



**HAL**  
open science

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

Marc-Antoine Vella, Nicolas Loget

► **To cite this version:**

Marc-Antoine Vella, Nicolas Loget. Geomorphological map of the Tiwanaku River watershed in Bolivia: implications for past and present human occupation. CATENA, 2021, 206, pp.105508. 10.1016/j.catena.2021.105508 . hal-03360090

**HAL Id: hal-03360090**

<https://hal.sorbonne-universite.fr/hal-03360090v1>

Submitted on 30 Sep 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

Vella Marc-Antoine<sup>1,2,\*</sup> and Loget Nicolas<sup>3</sup>

1. Institut Français d'Etude Andines, IFEA, UMIFRE 17 CNRS/MAEDI, La Paz, Bolivia

2. Sorbonne Université, CNRS-INSU, Institut des Sciences de la Terre de Paris, METIS UMR 7619, F-75005 Paris, France

3. Sorbonne Université, CNRS-INSU, Institut des Sciences de la Terre de Paris, IStEP UMR 7193, F-75005 Paris, France

\*. Corresponding author: Vella Marc-Antoine, mav.vella@gmail.com

UMR 7619 METIS - case courrier 105 - Sorbonne Université - 4 place Jussieu - 75252 Paris Cedex 05 - France

## 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.

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

35

## 36 **1. Introduction**

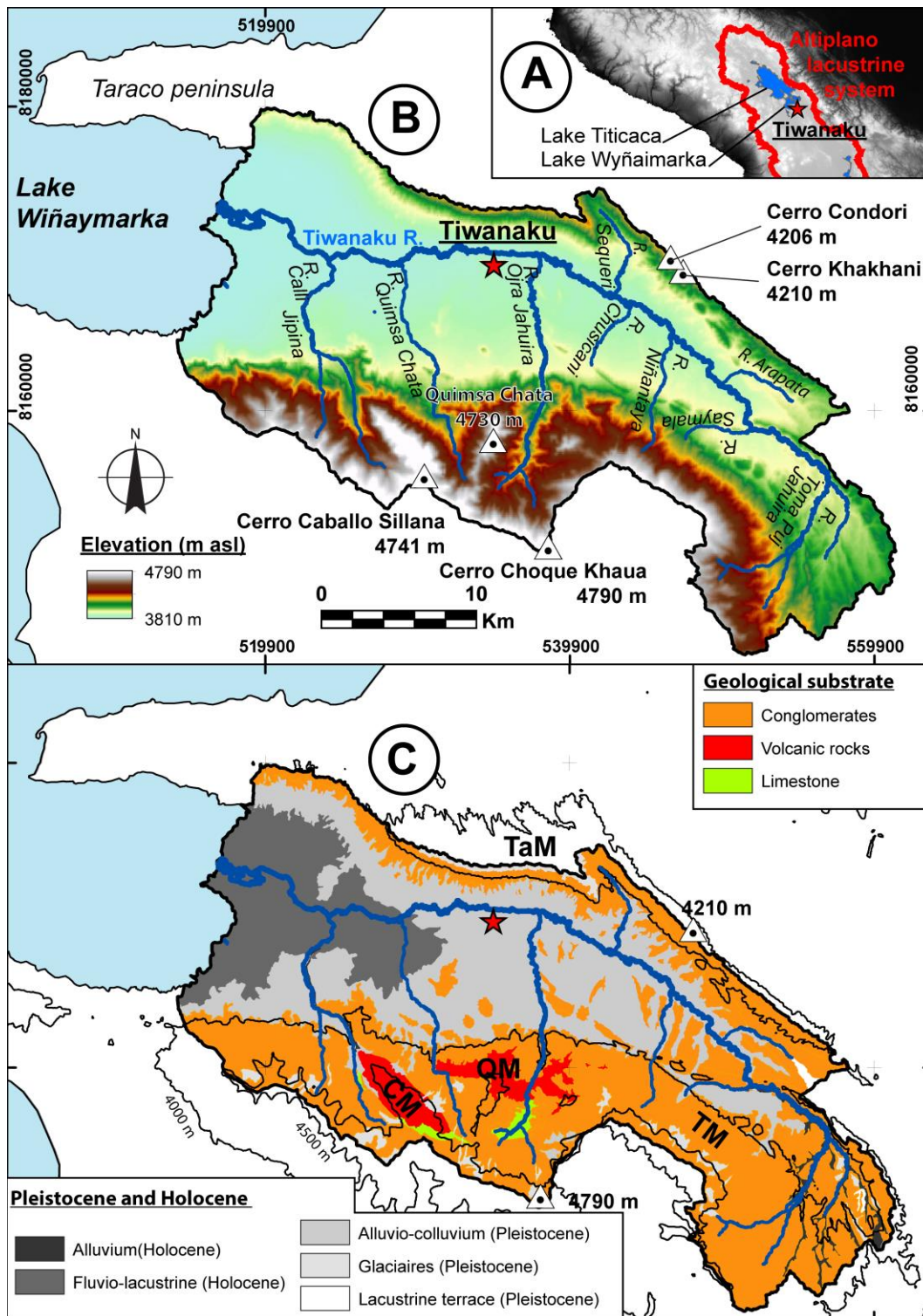
37 The Altiplano is a high plateau (between 3600 and 4200 m asl (Above Sea Level)) of about 190 000 km<sup>2</sup>,  
38 surrounded by peaks rising to over 6000 m altitude (Fig. 1A). The Altiplano lacustrine system (Titicaca-  
39 Desaguadero-Poopó-Coipasa Salt Lake) is the result of early Pleistocene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

