvial origin are characterized by two or three continuous sequences of fine deposits (clay, silts, sand and gravel) with intercalations of peat levels. These sedimentary formations are related to the evolution of alluvial fans at the base of the slopes of the valley in relation to an anastomosed hydrological system with small channels (Argollo et al. 2003). A significant number of sources are still located at the base of the main mountain ranges. The modern rivers occupy the channel carved out by the last incision episode (900-700 cal yr BP). Studies from Lake Wiñaymarka suggest that between 3500-700 BP, the Desaguadero River was not an effective outlet from Lake Titicaca (Abbott et al. 1997). However, all previous lake level changes have not been clearly identified within alluvial formations. Studies on Desaguadero, llave and Ramis Rivers indicated that after 3300 yr BP, the terrace formation is the result of at least three rapid water-level falls and migration of the River (Baucom and Rigsby 1999, Farabaugh and Rigsby 2005). Previous studies reported also stabilization phase valleys of the Altiplano presented evidences of soil formation during the early Holocene (between 8350-6780 BP, (Rigsby et al. 2003), followed by large incisions (6045-4545 BP; Farabaugh and Rigsby 2005, Servant and Servant-Vildary 2003) and two periods of sedimentary filling of the valleys coinciding with a phase of lake-level rise and overflow (4045 BP-2545 BP and 2045-1645 BP; Baucom and Rigsby 1999, Farabaugh and Rigsby 2005, Rigsby et al. 2003). During the late Holocene, studies suggest that precipitation may have decreased slightly over the Amazon Basin during the last ~2200 years while Andean precipitation continued to increase (Bird et al. 2011). Subsequent downcutting occurred after approximately 1600 yr BP but could not be chronologically located.

2.4 Geomorphological mapping

The Holocene sedimentary formations of the watershed are still insufficiently studied. Since the 1990's, some studies have characterized the large ecological and geomorphological units of the lower and middle valley. However, they are not based on the same cartographic methods and not mapped at the regional catchment scale (Fig. 2 and 3). The Table 1 summarize geomorphological features used for previous mapping as mainly based on remote sensing, historical photography and field acquisition at the watershed scale.

Tab. 1: Synthetic characteristics of geomorphological features from Albarracin-Jordan and Mathews 1990, Calla Maldonado 2011 and Argollo et al. 2003.

Albarracin-Jordan and Mathews 1990, Calla Maldonado 2011		**Argollo 2003**	
Elevation	***Feature***	***Elevation***	***Feature***
4100 - 4800 m	inter-mountainous areas (IM): rocky landscapes	~3940 m	T7: paleolake Mataro, early Pleistocene (~1.6 million years ago)
4000 - 4100 m	Upper Colluvial Zone (UCZ): deep quebrada with gravel sedimentary filling	~3900 m	T6: early Pleistocene
3900 - 4000 m	Lower Colluvial Zone (LCZ): peat and gravel	~3880 m	T5: middle Pleistocene
3820 - 3900 m	Springs and *bofedales* (SB)*:* peat and clay soils	~3860 m	T4: paleolake Ballivian middle Pleistocene, 600 - 500 ky ago)
3820 - 3840 m	Alluvial plain (AP): sandy loam sediments	3860 - 3825 m	T3: paleolake Michin 46–36 ky BP
3809 - 3820 m	Lacustrine zone (LZ): intermittently emerged area associated with seasonal variations of the lake	3818 - 3815 m	T2: paleolake Tauca ~26–15 ky BP
		<3810 m	T1: Holocene

The 1990's geomorphological pioneers' works are based on an altimetric approach and aims to reconstruct the large ecosystems forming the valley (Albarracin-Jordan and Mathews 1990) (Fig. 2). More recently, Calla Maldonado's (2011) work used a similar method to deduce the occupation strategies of pre-Hispanic societies that occurred in the middle valley. They distinguish 6 ecosystems (lacustrine zone, alluvial plain, springs and *bofedales*, Lower Colluvial Zone, Upper Colluvial Zone, inter-mountainous areas (Fig 2).

The work carried out by Argollo et al. (2003) is based on the geological composition of the subsoil. It provides detailed information on the location of Pleistocene and Holocene lacustrine formations in the lower valley (Fig. 3). Some terraces are associated with dated paleo shorelines (Bills et al. 1994, Servant et al. 1995, Sylvestre et al. 1999) and were related to high levels of Lake Titicaca (Argollo et al. 2003, Fritz and al. 2004, Mourguiard et al. 1997, Servant et Fontes 1978, 1984). Argollo et al. (2003) showed that the mountain range and the Taraco peninsula present a topography cut by several terraces of low slope (between 1 and 5 %).

Because of the scattering of geological and geomorphological data, no homogenized map exists in this area. In this paper, we propose to complete and merge existing mappings in order to obtain a regional mapping of the watershed. We then complement these observations with an innovative interdisciplinary approach that combines the methods of remote sensing, historical geography (old and recent aerial photographs) and field techniques on poorly studied areas.

2.5 Pre-Columbian agricultures and landscape inheritances

During the late Holocene and at the scale of Mesoamerica and South America, raised-field agriculture in wetlands was conducted in a wide range of environments from sea level to over 4000 m elevation, covering a great range of soils and climates (Renard et al. 2012). Among other examples, raised fields have been found in the Basin of Mexico (e.g., Sanders et al. 1979), in the Altiplano of Bolivia and Peru (Erickson 1992, 2003, Kolata 1996), within inter-Andean valleys marshes (Wilson et al. 2002), were also related to seasonally flooded savannahs in the lowlands (Plazas and Falchetti 1990, Reichel-Dolmatoff and Reichel-Dolmatoff 1974, Rostain 2008, Spencer et al. 1994, Walker 2004) and even in southern regions of Chile (Dillehay et al. 2007). Massive irrigation networks created as early as 4000 BP in desert coastal valleys of Peru, turned them into productive landscape for prehistoric inhabitants and provided the foundations for complex society (Moseley 1983). The 113 km long Chicama-Moche intervalley canal combining aqueducts and other sophisticated hydraulic structures constructed by the Chimu around AD 1400 is another example among other of water management knowledge (Erickson 1992). Previous studies in the Tiwanaku valley identified 3 types of agro-pastoral systems (Albarracin-Jordan and Mathews 1990, Kolata 2003). They distinguished the terraces of cultures, the *kochas* (artificial ponds of circular shape used for water retention, sometimes organized in groups connected by channels) and the *sukka khollus* (platforms of raised cultures organized in networks connected with natural and artificial channels). These inherited agricultural technics from the pre-Columbian civilizations attest to human adaptation to the environment (Kolata 2003). Raised field agriculture (*sukka khollus)* provided pre-Columbian farmers with better drainage and protection against flooding, soil aeration, moisture retention during the dry season and a fertility advantage. It also aimed at conserving water for long- and short-term droughts, using the stored water to extend growing seasons (Erickson 1992). This agricultural technic offers also more favorable microclimates as a greater frost tolerance in cold highland environments (Erickson 1992, Kolata and Ortloff 1989, Lhomme and Vacher 2002). Raised field from the Altiplano were cultivated beginning about 3000 years ago and formed much of the subsistence basis for the Tiwanaku Empire (Kolata 1996). Finally, Kolata (2003) highlights the existence of partial regularization of the Tiwanaku River, canals and platforms in association with raised fields in the lower and middle valleys. However, no chronological control exist to relate these landscape modifications. There is consensus that these canals and raised fields are attributed to the Tiwanaku culture (400-1150 AD) but a controversy still exists on the chronology of disappearance of these integrated regional agricultural system (Abbott et al. 1997, Erickson 1999, Graffam 1992, Janusek and Kolata 2004, Kolata et al. 2000, Ortloff and Kolata 1992, Vranich 2013).

3. Methods and technics

3.1 Remote sensing

We used Landsat 8-level 2 satellite image (date: 2016-september-18; multispectral 30 m, panchromatic 15 m and thermic 60 m resolution), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 3 (GDEM 003) (~30m pixel resolution) and Shuttle Radar Topography Mission Version 3.0 Global 1 arc second (SRTM 3) (SI Fig. 3) centered at the watershed scale. Landsat 8 and ASTER and SRTM 3 data were downloaded from the USGS (United State Geological Survey) Earth explorer website (earthexplorer.usgs.gov) and processed using Arcgis 10.3 software.

Remote sensing has long been used to characterize the wetlands within the Altiplano (Moreau et al. 2003, Moreau and Le Toan 2003, Otto et al. 2011, Vining and Williams 2020). Altiplano wet grasslands are composed of two distinct category of vegetation. The *totora* is a perennial reed (Cyperaceae family) which grows in water up to 5.5 m depth or in inland areas subject to summer flooding. The *bofedales* are characterized by permanently water-saturated highland short grasslands with over 60 plant species forming a dense carpet (~90% vegetation cover), crisscrossed during the wet season by seasonal shallow streamlets (Moreau and Le Toan 2003). Most of the valley vegetation is composed of bunchgrass (*Festuca* sp. and *Stipa* sp.) and/or low shrubs (*Parastrephia* sp.) (Vining and Williams 2020). Some scattered trees like eucalyptus are present near most important villages. Other type of vegetation in the Altiplano include trees like *Polylepis* sp. among other but are not represented in the Tiwanaku valley.

In order to characterize the hydric and vegetation state we calculated the NDVI index (Normalized Difference Vegetation Index) that corresponds to the normalized difference between red and near-infrared (NIR) energy reflectance of the vegetation cover (Bharathkumar and Mohammed-Aslam 2015, D'Allestro and Parente 2015, Gandhi et al. 2015, Tucker 1979). The NDVI calculation was processed in a GIS environment using the following formula:

$\frac{(\mathrm{NIR}-\mathrm{Red})}{(\mathrm{NIR}+\mathrm{Red})} = NDVI$ where Red= band 4, NIR= band 5 and $-1 < NDVI < 1$.

This vegetation index enables to distinguish the density of the vegetation cover (wet grassland, ie. *totora* and *bofedal*), waters (lakes, rivers, *kochas* and wetland) and soils (rocks, buildings, roads). Vegetated areas generally present relatively high near-infrared reflectance and low red reflectance and are associated to positive NDVI values; water and wet area present negative values as these features have larger reflectance in Red than in NIR. Rock and bare soil areas have similar reflectance in the two bands and produce values near zero. (D'Allestro and Parente 2015). In partial and sparse vegetation cover like the Altiplano, senescent plant reflectance converges with bare soils (Vining and Williams 2020). However, wet grasslands are the only native forage resources available around the year, including during the dry winter season (Moreau et al. 2003). The comparison of the evolution of the monthly mean NDVI and map (SI Tab. 1, SI Fig 1 and 2) along a year demonstrated that September was the most accurate period to distinguish wet grassland from bare soil area (SI Text).

We also extracted the slope from GDEM ASTER in order to access to basic geomorphic parameters of the watershed. We then classified the slope map following the approach of Touahir et al. (2018), which considers that the slope ranges of 0-5%, 5-15%, 15-35%, and > 35% correspond to low, medium, high and very high erosion domains, respectively. The GDEM ASTER was also used to extract drainage maps whose protocol is detailed in Supplementary Information with a specific focus on differences between ASTER and SRTM 3 results.