42 Holocene climatic evolution, identified from the study of lacustrine sediments, shows that Lake Titicaca  
43 (7131 km<sup>2</sup>, mean depth 100 m, max depth 285 m) and its southern sub basin (Lake Wiñaymarka, 1428  
44 km<sup>2</sup>, mean depth 9 m, max depth 40 m) has undergone several major fluctuations (up to 15 m) (Abbott  
45 et al. 2003, Abbott et al. 1997, Baker et al. 2001b, Dejoux and Iltis 1992, Delaere 2019, Mourguiart et  
46 al. 1998, Rowe et al. 2004, Servant et al. 1995, Weide et al. 2017). Although some sedimentary  
47 formations have been described and mapped in the lake's vicinity, few conclusions about the influence  
48 of lake level variations on the local sediment routing system or the stratigraphic organization have  
49 been proposed (Baucom and Rigsby 1999, Farabaugh and Rigsby 2005, Rigsby al. 2003, Servant and  
50 Servant-Vildary 2003). On the other hand, long term archaeological occupation have been found in  
51 most valley systems surround Lake Titicaca (Capriles et al. 2014, Craig et al. 2010, Erickson 2000,  
52 Hastorf et al. 2005, Silverman and Isbell 2008, Stanish 2003). The valleys located in the southern part  
53 of the Lake Wiñaymarka (Tiwanaku, Katari and Desaguadero River), are one example among other that  
54 highlight this continuity (Albarracin-Jordan and Mathews 1990, Bandy 2006, Hastorf 1999, Isbell and  
55 Silverman 2002, Janusek 2008, Kolata 2003). It has been shown that during Holocene times, some pre-  
56 Columbian civilizations emblematic of the central Andean sector have developed, then disappeared  
57 possibly related to the lacustrine landscape evolution and prolonged drought (Arnold et al. 2021,

58 Binford et al. 1997, Kolata and Ortloff 1996, Ortloff and Kolata 1992). There is still a strong controversy  
59 about the chronology and a lot of critique of the environmentally-driven view of pre-Columbian  
60 cultures collapse in Lake Titicaca area (Erickson 1999, Graffam 1992, Bandy 2005, Stanish 2003, Janusek  
61 2004). Taking into account the complex relationship between ancient civilization and their  
62 environment, it is needed to understand the interactions between allogenic forcing of the natural  
63 system and human adaptations. As such, this paper proposes to establish a reliable cartography of the  
64 superficial sedimentary formations at the scale of the watershed of the Tiwanaku River.

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

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



76

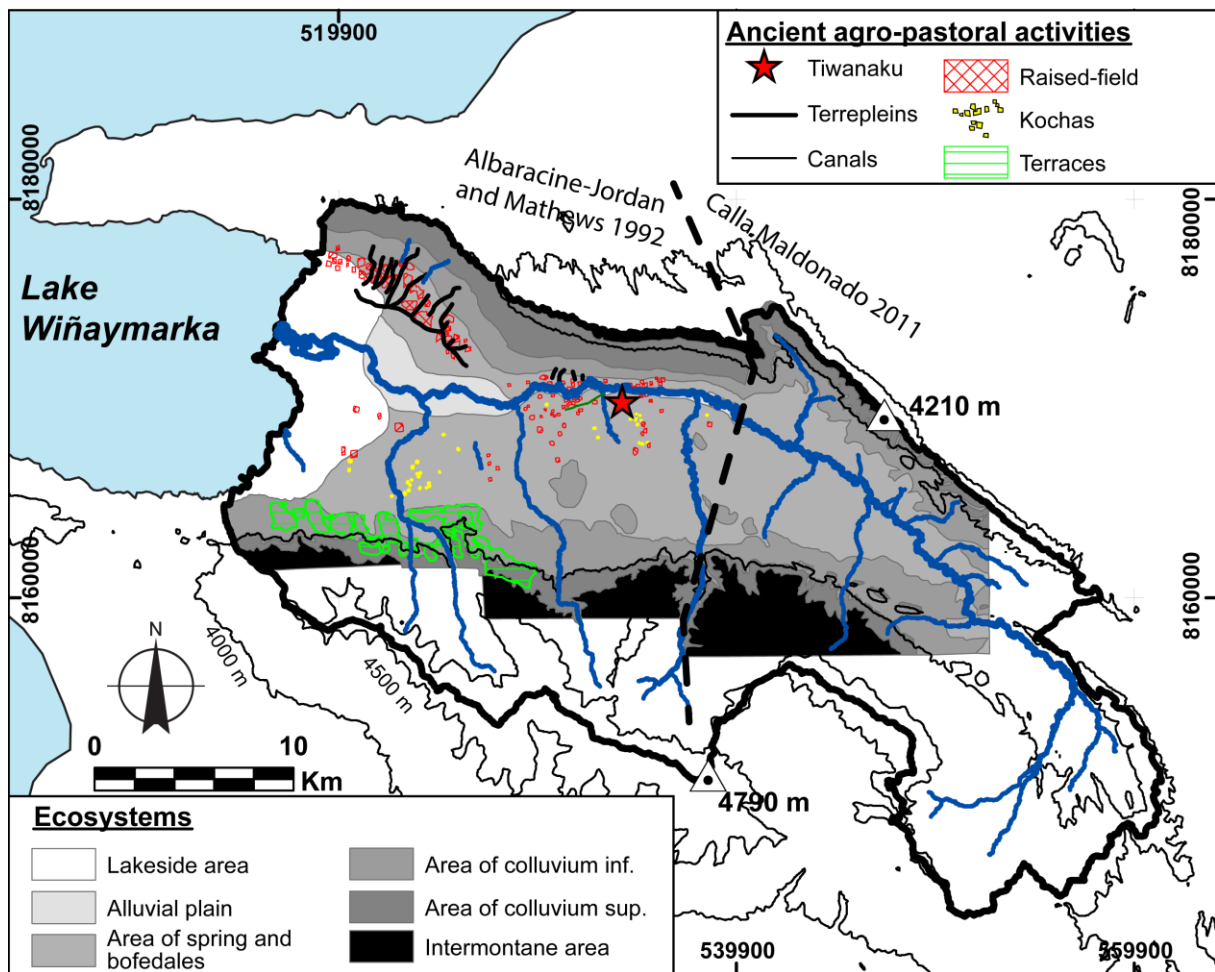
77 **Fig. 1: Geomorphological characteristics of the Tiwanaku watershed. A: Location of the study area in**  
 78 **South America. B: Geographical features and main rivers (topography: ASTER GDEM; Coord. System**  
 79 **UTM WGS 1984 zone 19S Lat., Long. in meters). C: Simplified lithology (after GEOBOL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