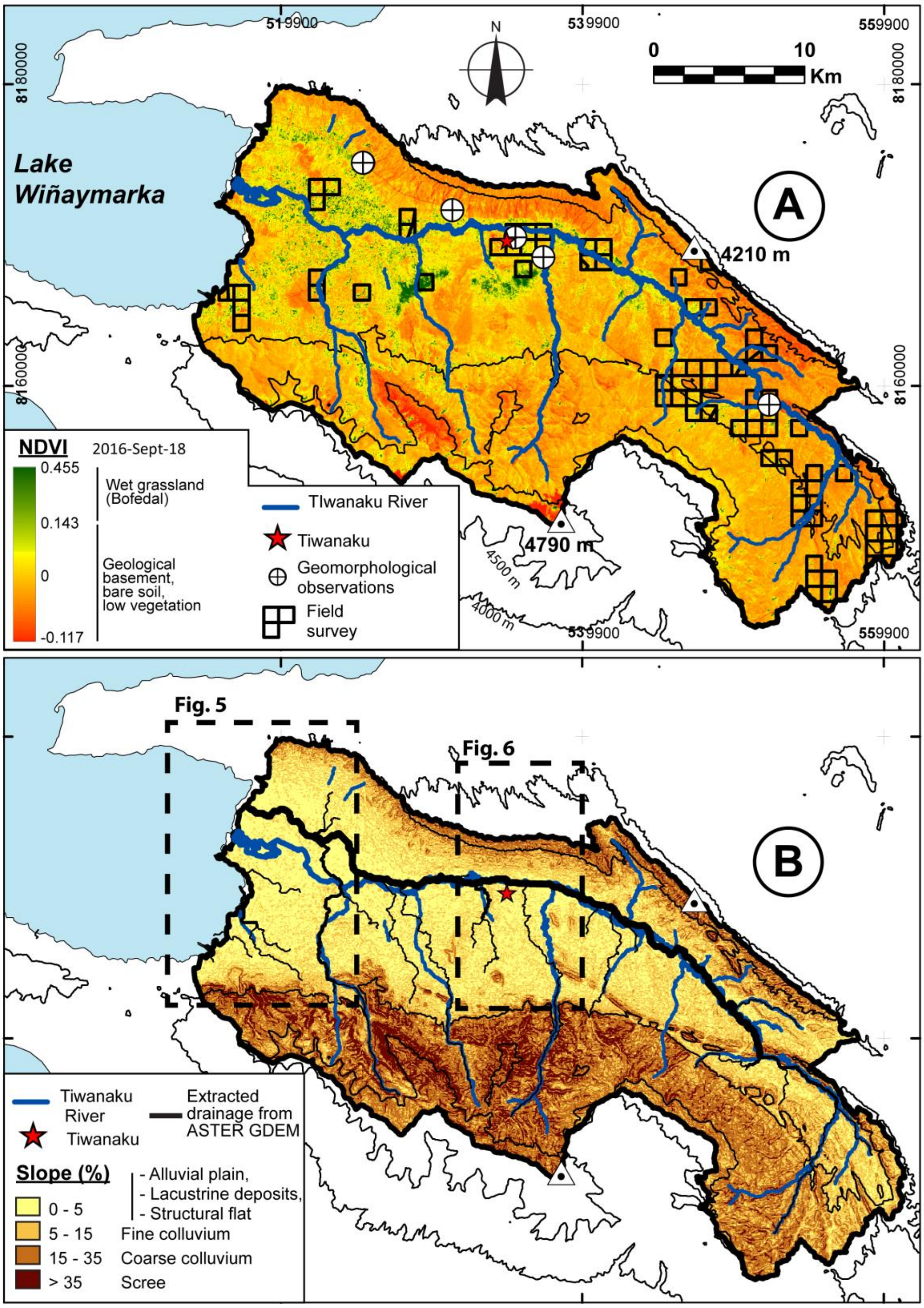

Fig. 4: Remote sensing and geomorphic parameters obtained on the Tiwanaku River watershed. **A: NDVI map** (date: 2016-september-18, Landsat 8 OLI/TIRS -level 2 images, source: U.S. Geological

Survey). The sectors that were the subject of field surveys are represented. **B: Slope map and flow map** (From ASTER data, source: U.S. Geological Survey). Location of Fig. 5 to 8 are represented.

3.2 Historical geography

For this study, we have compiled and georeferenced the geological, topographic, geomorphological maps and historical aerial photos taken between the 1930's and 2019 in an ArcGIS environment (Tab. 2, Fig 5 and 6, SI Fig. 4). The oldest cartographic documents available (dated from ~1930), were acquired specifically around the Tiwanaku archaeological site (1 mosaic, 4.84 km^2) (Ortloff 2014). The 1954-1955 and 1972 aerial photographs were obtained by the Bolivian national services. The 1954-1955 campaign concerned the full catchment area (110.25 km^2, 72 tiles), whereas the 1972 campaign was restricted to the medium course of the Tiwanaku River (1.4 km^2, 14 tiles). 2014 and 2019 satellite images were obtained from the U.S. Geological Survey database. 2017 aerial photographs of the Tiwanaku area were obtained from the Guaquira-Tiwanaku archaeological mission. All aerial photographs allow us to distinguish the channels of the Tiwanaku River, wetlands and the shoreline for each period. We completed this geodataset with published topographic maps reporting alluvial, lacustrine and shoreline positions mapping between 1983 and 1985 by the IGM (1985).

Tab. 2: List of aerial images used to reconstruct the evolution of the coastline and of the Tiwanaku River drainage system.

Document type	Date	Source	Description
Aerial photography	1930	Instituto Geográfico Militar de Bolivia	Aerial photographs of the archaeological site of Tiwanaku and the alluvial plain
Aerial photography	1954-55	Instituto Geográfico Militar de Bolivia	Aerial photo of the coastline and of the alluvial plain from the middle valley and the mouth
Aerial photography	1972	Instituto Geográfico Militar de Bolivia	Aerial photo of the alluvial plain
Topographical map	1985	Instituto Geográfico Militar de Bolivia	Topographic map of the Tiwanaku valley
Satellite image	7/14/1986	U.S. Geological Survey	Landsat 5 TM-level 2, satellite image of the watershed
Satellite image	8/2/1987	U.S. Geological Survey	Landsat 5 TM-level 2, satellite image of the watershed
Satellite image	7/11/2014	U.S. Geological Survey	Landsat 8 OLI/TIRS-level 2, satellite image of the watershed
Aerial photography	2017	Guaquira-Tiwanaku Project	UAV aerial photos of the archaeological site of Tiwanaku
Aerial photography	2019	Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES / Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community	Satellite image of the watershed

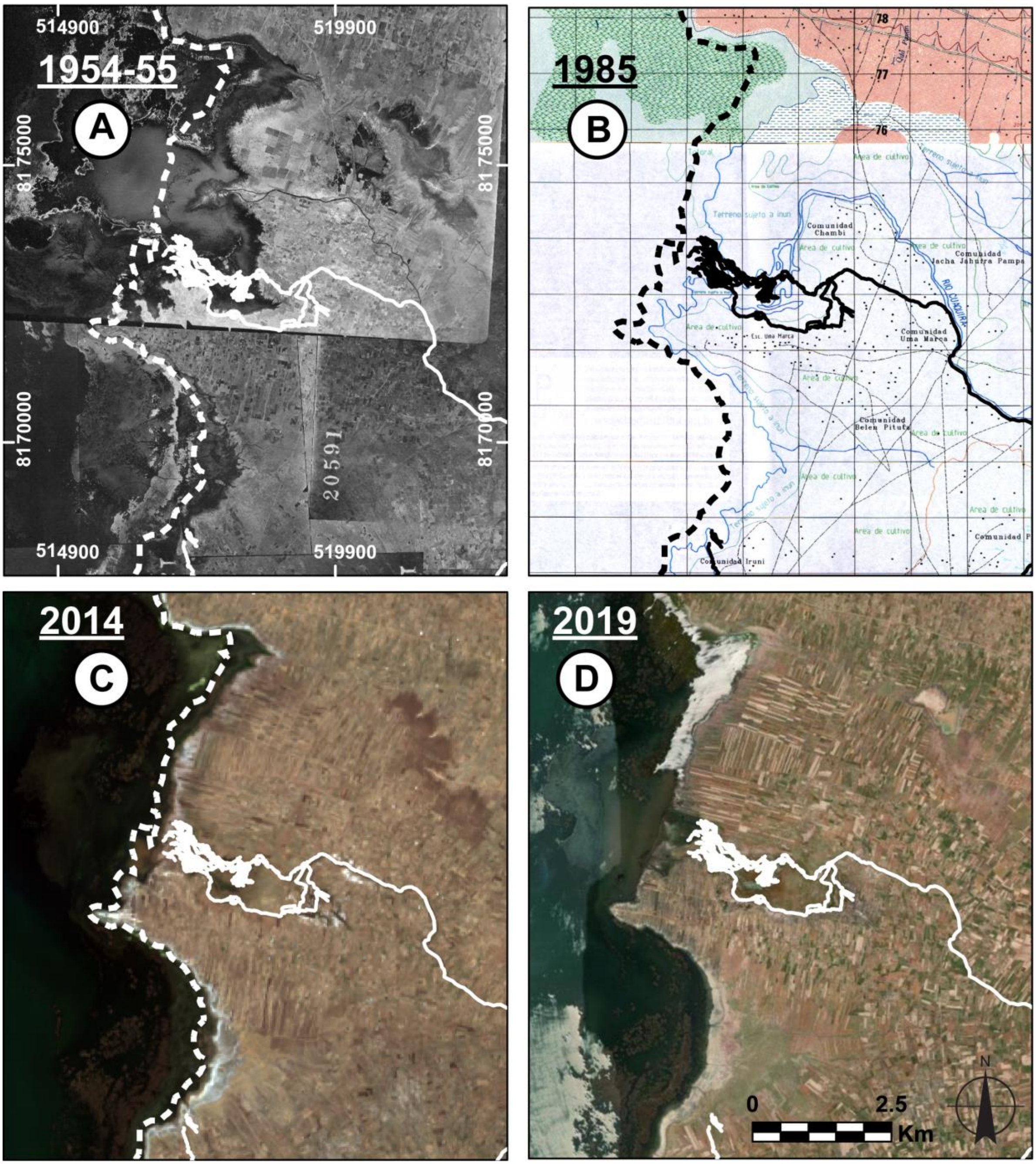

Fig. 5: Aerial photographs near the mouth of the Tiwanaku River in Lake Wyñaimarka. The dotted line represent the current situation of the coastline and the continuous line the current location of the Tiwanaku River. **A. 1954-55.** Source: Instituto Geográfico Militar de Bolivia. **B. 1985.** Source: Instituto Geográfico Militar de Bolivia. **C. 2014.** Source: Landsat 8 OLI/TIRS-level 2 courtesy of the U.S. Geological Survey. **D. 2019.** Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES / Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

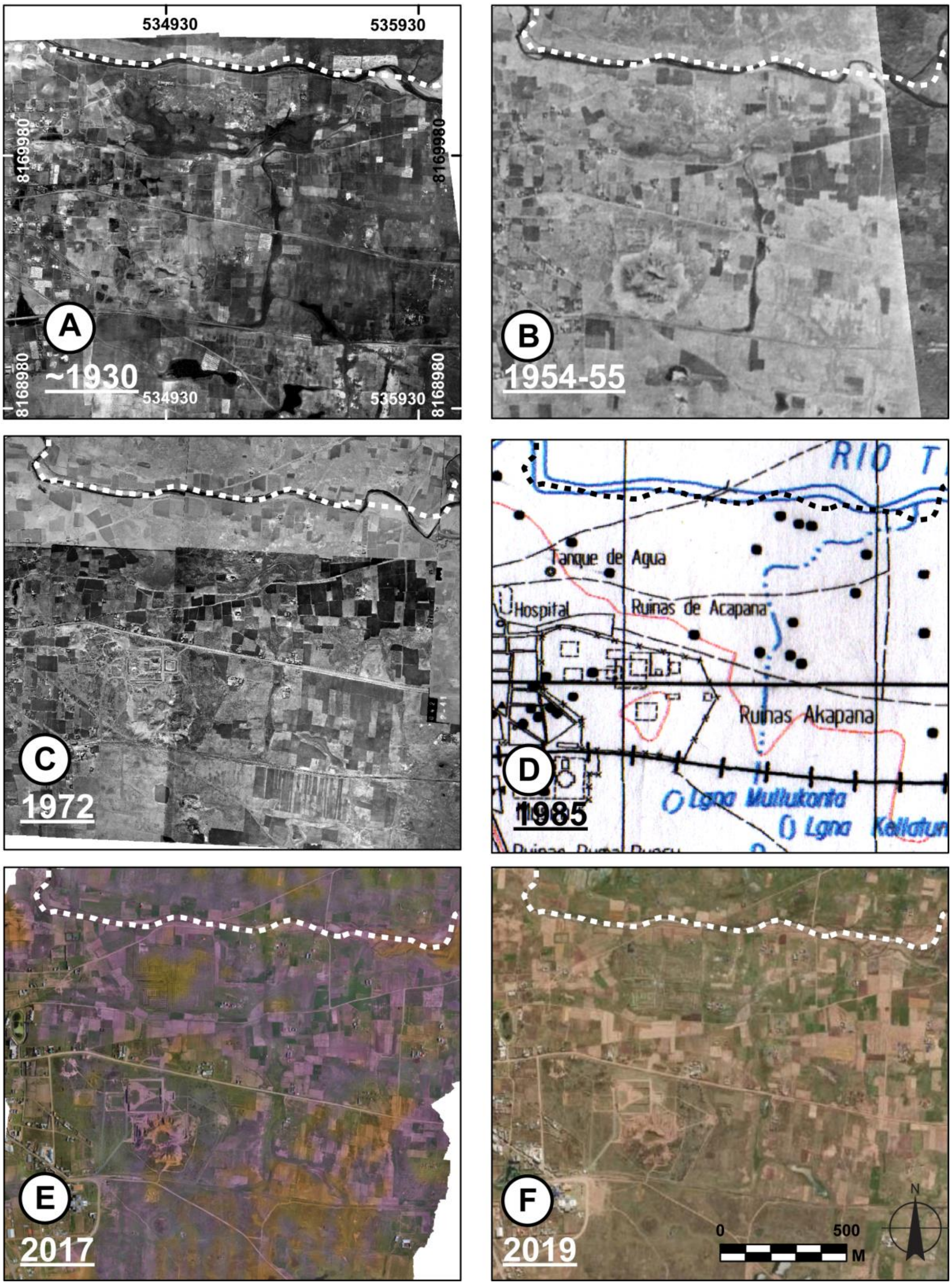

Fig. 6: Aerial photographs of the Tiwanaku archaeological site. The dotted line represent the current situation of the Tiwanaku River. **A. 1930'.** Source: Instituto Geográfico Militar de Bolivia. **B. 1954-55.** Source: Instituto Geográfico Militar de Bolivia. **C. 1972.** Source: Instituto Geográfico Militar de Bolivia. **D.1985.** Source: Instituto Geográfico Militar de Bolivia. **E. 2017.** Source: Guaquira-Tiwanaku project. F.

2019. Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES / Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

3.3 Field acquisition and observation

Field survey areas (location in Fig. 4A) were selected based on remote sensing and historical geography analysis, which identified main geomorphological features (such as wetlands, slope deposits) or a high variation of alluvial or lacustrine forms (alluvial plain, lacustrine deposits). The methodology has been already described in a previous paper (Vella et al. 2018) and follows a strategy used by several works in this area (Albarracin-Jordan and Mathews 1990, Argollo et al. 2003, Calla Maldonado 2011). In order to best explore the diversity of the landscape, the field survey takes into account the physical boundaries of the watershed. In mountain areas, ridges and low topography levels were favored. In flat areas, profiles spaced 50 m apart were made. General explored area tries to represent several cross sections across strike and one along strike to what we added some random point.

For the purpose of our study we present six geomorphological sections (Fig. 4A). C1 is located in the lower valley, C2 to C5 are located in the middle valley, and C6 in the high valley. These sections allow for the characterization of the stratigraphy of the lower Pleistocene lake terrace and the Holocene alluvial deposits.

4 Results

4.1 Remote sensing

We used the NDVI map as a first order approximation to distinguish 3 main classes of vegetation cover and as an indirect indicator of geomorphological feature (ie. wet grassland (*totora* and *bofedal*); water and wet area; rock and bare soil areas) (Fig. 4A). In the Tiwanaku valley, during the month of September, NDVI values ranged from -0.117 to 0.455. Water and wet areas are characterized by negative NDVI values (D'Allestro and Parente 2015) but no clear features associated to inland water bodies were identified in the Tiwanaku valley. Previous research on the Altiplano (Moreau et al. 2003, Moreau and Le Toan 2003) demonstrated that NDVI values ranging between 0.508 and 0.143 correspond to areas of wet grassland (*totora* and *bofedal*). They are mainly located along the Tiwanaku River (*bofedal*) and near the Lake Wiñaymarka (*totora*). These features are related to Pleistocene and Holocene alluvial plain as well as Holocene lacustrine deposits identified by previous studies (GEOBOL 1994). In particular, two sets of wet grassland (*bofedal*) stand out just on south of the Tiwanaku River in the middle valley. NDVI values ranging between 0.143 and 0 are located at high and medium elevation. These features are related to the geological basement, bare soils areas and to large domains where the vegetation is senescent. They coincide with a large part of lowlands and intermountain area identified by previous studies (Albarracin-Jordan and Mathews 1990, Calla Maldonado 2011).

We complemented the NDVI approach with slope classifications (Fig: 4B). The 0-5 % slope range corresponding to low erosion domains represents the main part of the valley and is roughly centered on major floodplain. This low range value is due to the occurrence of flat landforms (alluvial plain, lacustrine and alluvial terraces, horizontal tertiary layers). Pleistocene and Holocene alluvial plain as well as Holocene lacustrine deposits are located at low elevation while Pleistocene lacustrine deposits are located above 3815 m asl. The 5-15% slope range corresponding to medium erosion domains is located at the foot of both mountain flanks (3940 to 4100 m asl). This domain also partially corresponds to the LCZ mapped in previous studies (Albarracin-Jordan and Mathews 1990, Calla Maldonado 2011). The 15-35% slope range corresponding to high erosion domains (4100 to 4500 m asl), coincide approximately with the UCZ described by previous studies (Albarracin-Jordan and Mathews 1990, Calla Maldonado 2011). The >35% range slope corresponds to very high erosion domains (> 4500 m asl) and are related roughly to intermountain areas described in previous studies (Albarracin-Jordan and Mathews 1990, Calla Maldonado 2011).

The extracted drainage flow roughly mimics the course of the actual Tiwanaku River except in the downstream part and for several south confluences. This implies that discreet slope changes, undetected by the DEM's resolution using for drainage extraction, have possibly modified the course of the recent Tiwanaku River.

Ancient agricultural systems composed of *sukka kollus* and *kochas* are located in low erosion sectors (0-5% slope range). These features are associated with wet grassland area (*bofedal*, 0.143<NDVI<0.455) and bare soils area (0<NDVI<0.143) respectively.

4.2 Historical geography

The resolution of the historical aerial photographs allows to track the mobility of alluvial and lacustrine origin landforms since the first half of the 20th century. We mainly focus our analysis on Lake Wiñaymarka (Fig 5 and Fig. 7) and Tiwanaku archaeological areas (Fig. 6 and Fig. 8). On both areas, several ancient river courses and/or canals are present on most ancient cartographic documents available. As these features could not be related to a specific period they were mapped as undated.

We have mapped coastline variations of the Lake Wiñaymarka observed between 1954-1955 and 2019 (Fig 5 and Fig. 7). The displacement of the coastline shows a regressive pattern and can be estimated, on average, at 400 m between 1954-55 and 1985 (13.3 $m.yr^{-1}$), and at 100 m between 1985 and 2019 (2.9 $m.yr^{-1}$). However, this setback is not linear. A minor transgressive incursion with a fluctuation of the coastline could be observed between 1985 and 1987 (Gallego Revilla and Pérez González 2018) and was estimated at 5km inland in comparison to the position of 1985 (SI Fig. 4). We have also mapped a drainage shift (1.5 km) of the terminal course of the Tiwanaku River and delta toward the south during the 1954/1955-2019 period. The outlet and delta shifts occurred mainly during the 1954-1985 stage whereas the main stream shift occurred during the 1985-2019 stage. Furthermore, we can observe that automatic extracted drainage flows of the downstream part of the Tiwanaku River are more concordant with the 1954-1955 course than the 2019 course.

Around the Tiwanaku area (Fig. 6 and Fig. 8), we have observed some clear evidences of channel evolution since the 1930's. The stream is more meandering between 1930 and 1972 and the loops are intersected by the 2019 channel. However, some palaeochannels predate the oldest documents used in our study (undated paleochannels and/or canals). They are located in the northern part of the lower valley. They depict an anastomosed morphology which can be linked to a wetter period whose chronology cannot yet be specified. The historical geography results allow to roughly differentiate the Pleistocene alluvial deposits from those related to Holocene, but it is necessary to cross combine with field survey in order to better distinguish these two geomorphological features. Concerning documented archaeological features, our results are in agreement with previous researches (Albarracin-Jordan and Mathews 1990, Calla Maldonado 2011, Argollo 2003, Kolata 2003). The agricultural terraces could not be mapped with actual aerial photography and this still requires a specific field survey. On the contrary, the *kochas* are still visible and are mainly located on Pleistocene lacustrine terraces. Ancient canals are mainly associated to Pleistocene alluvial deposits and connect different part of the Holocene river courses. In the lower valley, some ancient canals correspond to the extracted drainage from the ASTER GDEM. Around Tiwanaku, they seem to be connected to the tributary located upstream of the archaeological site (Ojra Jahuira River). These ancient canals are located between the wet grassland areas identified on the NDVI map and permanent or intermittent watercourses in the lower valley and around Tiwanaku. Inside these wet areas, aerial photographs showed evidences of *sukka kollus* attested by the presence of remnant platforms separated by small canal.

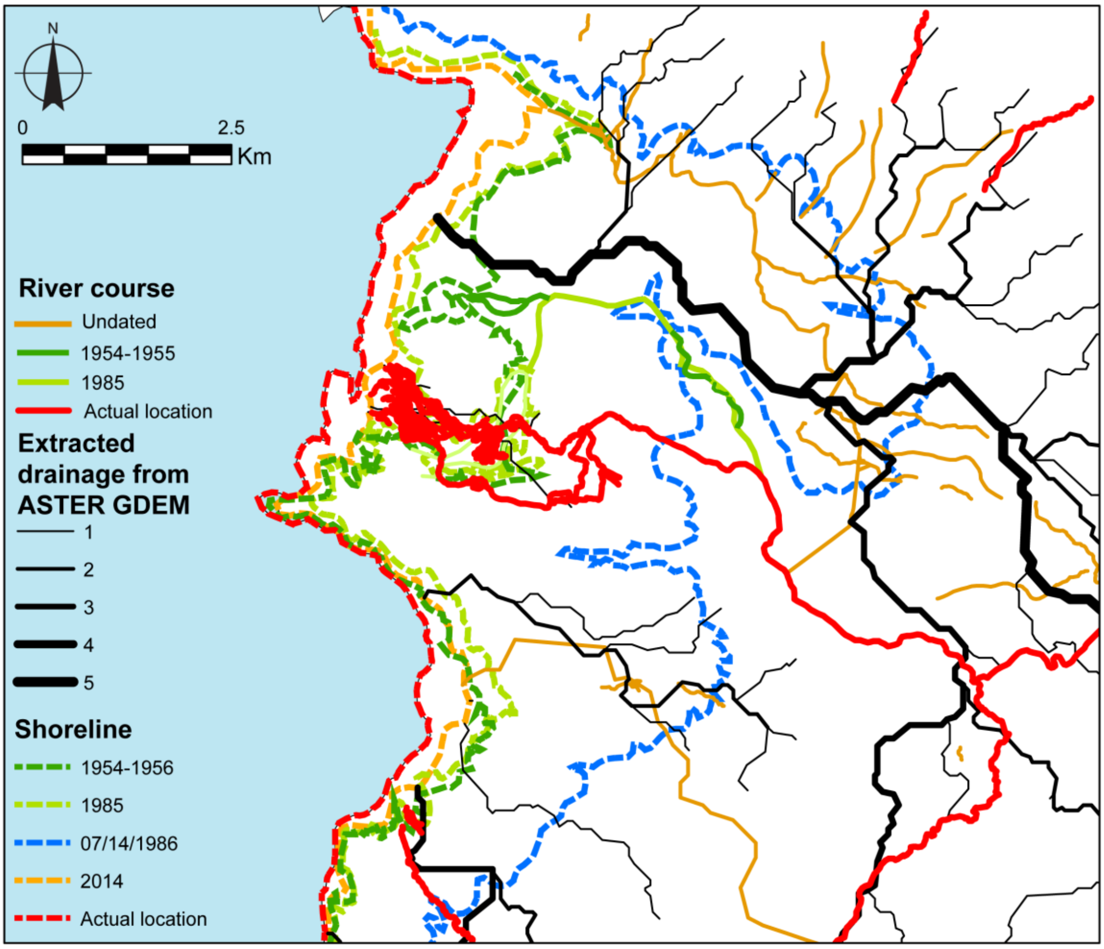

Fig. 7: Evolution of the coastline and of the Tiwanalu River since 1954-55. Location of Fig. 5 is represented in Fig 4B.