82

## 83 **2. Background**

### 84 **2.1 Geographical context**

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



98

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

101

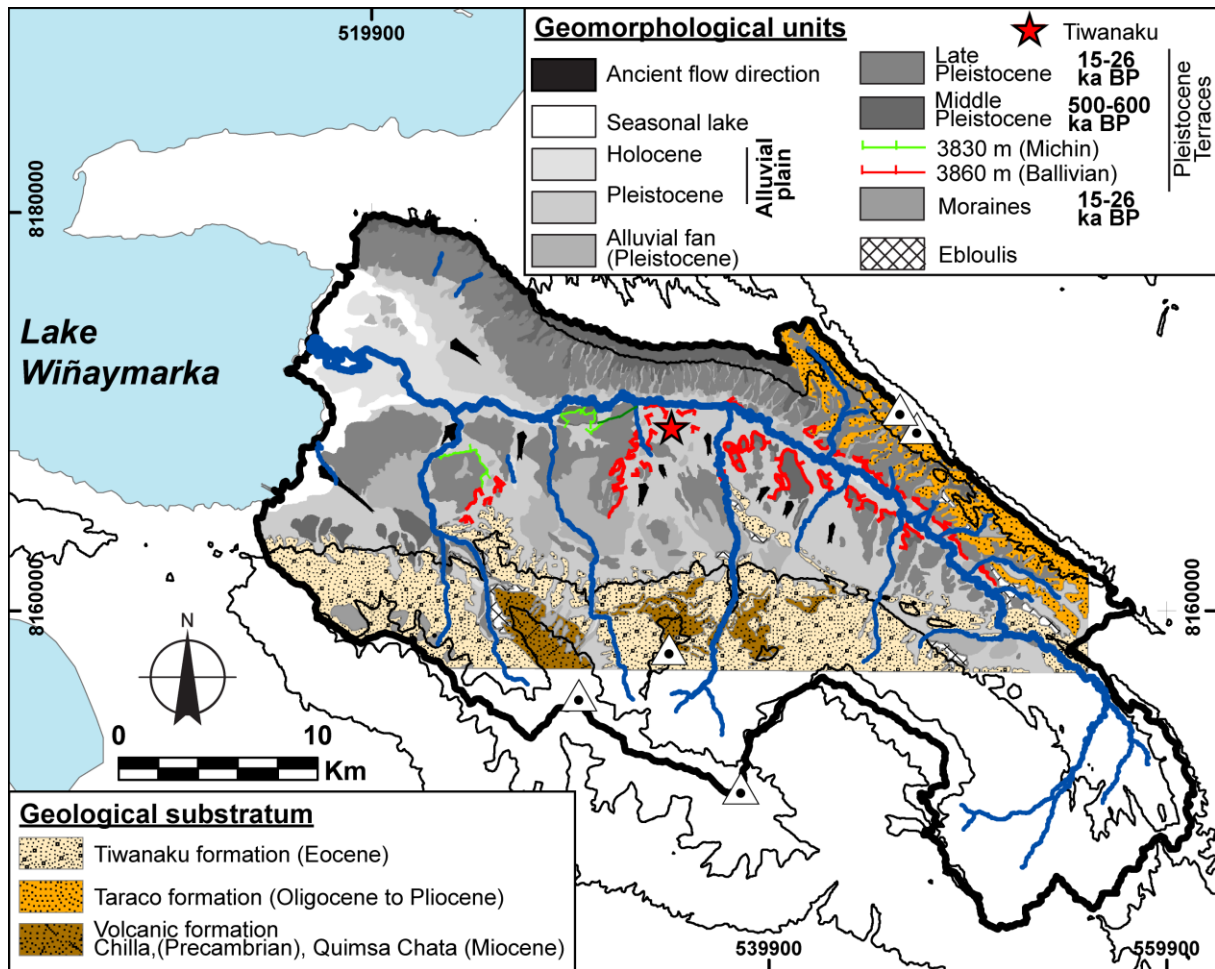
## 102 2.2 Geological context

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

108 The southern part of the Tiwanaku valley is flanked by the Tiwanaku mountain range oriented SE-NW,  
 109 and composed of highly folded sandstone and argillite dating from the Tertiary (Fig. 1C). This range is  
 110 connected eastward with the Quimsa Chata massif mainly composed by volcanic rocks and dated from