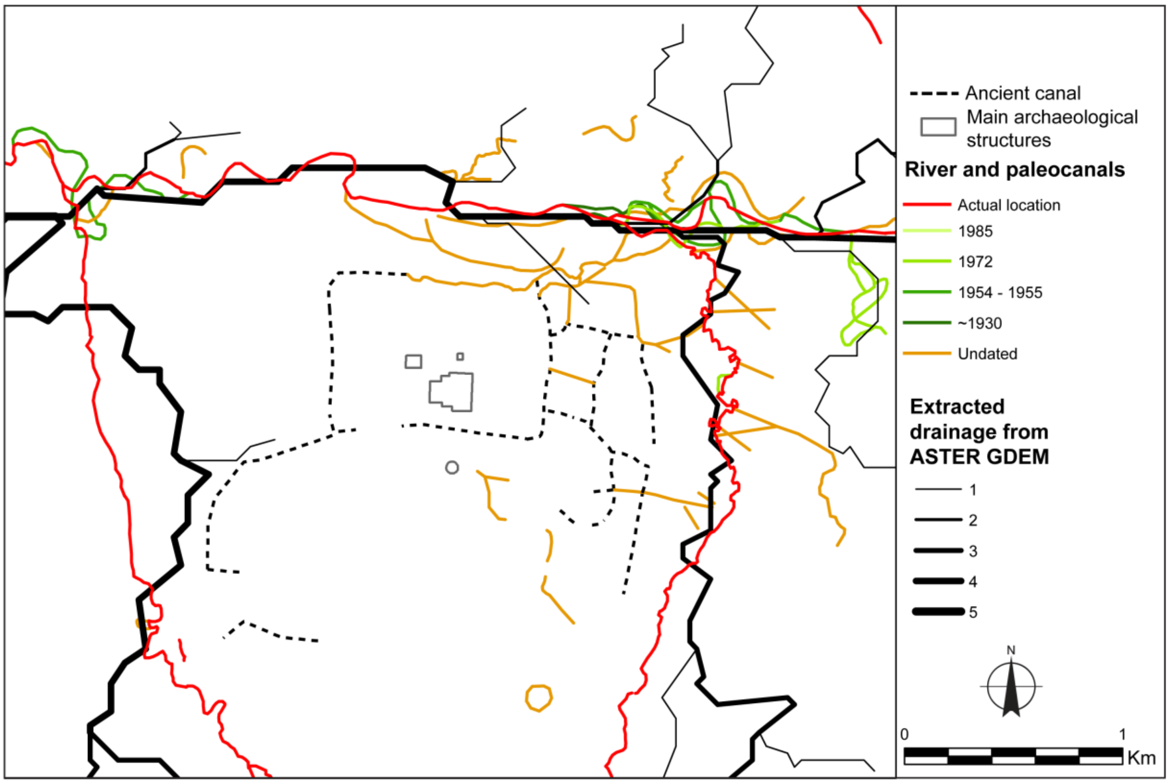

Fig. 8: Evolution of the Tiwanaku River near the Tiwanaku archaeological site since 1930'. Location of Fig. 6 is represented in Fig 4B.

4.3 Field acquisition and observation

The geomorphological features (wet grassland, slope deposits, fluvial deposit sand lacustrine deposits) have been partly characterized following NDVI and slope classification and the landform evolution is specified with historical geography analysis. Field survey provided accurate details about spatial and vertical organization of landforms and superficial sedimentary deposits except high mountain area (above 4500 m asl) in the Quimsa Chata and Chilla massifs on the southern flank (Fig. 4A).

Wet grasslands are characterized by dense hygrophilous vegetation and their location were confirmed during field surveys. They can be associated with the area of springs and *bofedales* or seasonal lake sectors identified by previous works, (Albarracin-Jordan and Mathews 1990, Argollo et al. 2003, Calla Maldonado 2011). However, our cartography provides more accurate details about their location, superficies and characteristics. Wet grasslands (*bofedal*, slope 0-5%, 0.143 < NDVI < 0.455) have been observed in front of the large Holocene sedimentary fans and on the Pleistocene lake terraces on the southern flank (near Quimsa Chata River and above Tiwanaku archaeological site) and along the river in the middle and high valley. They are compatible with the agrarian activities of the valley.

Slope deposits are related to LCZ, UCZ and intermountain identified by previous studies (Albarracin-Jordan and Mathews 1990, Calla Maldonado 2011). Our study, based on remote sensing cross combined with field survey, helps to refine the sedimentary composition and the spatial organization of slope deposits area. Slopes are composed of structural flats and medium to very high erosion domains. Structural flats are observed around 4500 m asl in the southern flank of the middle valley. They are related to bare soils and low vegetation with low erosion potential (slope 0-5%; 0 < NDVI < 0.143). Medium erosion domains (slope 5-15%) are identified at the bottom of the north and south slope and are mainly composed of fine colluvium with moderately developed soils. Nowadays, the most important part of the slopes is related to this geomorphological feature. Sectors of high erosion (slope 15-35%) are mostly located on the southern flank of the valley between 4100 and 4500 m asl and present a NDVI related to bare soils, low vegetation or geological basement (0 < NDVI < 0.143). High erosion sectors are characterized by coarse colluvium, with very little developed soils, with some scree lanes mostly located on the southern slope. Sectors of very high erosion domains (>35%) are mostly related to the geological basement (0< NDVI < 0.143).

Features inherited from Pleistocene and Holocene deposits are outcropping along the valley at low elevation with little hilly terrain and are sometimes deeply cut by streams. We add 6 geomorphological sections along the Tiwanaku valley in order to refine the distinction between Pleistocene and Holocene alluvial or lacustrine deposits (Figs. 9 and 10). Currently, no archaeological elements or radiocarbon chronological dates allow an accurate dating of these series. Probable Holocene lake terraces can be observed at high elevation compared to seasonal lake area and are no longer under their current seasonal fluctuations. On the field, these terraces present a sedimentary pattern composed of fine silty clayey sediments. We have observed some alluvial plains probably dated from Holocene (slope 0-5%;

$0.143 < NDVI < 0.455$) mainly along the main river and near the mouth of Lake Wiñaymarka (Figs. 9 and 10). These alluvial plains are composed of non-consolidated gravel, sand and silts, is highly permeable, and has well developed soils. These areas have currently a high concentration of canals and raised fields, some of which are still of unspecified age. C3 and C5 sedimentary logs provide valuable information about stratigraphy deposits (Figs. 9 and 10). C3 stratigraphy is related to recent deposits likely date from Holocene (maximum depth ~ 2.00 m). From top to bottom, the stratigraphy is composed of silty formations (0-0.30 m depth), well-sorted red sands (0.30-0.80 m depth) and silt formation (0.80-1.20 m depth). C5 is related with early Holocene lower alluvial terrace incised by the current Tiwanaku River (maximum depth ~ 3.50 m). The stratigraphy is composed of silty formations (0-1.50 m depth) interbedded with clayey and more organic layers (1.50-3.00 m depth). We interpret this formation as a probable Holocene alluvial fan with low consolidated sediments and coarser elements (gravels and pebbles) layers.

Pleistocene lacustrine terraces show a flat relief (slope 0-5%), a NDVI related to bare soils and low vegetation in general ($0 < NDVI < 0.143$) and are located between 3810 and 3940 m asl. The Pleistocene lacustrine terraces (Lake Michin, 3830 m asl, late Pleistocene and Lake Balivian, 3860 m asl, mid-Pleistocene) have already been distinguished from those associated with early Holocene (Lake Tauca, 3815 m asl) (Argollo et al. 2003, Fritz et al. 2004, Mourguiart et al. 1998). These terrace levels are composed of an alternation of weak consolidated sand, silts and clays. The low hydraulic permeability of these formations allows them to constitute a good reservoir of surface water. C1 log show an alternation of clay formations with calcareous crust intercalations. These formations can be related to late Pleistocene lacustrine deposits (clay) with lake level variations (emerge land with calcareous precipitation).

C2, C4 and C6 logs illustrate other sedimentary facies which contrast with the C1 one. C2 log (maximum depth ~ 2.00 m) is composed of decimetric thick medium indurated sandy to silty levels and centimeter thick gravel and pebble layers. C4 (maximum depth ~2.50 m) is characterized by silty deposits interbedded with decimeter thick coarser layer composed of well sorted gravels. C6 (maximum depth

~1.50 m) is composed from top to bottom by sandy and silty layers (0-0.70 m depth) and gravels (0.70-1.50 m depth). It has been shown in previous studies in the Tiwanaku valley (Argollo et al. 2003, GEOBOL 1994) and in other valley in the Lake Titicaca basin (Rigsby et al. 2003) that these sedimentary deposits are compatible with Pleistocene and early Holocene alluvial fans mostly located on the southern flank of the valley.

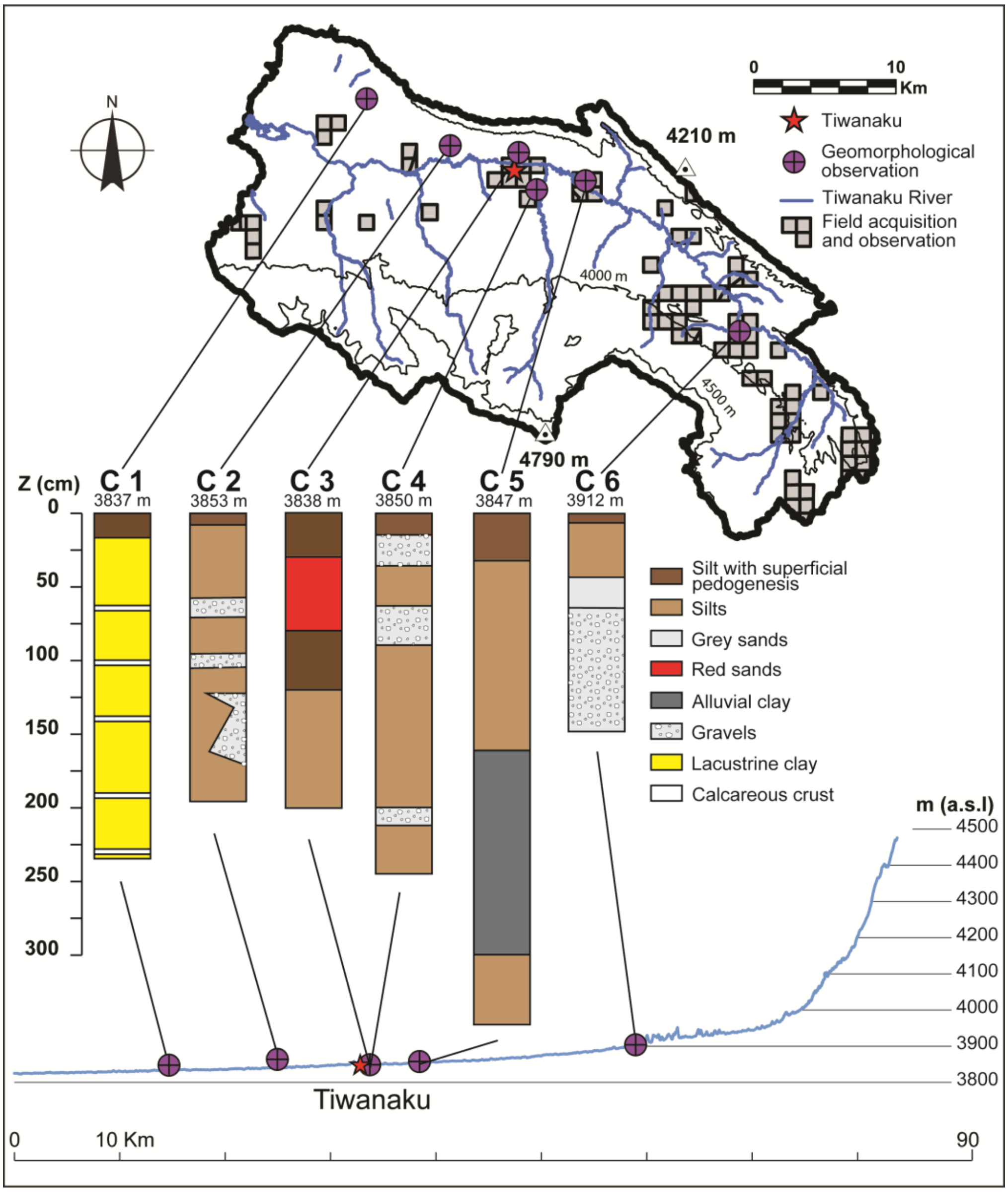

Fig. 9: Geomorphological sections along the Tiwanaku valley. Location are presented on the watershed map and along the topographic profile of the river.