111 the Upper Miocene. Glacial formations dated from Pleistocene can be mainly observed on this  
112 southern flank. The northern flank is characterized by the Taraco mountain range. It is composed of  
113 conglomerates of the Coniri, Kollu Kollu (Oligo-Miocene) and Taraco (Pliocene) formations, organized  
114 in a NW-SE folded structure (Argollo 2003, GEOBOL 1994). Paleolimnological studies on Lake Titicaca  
115 identified large and rapid lake-level fluctuations during the Quaternary (Abbott et al. 1997, Abbott et  
116 al. 2003, Delaere 2017, Fritz et al. 2004, Mourguiart et al. 1998, Rowe et al. 2003, Servant and Servant-  
117 Vildary 2003, Theissen et al. 2008, Weide et al. 2017). Some lacustrine terraces can be observed in the  
118 lower parts of the Tiwanaku valley (between 3815 and 3940 m asl) and are related to Pleistocene high  
119 lake stands (Argollo 2003). The Bolivian Altiplano is a tectonically quiescent plateau situated between  
120 the fold-and-thrust belt of the eastern Cordillera and the active arc of the western Cordillera (Baucom  
121 and Rigsby 1999). The occurrence of tilted paleo shorelines associated to the Pleistocene Lake Minchin  
122 and located above the current Titicaca's shoreline, indicated some large scale tilting processes over  
123 the last 17 ky in the central Altiplano (Bills et al. 1994).





124

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

126

### 127 **2.3 Holocene alluvial and lake level variations**

128 The fluvial and lacustrine terraces as well as incision features of the Tiwanaku River can be linked to  
 129 Lake Titicaca variations (Abbott et al. 1997, Baker and Fritz 2015, Delaere 2017, Martin et al. 1993,  
 130 Mourguiart et al. 1998, Roche et al. 1992, Rowe et al. 2003, Weide et al. 2017). ). Annual variations can  
 131 be correlated to the tropical Andean South American Summer Monsoon rainfall (SASM) (Bird et al.  
 132 2011). At a decadal time scale, these variations are linked in response to events such as El Niño-  
 133 Southern Oscillation (ENSO) (events often associated with a prolonged dry season on the Altiplano  
 134 and/or a lake-level drops) (Martin et al. 1993, Vuille and Werner, 2005). Records from lacustrine  
 135 sediments (Abbott et al. 2003, Arnold et al. 2021, Bird et al., 2011), speleothems (Apaestegui et al.,  
 136 2014), and ice cores (Thompson et al. 2006, Thompson et al 2000, Thompson et al., 1998), suggest that

137 at centennial to millennial timescales precipitation levels in the Altiplano are linked to shifts in the  
138 Intertropical Convergence Zone (ICTZ) over the tropical Atlantic and Pacific (Abbott et al. 2003, Arnold  
139 et al. 2021).

140 Lake Titicaca experienced long phases of drought with lake levels sometimes much lower than the  
141 current one, in particular around 8 000 BP (Abbott et al. 1997, Abbott et al. 2003, Fritz et al. 2004,  
142 Weide et al. 2017, Wirrman et al., 1992).The Late Holocene water-level fluctuations in Lake  
143 Wiñaymarka evolved with (i) a minor lake-level rise (6–8 m) around 4000 BP (Wirrmann and  
144 Mourguiart 1995), (ii) a rapid 15–20 m lake-level rise around 3500 BP and (iii) 4 major cycles of lake-  
145 level transgression and regression during this global high-level stage (3200-2800 cal yr BP, 2200-2000  
146 cal yr BP, 1650-1450 cal yr BP, 900-700 cal yr BP; Abbott et al. 2003, Abbott et al. 1997, Binford et al.  
147 1997). Studies from the main basin of Lake Titicaca (Baker et al. 2001a, Seltzer et al. 1998) indicate that  
148 Lake Titicaca was below the modern spill level until at least 3000 BP. The current period reached a  
149 maximum lake level in the 17<sup>th</sup> and 18<sup>th</sup> centuries (Wirrmann 1988) and can be correlated to the wet  
150 period of the Little Ice Age (LIA, Mourguiard et al. 1997, Rabatel et al. 2008, Thompson et al. 1986). The  
151 lake water level fluctuated more than six meters during the 20<sup>th</sup> century (Roche et al. 1992).

152 Holocene sedimentary formations of fluvial origin are characterized by two or three continuous  
153 sequences of fine deposits (clay, silts, sand and gravel) with intercalations of peat levels. These  
154 sedimentary formations are related to the evolution of alluvial fans at the base of the slopes of the  
155 valley in relation to an anastomosed hydrological system with small channels (Argollo et al. 2003). A  
156 significant number of sources are still located at the base of the main mountain ranges. The modern  
157 rivers occupy the channel carved out by the last incision episode (900-700 cal yr BP). Studies from Lake  
158 Wiñaymarka suggest that between 3500-700 BP, the Desaguadero River was not an effective outlet  
159 from Lake Titicaca (Abbott et al. 1997). However, all previous lake level changes have not been clearly  
160 identified within alluvial formations. Studies on Desaguadero, Ilave and Ramis Rivers indicated that  
161 after 3300 yr BP, the terrace formation is the result of at least three rapid water-level falls and  
162 migration of the River (Baucom and Rigsby 1999, Farabaugh and Rigsby 2005). Previous studies

163 reported also stabilization phase valleys of the Altiplano presented evidences of soil formation during  
164 the early Holocene (between 8350-6780 BP, (Rigsby et al. 2003), followed by large incisions (6045-4545  
165 BP; Farabaugh and Rigsby 2005, Servant and Servant-Vildary 2003) and two periods of sedimentary  
166 filling of the valleys coinciding with a phase of lake-level rise and overflow (4045 BP-2545 BP and 2045-  
167 1645 BP; Baucom and Rigsby 1999, Farabaugh and Rigsby 2005, Rigsby et al. 2003). During the late  
168 Holocene, studies suggest that precipitation may have decreased slightly over the Amazon Basin during  
169 the last ~2200 years while Andean precipitation continued to increase (Bird et al. 2011). Subsequent  
170 downcutting occurred after approximately 1600 yr BP but could not be chronologically located.

171

## 172 **2.4 Geomorphological mapping**

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

179

180

181

182

183

184

185

186

187

188

189 **Tab. 1: Synthetic characteristics of geomorphological features from Albarracin-Jordan and Mathews**  
 190 **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 <i>bofedales</i> (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

191

192 The 1990's geomorphological pioneers' works are based on an altimetric approach and aims to  
 193 reconstruct the large ecosystems forming the valley (Albarracin-Jordan and Mathews 1990) (Fig. 2).  
 194 More recently, Calla Maldonado's (2011) work used a similar method to deduce the occupation  
 195 strategies of pre-Hispanic societies that occurred in the middle valley. They distinguish 6 ecosystems  
 196 (lacustrine zone, alluvial plain, springs and *bofedales*, Lower Colluvial Zone, Upper Colluvial Zone, inter-  
 197 mountainous areas (Fig 2).  
 198 The work carried out by Argollo et al. (2003) is based on the geological composition of the subsoil. It  
 199 provides detailed information on the location of Pleistocene and Holocene lacustrine formations in the  
 200 lower valley (Fig. 3). Some terraces are associated with dated paleo shorelines (Bills et al. 1994, Servant  
 201 et al. 1995, Sylvestre et al. 1999) and were related to high levels of Lake Titicaca (Argollo et al. 2003,  
 202 Fritz and al. 2004, Mourguiard et al. 1997, Servant et Fontes 1978, 1984). Argollo et al. (2003) showed  
 203 that the mountain range and the Taraco peninsula present a topography cut by several terraces of low  
 204 slope (between 1 and 5 %).

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

210

## 211 **2.5 Pre-Columbian agricultures and landscape inheritances**

212 During the late Holocene and at the scale of Mesoamerica and South America, raised-field agriculture  
213 in wetlands was conducted in a wide range of environments from sea level to over 4000 m elevation,  
214 covering a great range of soils and climates (Renard et al. 2012). Among other examples, raised fields  
215 have been found in the Basin of Mexico (e.g., Sanders et al. 1979), in the Altiplano of Bolivia and Peru  
216 (Erickson 1992, 2003, Kolata 1996), within inter-Andean valleys marshes (Wilson et al. 2002), were also  
217 related to seasonally flooded savannahs in the lowlands (Plazas and Falchetti 1990, Reichel-Dolmatoff  
218 and Reichel-Dolmatoff 1974, Rostain 2008, Spencer et al. 1994, Walker 2004) and even in southern  
219 regions of Chile (Dillehay et al. 2007). Massive irrigation networks created as early as 4000 BP in desert  
220 coastal valleys of Peru, turned them into productive landscape for prehistoric inhabitants and provided  
221 the foundations for complex society (Moseley 1983). The 113 km long Chicama-Moche intervalley  
222 canal combining aqueducts and other sophisticated hydraulic structures constructed by the Chimú  
223 around AD 1400 is another example among other of water management knowledge (Erickson 1992).  
224 Previous studies in the Tiwanaku valley identified 3 types of agro-pastoral systems (Albarracín-Jordan  
225 and Mathews 1990, Kolata 2003). They distinguished the terraces of cultures, the *kochas* (artificial  
226 ponds of circular shape used for water retention, sometimes organized in groups connected by  
227 channels) and the *sukka khollus* (platforms of raised cultures organized in networks connected with  
228 natural and artificial channels). These inherited agricultural techniques from the pre-Columbian  
229 civilizations attest to human adaptation to the environment (Kolata 2003). Raised field agriculture  
230 (*sukka khollus*) provided pre-Columbian farmers with better drainage and protection against flooding,

231 soil aeration, moisture retention during the dry season and a fertility advantage. It also aimed at  
232 conserving water for long- and short-term droughts, using the stored water to extend growing seasons  
233 (Erickson 1992). This agricultural technic offers also more favorable microclimates as a greater frost  
234 tolerance in cold highland environments (Erickson 1992, Kolata and Ortloff 1989, Lhomme and Vacher  
235 2002). Raised field from the Altiplano were cultivated beginning about 3000 years ago and formed  
236 much of the subsistence basis for the Tiwanaku Empire (Kolata 1996). Finally, Kolata (2003) highlights  
237 the existence of partial regularization of the Tiwanaku River, canals and platforms in association with  
238 raised fields in the lower and middle valleys. However, no chronological control exist to relate these  
239 landscape modifications. There is consensus that these canals and raised fields are attributed to the  
240 Tiwanaku culture (400-1150 AD) but a controversy still exists on the chronology of disappearance of  
241 these integrated regional agricultural system (Abbott et al. 1997, Erickson 1999, Graffam 1992, Janusek  
242 and Kolata 2004, Kolata et al. 2000, Ortloff and Kolata 1992, Vranich 2013).

243

## 244 **3. Methods and technics**

### 245 **3.1 Remote sensing**

246 We used Landsat 8-level 2 satellite image (date: 2016-september-18; multispectral 30 m, panchromatic  
247 15 m and thermic 60 m resolution), Advanced Spaceborne Thermal Emission and Reflection  
248 Radiometer (ASTER) Global Digital Elevation Model Version 3 (GDEM 003) (~30m pixel resolution) and  
249 Shuttle Radar Topography Mission Version 3.0 Global 1 arc second (SRTM 3) (SI Fig. 3) centered at the  
250 watershed scale. Landsat 8 and ASTER and SRTM 3 data were downloaded from the USGS (United State  
251 Geological Survey) Earth explorer website ([earthexplorer.usgs.gov](http://earthexplorer.usgs.gov)) and processed using Arcgis 10.3  
252 software.