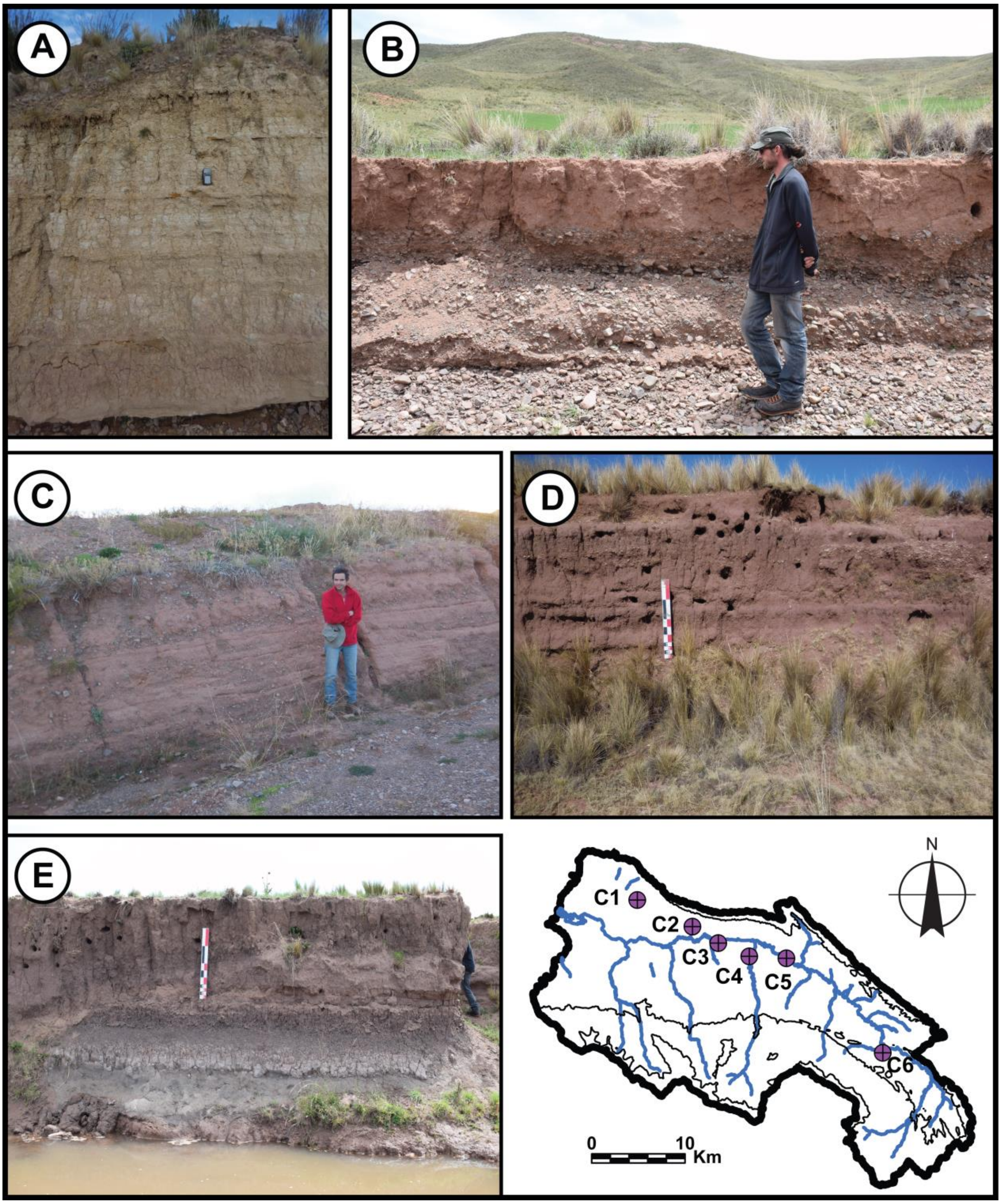

Fig. 10: Photo board of geomorphological observation illustrating lacustrine terraces and Quaternary alluvial deposits. A: C1, late Pleistocene lacustrine deposits. **B: C6**, Pleistocene alluvial fans. **C: C2**, Pleistocene alluvial fans. **D: C4**, Pleistocene alluvial fans. **E: C5**, early Holocene lower alluvial terrace.

5. Discussion

5.1 Geomorphology of the Tiwanaku valley

By leveraging remote sensing, historical photographs and field data we have restated and detailed a new cartographic synthesis of the of the Tiwanaku valley geomorphology (Fig. 11A, B and C). Our results show that the southern flank presents paleo to modern slope deposits more or less connected with Pleistocene to Holocene alluvial fans and then are connected either to Holocene alluvial formations or to Pleistocene lake levels. This pattern is also shown on the north flank, but presents almost no alluvial fans and a shorter flank. Slope classification show that high erosion areas are located in the Quimsa Chata and Chilla massifs.

The sedimentary composition of the Pleistocene lake terraces previously identified (Argollo et al. 2003) and observed on the C1 log indicates a high concentration of clay which may be controlled by the development of the wetlands. Alluvial fan identified on C2, C4 and C6 log is characterized by silty deposits interbedded with well sorted gravels. Recent studies on the pedogenetic processes in the Bolivian Andes, has demonstrated that in the Altiplano area, soil formation began from 3500 BP. Depositional processes related to the coarser elements identified in profiles C2, C4 and C6 must then be related to earlier periods. They might then attest to different levels of Lake Titicaca in relation with glaciation cycles during late Pleistocene period (Argollo et al. 2003) or to lake level variations during early to mid Holocene (Rigsby et al. 2003) Holocene alluvial formation observed on C3 and C5 is composed of silty formations and well-sorted red sands interbedded with clayey and more organic layers. They are probably related to respectively low and high levels of Lake Titicaca. In the lower valley, Holocene lacustrine formations are mostly located on the north bank to a distance of at least 4 km inland. They are associated to the Holocene delta of the Tiwanaku River whose dimensions we were able to assess at 5 km wide and about 6 km long.

Our results are therefore roughly in agreement with the major geomorphological features mapped by previous studies (Albarracin-Jordan and Mathews 1990, Argollo et al. 2003, Calla Maldonado (2011). The map produced by Albarracin-Jordan and Mathews (1990) then extended by Calla Maldonado (2011) contains information on soils and also ecosystems (fauna and flora). However, it is only based on altitudinal parameters and does not completely reflect the diversity of the valley's landform. In our study we have, for example, shown that the LCZ is not homogeneous; this area is composed of wet grassland (*bofedal*) separated by Pleistocene to Holocene alluvial fan. The map proposed by Argollo et al. (2003) takes into account the geology and specifies the chronology of the lake terraces, but does not distinguish between different categories of slope deposits and therefore the origin of sedimentary sources. We have clearly shown that we can distinguish structural flat, fine colluvium, coarse colluvium using slope classification and remote sensing. Our work also shows that the wet grasslands are mainly located on the south bank of the middle valley. We have shown that they are associated with the Pleistocene lake terraces. However, the lack of chronological control does not allow us to precise the landscape evolution during Early to Late Holocene period.

Finally, the result of this interdisciplinary approach (i) allows to better distinguish the lacustrine and alluvial forms related to the Pleistocene and Holocene, (ii) allows a better location of wet grasslands (*bofedal*) within the valley, (iii) specifies depositional environments located on the slopes and (iv) offers the first synthetized geomorphological map on the scale of a watershed combined with modern landform evolution (since 60-70 years) and pre-Columbian agricultural structures in South or Central America.

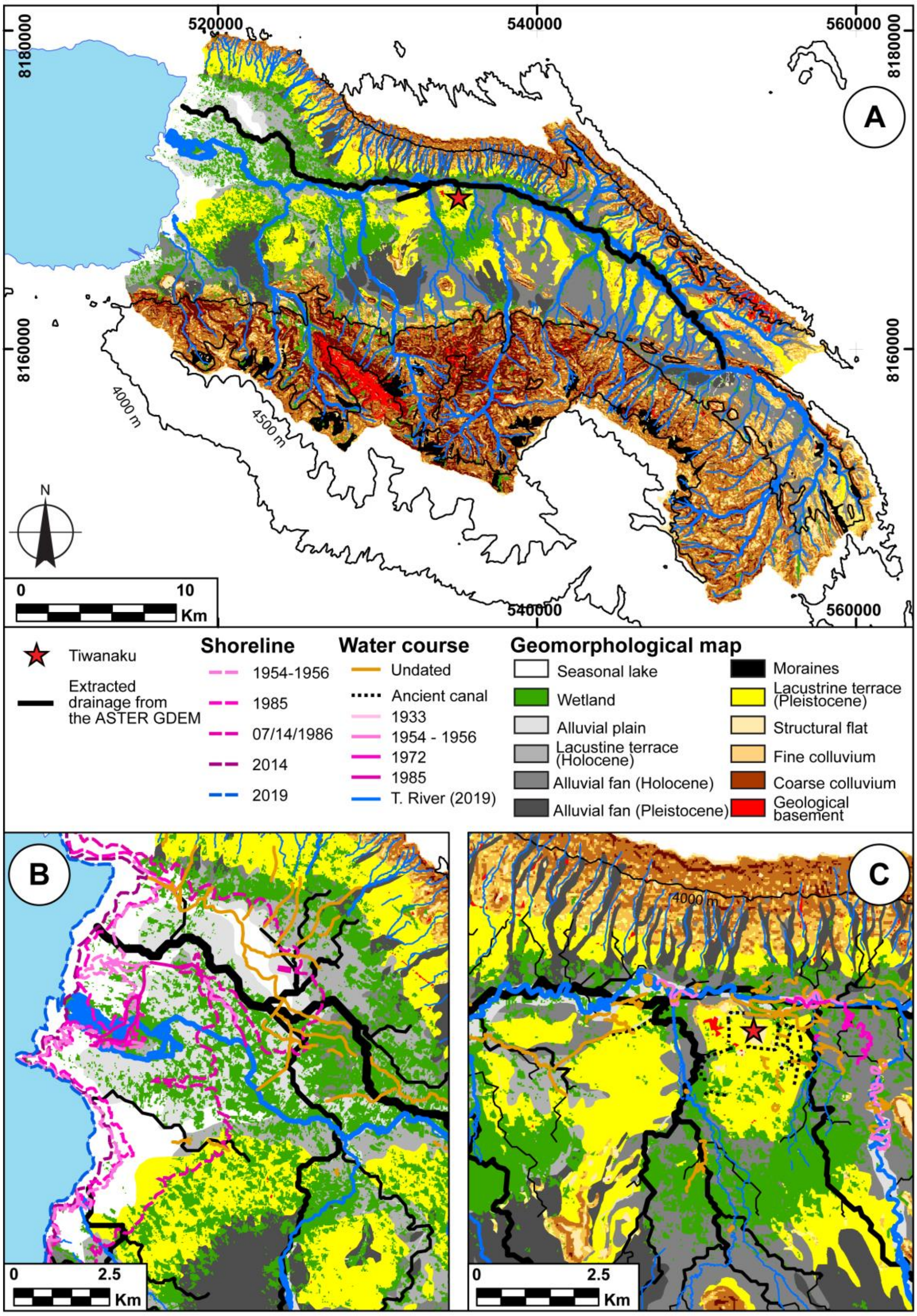

Fig. 11: Synthetized and extended geomorphological cartography of the Tiwanaku valley combined with landform evolution since 60-70 years and probable pre-Columbian canals. A: At the scale of the watershed. B: Downstream sector. C: Tiwanaku sector.