253 Remote sensing has long been used to characterize the wetlands within the Altiplano (Moreau et al.  
254 2003, Moreau and Le Toan 2003, Otto et al. 2011, Vining and Williams 2020). Altiplano wet grasslands  
255 are composed of two distinct category of vegetation. The *titora* is a perennial reed (Cyperaceae family)

256 which grows in water up to 5.5 m depth or in inland areas subject to summer flooding. The *bofedales*  
257 are characterized by permanently water-saturated highland short grasslands with over 60 plant species  
258 forming a dense carpet (~90% vegetation cover), crisscrossed during the wet season by seasonal  
259 shallow streamlets (Moreau and Le Toan 2003). Most of the valley vegetation is composed of  
260 bunchgrass (*Festuca* sp. and *Stipa* sp.) and/or low shrubs (*Parastrephia* sp.) (Vining and Williams 2020).  
261 Some scattered trees like eucalyptus are present near most important villages. Other type of  
262 vegetation in the Altiplano include trees like *Polylepis* sp. among other but are not represented in the  
263 Tiwanaku valley.

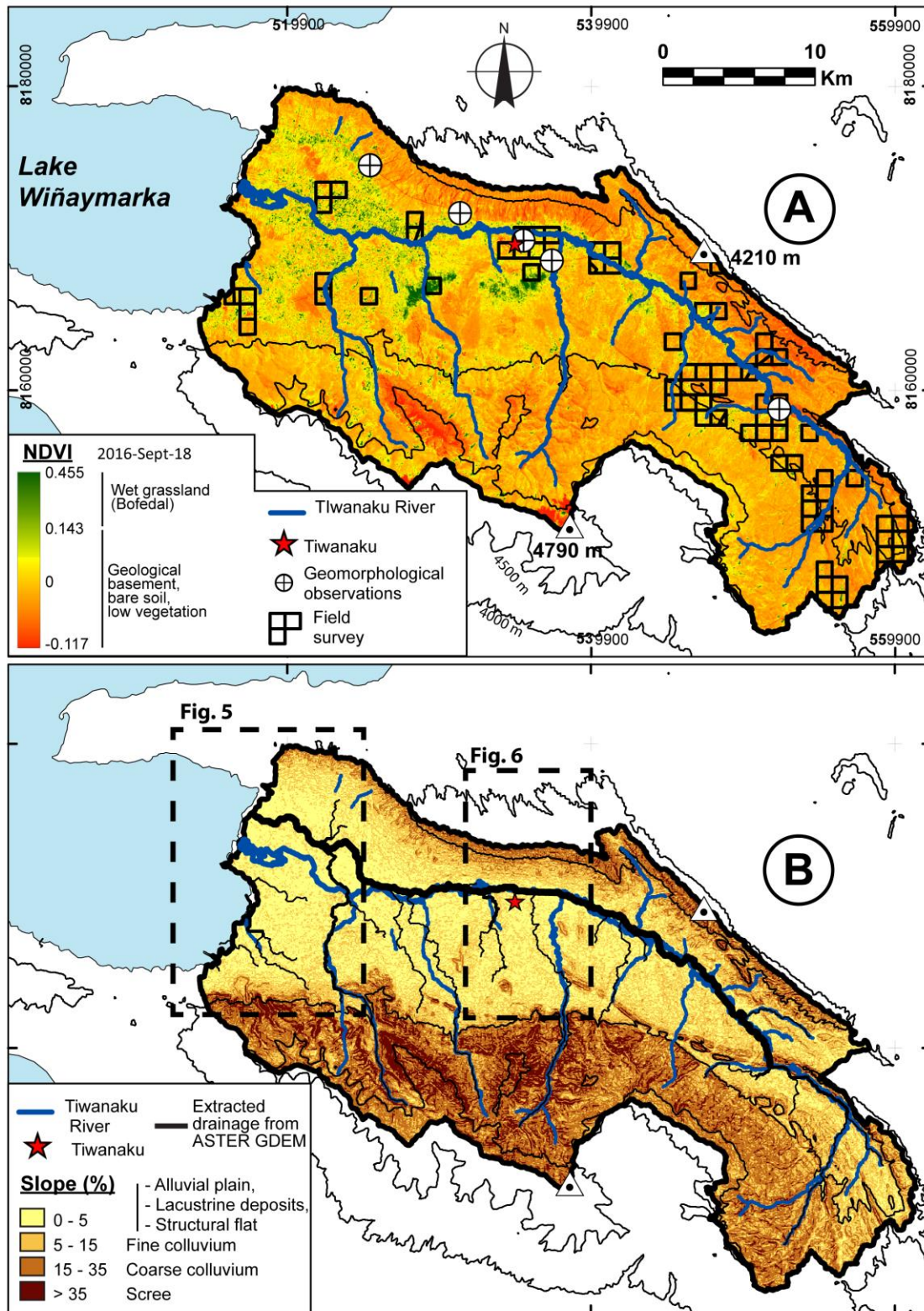
264 In order to characterize the hydric and vegetation state we calculated the NDVI index (Normalized  
265 Difference Vegetation Index) that corresponds to the normalized difference between red and near-  
266 infrared (NIR) energy reflectance of the vegetation cover (Bharathkumar and Mohammed-Aslam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

$$269 \frac{(NIR-Red)}{(NIR+Red)} = NDVI \text{ where Red= band 4, NIR= band 5 and } -1 < NDVI < 1.$$

270 This vegetation index enables to distinguish the density of the vegetation cover (wet grassland, ie.  
271 *titora* and *bofedal*), waters (lakes, rivers, *kochas* and wetland) and soils (rocks, buildings, roads).  
272 Vegetated areas generally present relatively high near-infrared reflectance and low red reflectance and  
273 are associated to positive NDVI values; water and wet area present negative values as these features  
274 have larger reflectance in Red than in NIR. Rock and bare soil areas have similar reflectance in the two  
275 bands and produce values near zero. (D'Allestro and Parente 2015). In partial and sparse vegetation  
276 cover like the Altiplano, senescent plant reflectance converges with bare soils (Vining and Williams  
277 2020). However, wet grasslands are the only native forage resources available around the year,  
278 including during the dry winter season (Moreau et al. 2003). The comparison of the evolution of the  
279 monthly mean NDVI and map (SI Tab. 1, SI Fig 1 and 2) along a year demonstrated that September was  
280 the most accurate period to distinguish wet grassland from bare soil area (SI Text).

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





287

288 **Fig. 4: Remote sensing and geomorphic parameters obtained on the Tiwanaku River watershed. A:**

289 **NDVI map (date: 2016-september-18, Landsat 8 OLI/TIRS -level 2 images, source: U.S. Geological**

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

292

### 293 **3.2 Historical geography**

294 For this study, we have compiled and georeferenced the geological, topographic, geomorphological  
295 maps and historical aerial photos taken between the 1930's and 2019 in an ArcGIS environment (Tab.  
296 2, Fig 5 and 6, SI Fig. 4). The oldest cartographic documents available (dated from ~1930), were  
297 acquired specifically around the Tiwanaku archaeological site (1 mosaic, 4.84 km<sup>2</sup>) (Ortloff 2014). The  
298 1954-1955 and 1972 aerial photographs were obtained by the Bolivian national services. The 1954-  
299 1955 campaign concerned the full catchment area (110.25 km<sup>2</sup>, 72 tiles), whereas the 1972 campaign  
300 was restricted to the medium course of the Tiwanaku River (1.4 km<sup>2</sup>, 14 tiles). 2014 and 2019 satellite  
301 images were obtained from the U.S. Geological Survey database. 2017 aerial photographs of the  
302 Tiwanaku area were obtained from the Guaquira-Tiwanaku archaeological mission. All aerial  
303 photographs allow us to distinguish the channels of the Tiwanaku River, wetlands and the shoreline  
304 for each period. We completed this geodataset with published topographic maps reporting alluvial,  
305 lacustrine and shoreline positions mapping between 1983 and 1985 by the IGM (1985).