5.2 Landform evolution over the past 60-70 years

Historical geography results show a significant variation of rivers in the lower (Fig. 11B) and in the middle valley (Fig. 11C) since the first third of the 20th century. Furthermore, the extracted drainage shows a difference with the actual course of the Tiwanaku River. From 9 km before its mouth into Lake Wiñaymarka, the calculated flows have a northward shift of 2 km on average. This difference might be related to an ancient course of the river. The association of the calculated drainage and the maximal transgressive coastline observed on the satellite image from 1986 (SI) seems to comfort this hypothesis. At the watershed scale, we note a reduction in the surface of Lake Titicaca since the second half of the 20th century with a shift of the shore in the Tiwanaku valley of 13.3 $m.yr^{-1}$ between 1954-55 and 1985 and 2.9 $m.yr^{-1}$ between 1985 and 2019. We have detected a delta avulsion of the River that we have estimated about 2 km towards the South. This shift seems to be associated with an important sediment progradation of the alluvial plain. This event could not be related to a precise date. However, considering that the last major flooding of the lake, linked to intense periods of rainfall associated with the El Niño phenomenon, was recorded in 1985-86 and 1987 (Erickson 1999, Gallego Revilla and Pérez González 2018, Roche et al 1992), we can assume that the start of this shift dates from this period.

The medium valley shows a significant displacement of alluvial forms upstream of the archaeological site of Tiwanaku (Fig. 11C). Our work highlights significant avulsion between 1954 and 1972, the decrease in the number of meander bends and the adoption of a straighter course between 1985 and 2019.

Previous climatic conditions inherited from the Medieval Climatic Anomaly (MCA) and Little Ice Age (LIA) period may have influenced actual landform organization. Andean glaciers can provide valuable information on precipitation rates. The glaciers have experienced a major recession since the LIA maximum, losing 89 % of its surface area. The recession was moderate from 1940 to 1963 and increased in the period 1963-1983. Since 1983, the glacier experienced a major recession rate (Coudrain et al. 2005, Ramirez et al. 2001). A complete extinction of the glacier would reduce drastically the total runoff of the proglacial stream that feed the Lake Titicaca (Coudrain et al. 2005, Ramirez et al. 2001). Our observations on the retreat of the shoreline of Lake Wiñaymarka therefore seem to be consistent with the decrease in precipitation on the Altiplano since the second half of the 20th century. Historical lake-level records document numerous short- and long-term droughts and floods (Dejoux and Iltis 1992, Kessler and Monheim 1968, Monheim 1963) that can be related to modern glacial recession. There is some evidence of droughts of 36 continuous years in the 17th century and 29 continuous years in the 18th century (Stanish 2003). Since the beginning of the 20th century, records show that the lake level (~3810 m asl today) has fluctuated about 6.4 m (Roche et al 1992). Around 1914 the lake level was ~ -1 m; between 1920-1935 the lake level was around 0 m; between 1935-1950 the lake level was located ~-3 m; between 1950- 1970 ~0 m; between 1970-1990 ~+1m. During 1860 and 1959, communities confronted 15 continuous years of droughts (especially 1942 (~-3.5 m) and 1982-83 (~-0.5 m) and a record-breaking flood between 1985 and 87 (+2 m) (Erickson 1999, Kessler and Monheim 1968, Monheim 1963, Roche et al 1992, Gallego Revilla and Pérez González 2018) (SI text and SI Fig. 4).

Major avulsion of the delta and river course shift identified since the second half of the 20th century can be related to these variations in precipitation rates and lake level. Droughts in 1982-83 followed by a record-breaking flood during 1985-86 in a larger period of lake level rise, may have influenced the shift of the shore between 1954-55 and 1985, as well as the delta avulsion. However, the mean lake level rise since the second half of the 20th century does not control the inland migration of the shoreline in the vicinity of the Tiwanaku outlet. We propose that the shoreline migration toward the lake is due to the progression of the delta which is probably linked to an increase in the erosion processes in the upstream sectors and in sedimentation in the lower valley.

5.3 Implications for ancient and current populations

After about 4000 cal. yr. BP the alluvial terraces present an increased sediment load that may also have been fed by agricultural runoff as human populations rose in the Lake Titicaca watershed (Farabaugh and Rigsby 2005). The river basin of the Tiwanaku River and Lake Titicaca constituted the main ecosystems of the Chiripa (3500 to 1900 BP) and Tiwanaku civilization (1500-850 BP) (Janusek and Kolata 2004, Kolata et al. 2000). Within the Altiplano area, combined land survey, excavation results and radiocarbon dates demonstrate that the construction and use of raised field systems and technology began during the late Formative Period (2200-1350 BP, Bruno 2014, Janusek and Kolata 2004). These agricultural structures were then developed on a large scale between 1500-850 BP during favorable climatic conditions (Erickson 1999, Janusek and Kolata 2004, Kolata et al. 2000). Raised fields, built in various forms, were concentrated along the lake edge, along rivers, and in the low pampas near the lake and in the river floodplains (Erickson 1988, 1993, 1994, Kolata 2003, Smith et al. 1968, Stanish 2003). The functions of these canals include channels for reed boat traffic, water management, and boundary markers for community fields and aquatic resources (Erickson 1999). The final low lake stand (900-700 cal yr BP) coincides with the decline of raised field agriculture and the collapse of Tiwanaku culture (Abbott et al. 1997, Janusek and Kolata 2004, Kolata et al. 2000, Ortloff and Kolata 1992). After this period, local groups continued to cultivate raised fields on a much-reduced scale, as part of a more diversified subsistence strategy (Stanish 2003, Janusek and Kolata 2004). Other studies assume that pre-Columbian states and urban centers were ephemeral, rising and falling with some regularity in the Lake Titicaca Basin (Erickson 1999, Vranich 2013). These studies demonstrated that farming communities and intensive agriculture did not disappear during the post-Tiwanaku periods (Erickson 1999). It has been also speculated that most of the raised fields in the Katari Valley were built and managed after Tiwanaku state collapse, as a local adaptation to changing sociopolitical conditions and the onset of a long-term drought (Graffam 1990). This source (1990) has today been nuanced by other works that demonstrated that the use of these raised field agriculture continued as relics during post-Tiwanaku periods (Bruno 2014, Harstorf 2008). The appearance and development of raised field technology within the circum-lacustre area of the Altiplano supports the long term tradition of agricultural landscape construction observed at a larger scale from Mesoamerica (Sanders et al. 1979) to South America (Erickson 2003, Kolata 1996, Rostain 2008, Wilson et al. 2002) during pre-Columbian times.

The large number of channels in the lower valley suggest that the alluvial plain morphology has adopted an anastomosing organization during early Holocene (Argollo et al. 2003), probably at a period of high lake levels (Fig. 11B). However, without absolute dates, their chronology cannot be verified. The probable presence of an old course of Tiwanaku River near the northern slope of the lower valley is suggested through remote sensing and historical geography results, but its chronology cannot be defined with precision. Part of the channels that we have mapped (Fig. 11 A, B and C) correspond to the hydraulic structures identified by previous studies which have linked them chronologically to the Tiwanaku civilization (Janusek and Kolata 2004, Kolata et al. 2000, Kolata 2003, Ortloff 2014). In the middle valley several linear-shaped wetlands exist near the archaeological site. These landforms can be linked to a complex hydraulic network (Kolata 2003, Ortloff 2014). However, without further study of the filling of these probable ancient canals, we cannot make further interpretations. As suggested by recent studies (Pérez González and Gallego Revilla 2019), our work also demonstrates that these canals and raised-field aimed to drain the wetlands southward of the watershed to the monumental core of Tiwanaku. These canals seem to connect different portions of the major course of the Tiwanaku River and its tributaries upstream (Kolata 2003, Ortloff 2014) and downstream (Pérez González and Gallego Revilla 2019) of the archeological site of Tiwanaku. These canals also connect different wetland of the valley and associate the Pleistocene lake terraces with Holocene alluvial formations of the middle and the lower valley. Their implementations are therefore probably to be linked to water management for both agro-pastoral and water management purposes. The situation of the monumental core of Tiwanaku seems then to be surrounded by wetland to the south, the Ojra Jahuira River to the East, the Challa River to the west and the Tiwanaku River to the north defining an island like landscape during wet periods. The pattern of the ancient canals in peripheral parts of Tiwanaku suggests that this hydraulic network could be a heritage from ancient natural palaeochannels from the Ojra Jahuira River.

Downstream of the archaeological site, on the south bank of the Tiwanaku River and on the west side of the Challa River (Fig. 11C), we identified a Pleistocene or early Holocene natural channel that could be identified at the same location of ancient canals (Kolata 2003). This canal allows a diversion of the main course of the Tiwanaku River, thus distinguishing a second "island" that roughly corresponds to a Pleistocene lake terrace (Fig. 11A, B and C). In a previous work, Kolata (2003) argued for a comparable derivation process. He showed the probable presence of a canal linking the diversion and one of the main tributaries of Tiwanaku River. On the other hand, all these channels cannot be linked to a specific chronological period in the absence of absolute dates made on their sedimentary filling. More recent studies have highlighted several hydraulic structures and derivations of natural streams downstream of the archaeological site (Pérez González and Gallego Revilla 2019). Our work confirms the hypothesis that water flow could be originated in part from the southern wetland identified by our present studies. The kochas are mainly located on the Pleistocene lake terraces. They are associated to agro-pastoral structures (Janusek and Kolata 2004), however, their frequent re-use by the old and current populations makes any chrono-cultural affiliation difficult. Finally, without absolute dates in the Tiwanaku valley, the chronology of the construction of the various developments (*sukka kollus*, *kochas*, canal, river avulsion) cannot be specified.

Broader studies realized in the Andean area have demonstrated that long term drought have affected the Altiplano. The climate-collapse hypothesis (Ortloff and Kolata 1993, Abbott et al. 1997, Binford et al. 1997) versus anthropogenic environment perspective (Erickson 2000, Williams 2002) is still vigorously debated. However, the aridity signal is recorded at several location in South America during the MCA (Stine 1994) from 800 to 1200 AD. Recent studies on Lake Orurillo attest that the driest climate conditions occur between ca. 915 and 1200 AD, with a more extreme phase between 950 and 1025 AD (Arnold et al. 2021). Records from northern Peruvian coast attested a period of extreme drought during the MCA 900 to 1250 AD (Rein et al. 2004). In the north-central Andes forest regrowth was evident between 800 and 1000 AD, but this trend was reversed between 1000 and 1200 AD as drier conditions coincided with renewed land clearance, (Åkesson et al. 2020). Dry period associated to the MCA has been related to the decline of the Moche civilization in the north coast of Peru at 900 AD (Koons and Alex 2014) and of the Wari state in central Peru at about 1000 CE (Finucane et al. 2007) suggesting that these Andean states were vulnerable to prolonged drought during the MCA (Arnold et al. 2021). Drier period associated to low lake level in Lake Wiñaymarka during this period might have significantly affected raised field agricultural system by limiting the amount of land amenable to irrigation (Arnold et al. 2021). It is also needed to underline that drastic lake level drop (between 8 and 12 m, Binford et al. 1997, Abbott et al. 1997) certainly induced important erosion in the lower valley, affecting the general landscape of the Tiwanaku civilization during the MCA.

Concerning actual populations, the raised field evidences observed during the study of ancient and recent aerial photographs reflect more relics than a real operational and integrated system (Fig. 11A, B and C). However, they bear witness to the persistence of this type of agriculture in the sector to this day. It has also to be noticed that recent experimental raised fields near Lake Titicaca gave some yield during the severe 1982-1983 drought and gave excellent yields in 1985-1987, when flooding devastated other types of farms (Erickson, 1992). This demonstrate that raised field agriculture could be a rich sources of inspiration for applying ecological engineering in agriculture today (Renard et al. 2012). Our results clearly demonstrate important and rapid landscape transformations during pre-Columbian times. Current climate changes are associated to glacier recession, drying up of wetland and of Lake Wiñaymarka and are expected to have important consequences on agricultural activities of present populations. Increasing population in El Alto (1.5 M ha.) inside the watershed of Lake Wiñaymarka and the lack of water treatments could also lead to critical environmental situations.

6. Conclusion

In this paper, we have synthetized and specified the chronology of events of the Tiwanaku valley since the Recent Holocene thanks to a multi-disciplinary approach (historical geography, geomorphology, geophysical surveys, photogrammetry, remote sensing and cores) crossed with pre-existing geomorphological data.

We produced a new geomorphological map showing that the Tiwanaku River watershed is composed of a mosaic of geomorphological assemblages that are organized according to the morphology of the geological substratum and the altitudinal and climatic parameters. Additionally, our work put in evidence several large wet grasslands in the middle valley sometimes in connection with the hydrographic network. Our results allow to bring new information on slope deposits and to better distinguish the lacustrine and alluvial forms related to the Pleistocene and Holocene.

Our work locates several canals probably of anthropic origin, which could be related to the Tiwanaku culture (1500-850 BP). These canals connect the wetlands, the tributaries upstream (Ojra Jahuira River) and downstream (Quimsa Chata River) of the monumental site as well as the main water course of the Tiwanaku River. This entire hydraulic system is also linked to sectors with a high concentration of ancient raised field. For the past 70 years, our work has shown a general reduction in wetlands, several river avulsion in the middle valley, a decrease in the maintenance of canals and the abandonment of ancestral cultivation techniques. In addition, the reduction in the size of the lake, associated to a major shift of the river watercourse in the delta, leads to the appearance of new lands with significant agricultural potential but is also accompanied by a decrease in favorable areas in the middle valley.

However, there is still a contradiction that need to be reconciled between the consideration that ancient societies have being able to construct anthropogenic agricultural landscapes and environmental factors which act as “allogenic forcing mechanisms”. As other studies, our observation support that climate and lake level variation do not explain major past social and political transformations but contributed to the development of flexible and diverse subsistence practices in the Titicaca Basin (Bruno et al. 2021). Further work, based on a multidisciplinary approach (geophysical surveys, photogrammetry and cores), is still necessary to characterize the geometry and the chronostratigraphy of the canal in the lower and middle valley in relation with recent Holocene lake level change. This work will provide a better understanding of the alluvial formations that border the

South East basin of Lake Titicaca in order to better anticipate the actual environmental challenge of the populations of the Altiplano.

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Competing Interests

The authors declare no competing interests.

Author contributions statement

M.A.V. designed the study. M.A.V. performed the field acquisition, the historical geography mapping and remote sensing analysis. M.A.V. and N.L. interpreted the results and wrote the manuscript.

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Supplementary information

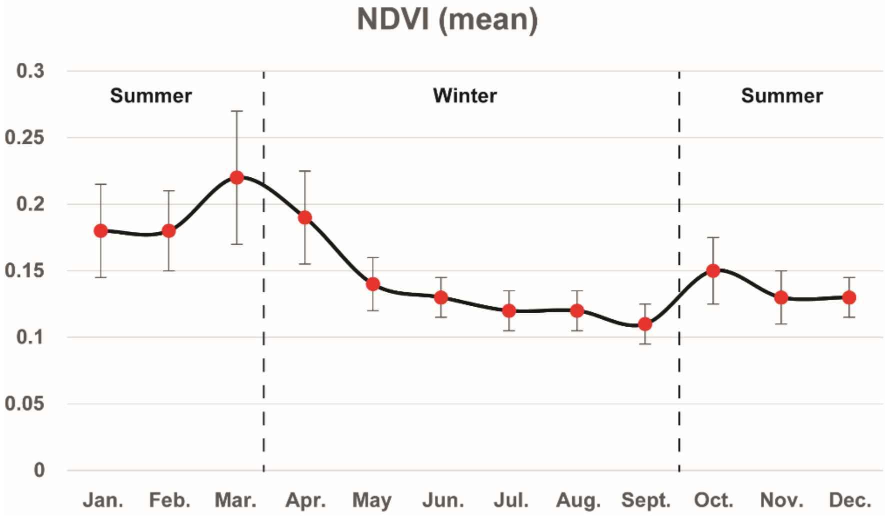
1. Remote sensing

1.1. NDVI

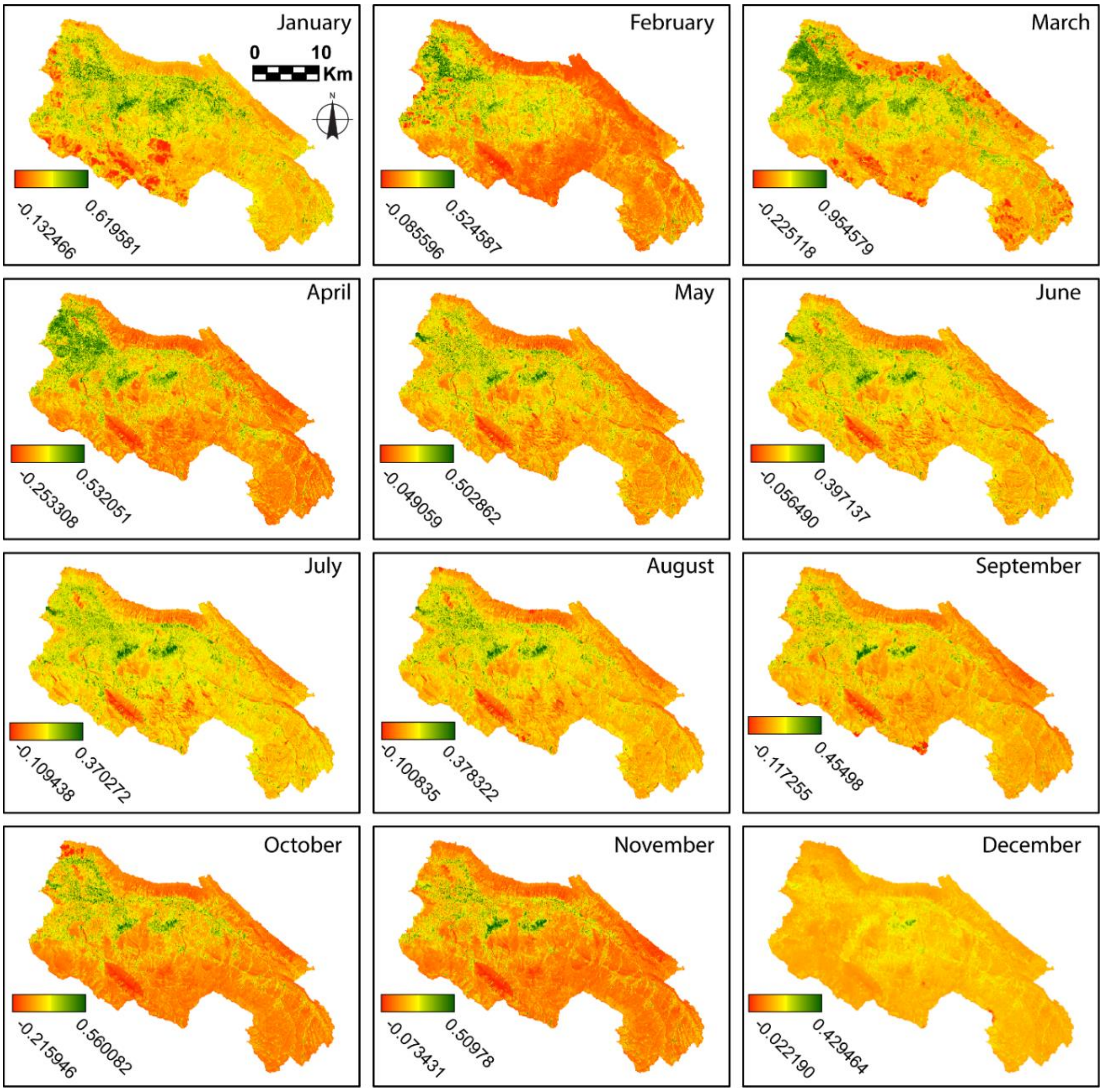
NDVI has been the most widely used spectral vegetation indices (Moreau et al. 2003). NDVI is sensitive to relative differences in absorbed/reflected light in the red and NIR spectra. Soils and senescent vegetation converge in this region, particularly where vegetation cover is not complete (Vining and Williams 2020). Taking this into account many of studies performed on semi-arid environments involved the development of spectral indices taking into account the influence of bare, unsaturated soil backgrounds to minimize soil noise like the Soil adjusted vegetation index (SAVI) developed by Baret, Guyot, and Major (1989). However Purevdorj and Tateishi (1998) indicated the superiority of NDVI and SAVI for the estimation of the green vegetation cover, with a better performance of NDVI. Bork, West, and Price (1999) demonstrated that SAVI often resulted in either no improvement or a minimal improvement relative to NDVI.
Landsat 8 OLI/TIRS-level 2 images have been chosen with regards to the less cloud cover. 10 images were selected in order to cover all the vegetation phases during one year (SI Tab. 1). As the cloud cover was too important (>10%) from October to March 2020 and 2019 (summer in the southern hemisphere), we choose to select best images for each month during the last decade (2014-2020). The evolution of the mean NDVI highlight the division in two distinct season (SI Fig. 1). For the purpose of our study, we selected the image of the month of September (SI Fig. 2). This map is related to the Austral winter period were most of the vegetation is senescent. It has already be noted that the continued growth and low senescence of Andean wet grasslands during the Austral dry winter is highlighted by the small variation of the green tissue cover in *bofedales* between summer and winter (Buttolph, 1998). The cultivated plant are then less represented and only the minimal distribution of wet grassland (*totora* and *bofedal*) are highlighted (Vining and Williams 2020).

SI Tab. 1. Characteristics and statistics of the Landsat 8 OLI/TIRS -level 2 images selected for the NDVI (source: U.S. Geological Survey)

Date (year-month-day)	Cloud cover	NDVI
2016-01-22	2-10%	-0.132466<NDVI<0.619581
2017-02-09	2-10%	-0.085596<NDVI<0.524587
2016-03-26	2-10%	-0.225118<NDVI<0.954579
2016-04-27	0-2%	-0.253308<NDVI<0.532051
2020-05-24	0-2%	-0.049059<NDVI<0.502862
2020-06-25	0-2%	-0.056490<NDVI<0.397137
2020-07-27	0-2%	-0.109438<NDVI<0.370272
2020-08-28	0-2%	-0.100835<NDVI<0.378322
2016-09-18	0-2%	-0.117255<NDVI<0.454980
2014-10-15	2-10%	-0.215946<NDVI<0.560082
2015-11-19	2-10%	-0.073431<NDVI<0.509780
2017-12-10	2-10%	-0.022190<NDVI<0.429464



SI Fig. 1. Evolution of mean NDVI during a calendar year (Landsat 8 OLI/TIRS -level 2 images, source: U.S. Geological Survey).



SI Fig. 2. NDVI extracted from Landsat 8 OLI/TIRS -level 2 images (source: U.S. Geological Survey).

1.2. Slope and drainage extraction

National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission Version 3.0 Global 1 arc second (SRTM 3) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 3 (GDEM 003) datasets were imported in an ARCGIS 10.3 environment in order to compare the influence of their respective resolution (90m and 30m) on the slope and drainage extraction.

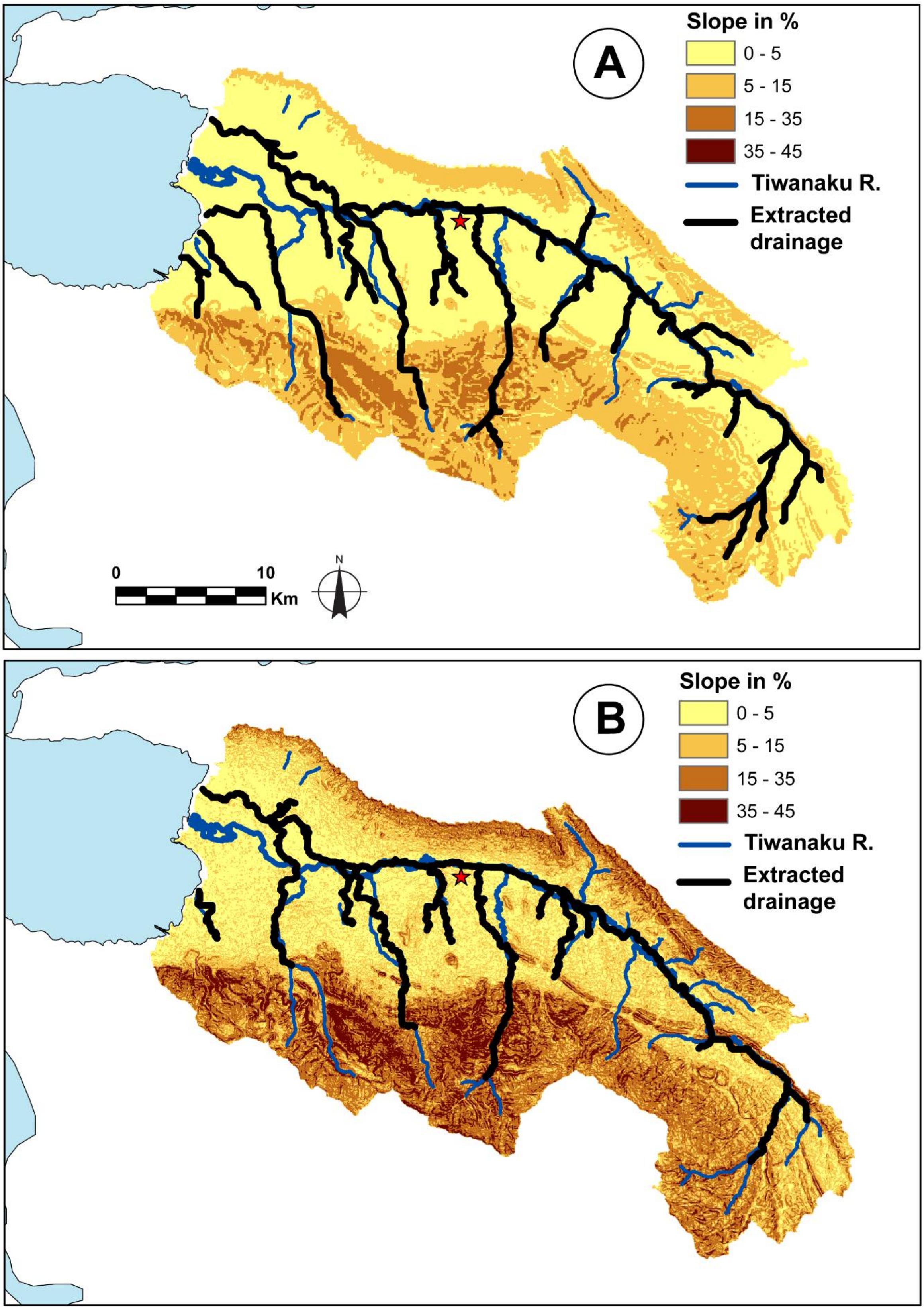
- The Slope tool from Arcgis 10.3 environment is performed on a projected flat plane using a 2D Cartesian coordinate system. The slope value is calculated using the average maximum technique (Arcgis Pro documentation Slope, Burrough 1998).

Same procedure was used for the extraction of the slope from NASA SRTM 3 and ASTER GDEM. The slope map from both datasets show some same general tendencies. Lower values represent the main part of the valley and are located in the center of the map; medium values are located at the foot of both mountain flanks (northern and southern); higher values are observed in the southern flank of the valley. However, some differences could be identified between both dataset. First of all, the DEM from ASTER shows higher values (SRTM 3, mean slope ~6.1% and ASTER, mean slope ~14.7%). Then on the ASTER slope map, the values above 35% are more represented on the southern flank of the valley and thus highlight more the shapes of the relief in comparison with the SRTM slope map. These differences do not change the general tendencies of both datasets and might be related to the presence of noisier values on the ASTER GDEM

- The flow direction can be obtained from a D8 method or MFD algorithms extracted from an initial DEM. Here we adopt the D8 method implemented in the Arcgis 10.3 software (Arcgis Pro documentation Stream Order, Tarboton 1991). The calculated flow direction is then included as an input to deduce a flow accumulation map that calculates the number of upstream cells flowing in every pixel. Thanks to a threshold value, this flow accumulation map allows to reproduce a drainage network starting from any initial DEM.

Same procedure was used for the extraction of the drainage system from the SRTM and ASTER GDEM. Flow accumulation map has been classified selecting values $\geq$1000. Major differences from the current situation concern the drainage extracted from the SRTM 3 GDEM: the Tiwanaku River is located closer to the northern flank of the valley; the closest tributary to Lake Wiñaymarka does not join the course of the Tiwanaku River but has a mouth in the lake; the watercourse of the tributary located upstream of the archaeological site is located closer to the pre-Columbian city. However the extracted drainage from the ASTER GDEM present also some differences with current situation. Even if the Tiwanaku River is nearer to the actual watercourse, the extracted drainage is still located closer to the northern flank of the valley; the tributary associated to the archaeological site present a similar watercourse as the one observed with the SRTM 3 map. The medium vertical sensitivity and spatial resolution of the SRTM DEM clearly induced some artifacts in the extracted drainage. Although the one extracted from the ASTER GDEM seems more reliable, some differences with the current situation are still observed. These differences might still be related to the resolution of the GDEM but these discreet slope changes could also indicate some inherited topography from previous erosion phases and low lake level stands. These palaeo-flows, well developed and preserved in the topography, are indirectly found by the flow algorithm of the SIG (which fills the depressions linked to discrete divides to find an outlet).

In conclusion, because of its greater resolution, ASTER GDEM and its by-products (slope and drainage) were retained for our study.



SI Fig. 3. Comparison of the DEM extracted from the SRTM and ASTER dataset (source: U.S. Geological Survey). The drainage is presented with Strahler classification (Strahler 1957). The red star represent Tiwanaku archaeological site.

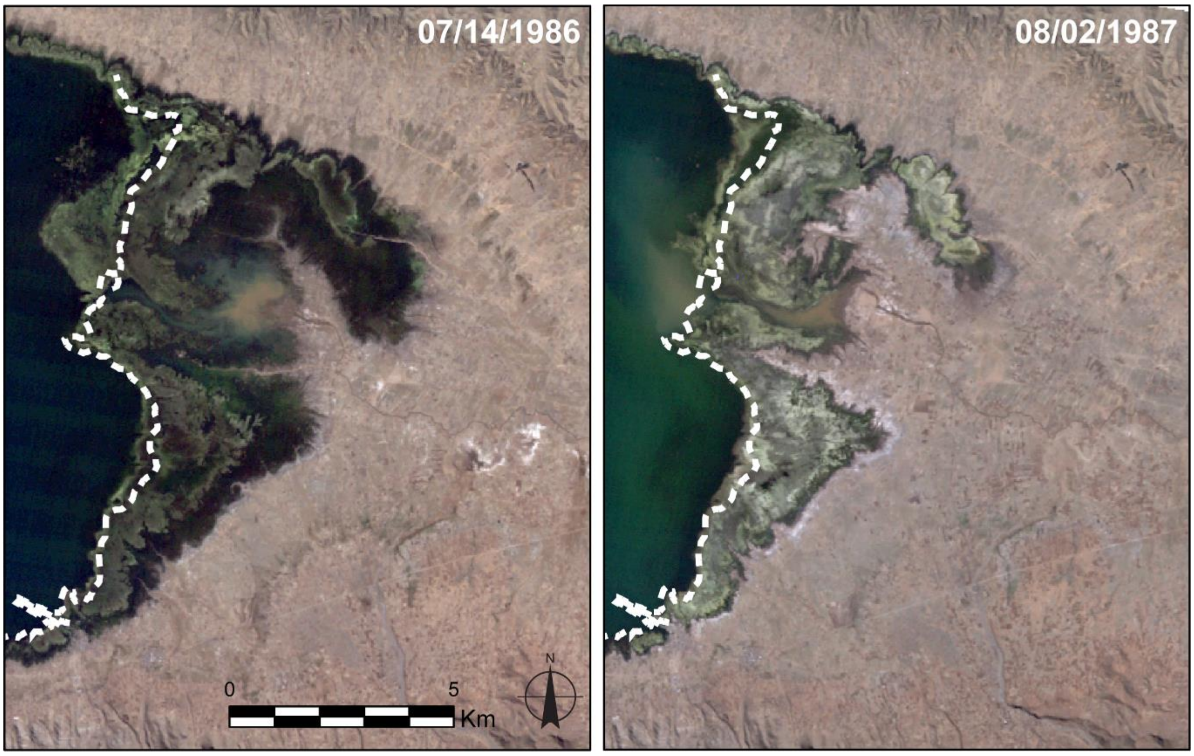
2. Historical geography

Nine set of aerial images have been gathered to reconstruct the evolution of the coastal and alluvial morphology (Main body of the article, Tab. 2).

Two satellite images (Landsat 5 TM-level 2; 1986-07-14 and 1987-08-02) allow to document the major floods observed consecutively between 1985 and 1987 (Erickson 1999, Gallego Revilla and Pérez González 2018, Roche et al 1992). The highest lake level is observed during winter 1986 (SI Fig 4). The related coastline has been extracted in order to highlight most important lake level variations and is represented in the main body of the article (Fig. 5). However for the same period, the topographical map of 1985 highlights the coastline related to years without flood (main body of the article, Fig. 5 B).

The aerial images we collected allow to reconstruct the coastline evolution since 1954-1955 (Main body of the article, Fig. 5). The general pattern, without taking into consideration the extreme event of 1985-1987, is a reduction of the surface of the Lake Wiñaymarka. This decrease can be estimated at 11.4 km^2 in 65 years (0.17 $km^2.yr^{-1}$). More details on the evolution of the coastline are given in the main body of the article.

Regarding the evolution of rivers in the lower valley (main body of the article, Fig. 5), it is possible to identify the ancient delta of the Tiwanaku River and its displacement to the current location. In the middle valley near the archaeological site of Tiwanaku (main body of the article, Fig. 6), the monumental quadrangular canal identified by previous studies (Kolata 2003, Pérez González and Gallego Revilla 2019) is clearly visible. The course of the Tiwanaku River is also clearly identifiable. Several meanders are still visible until 1972 in the area upstream of the archaeological site and are gradually adopting a straighter course.



SI Fig. 4. Landsat 5-level 2 images from 1986 and 1987. The images are represented in natural colors (Band 3-2-1). The white dashed line represent the current situation of the coast line.

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