306

307

308

309

310

311

312

313

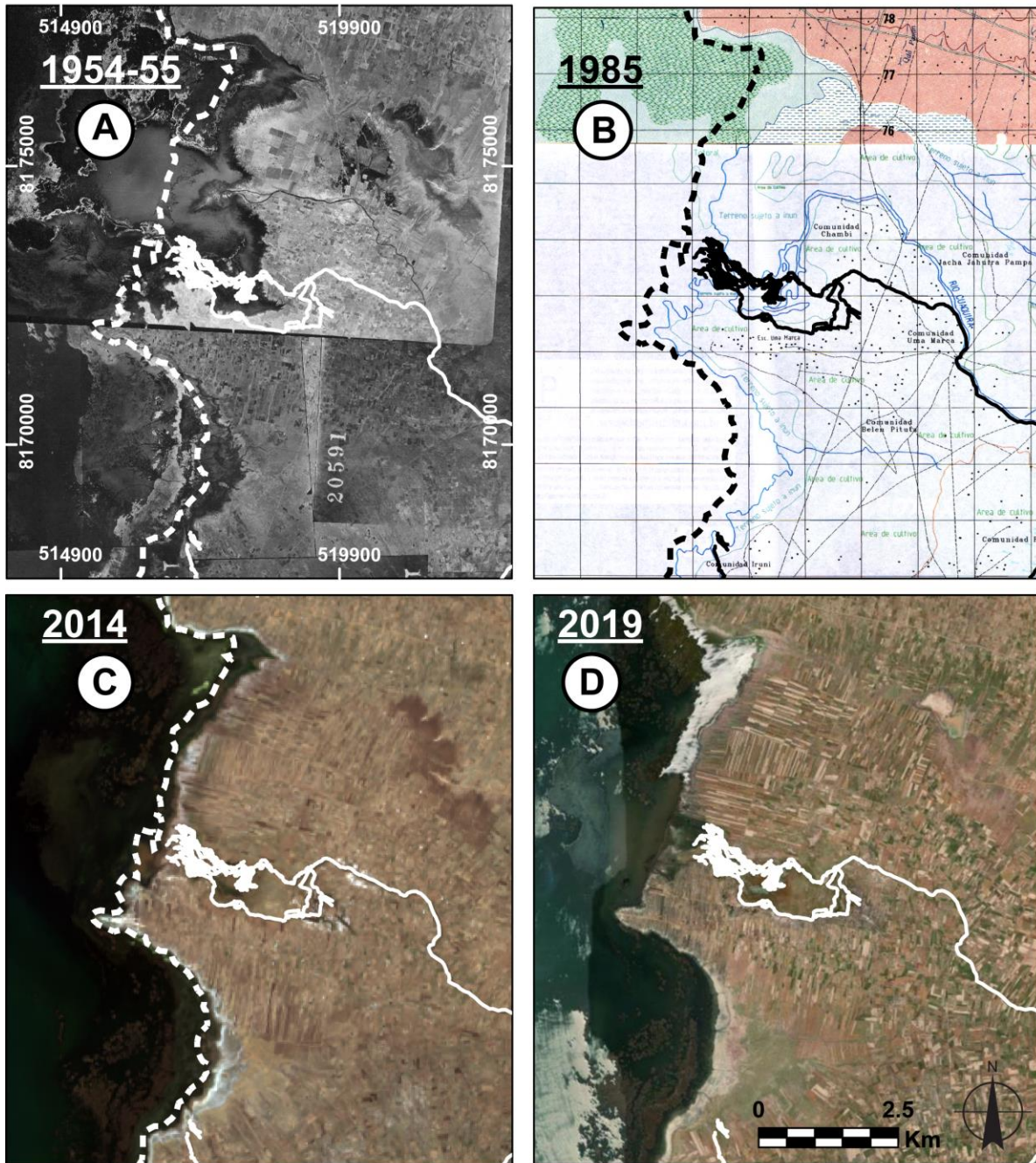
314

315

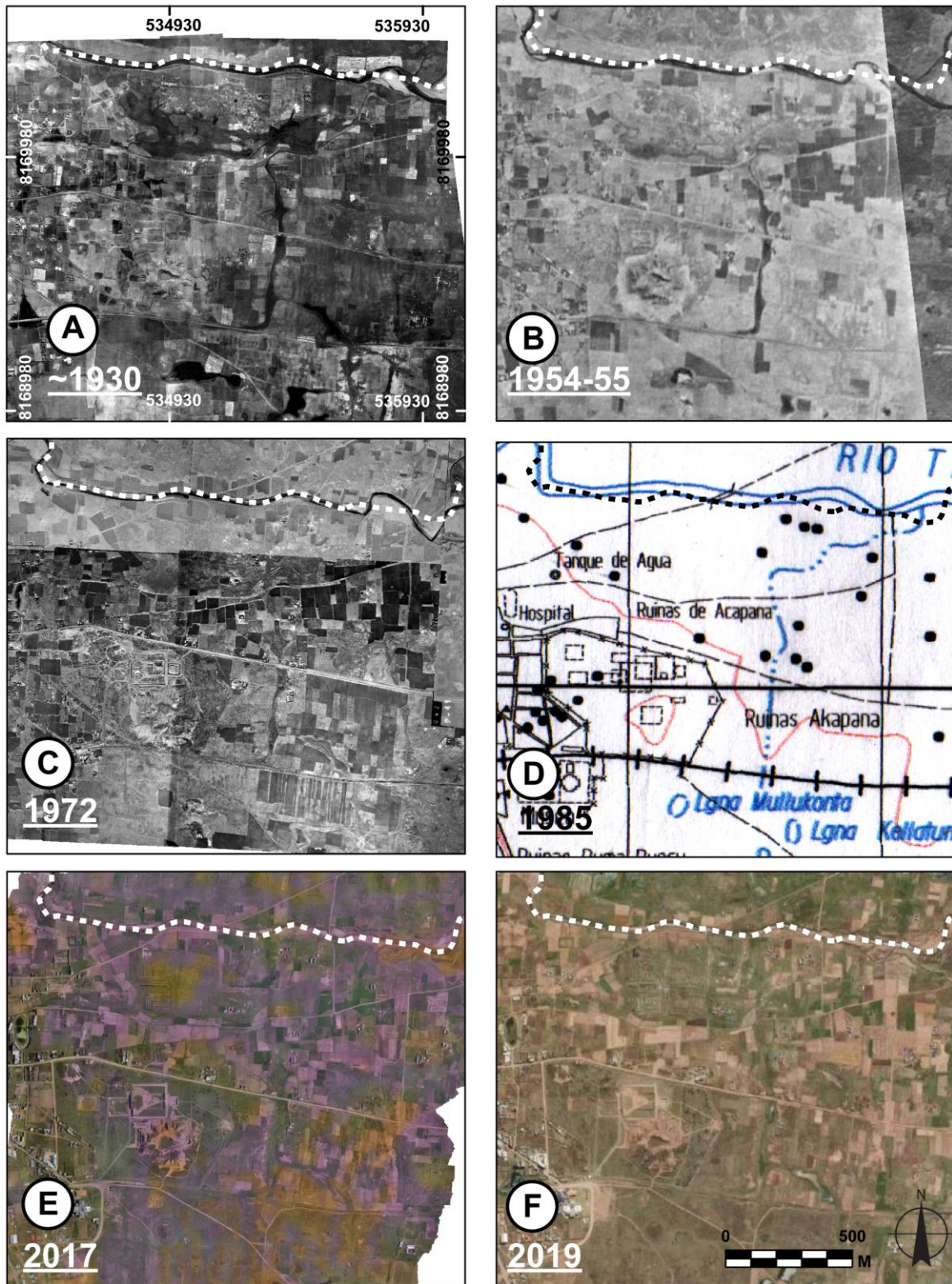
316 **Tab. 2: List of aerial images used to reconstruct the evolution of the coastline and of the Tiwanaku**  
 317 **River drainage system.**

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

318



319  
 320 **Fig. 5: Aerial photographs near the mouth of the Tiwanaku River in Lake Wyñaimarka.** The dotted  
 321 line represent the current situation of the coastline and the continuous line the current location of the  
 322 Tiwanaku River. **A. 1954-55.** Source: Instituto Geográfico Militar de Bolivia. **B. 1985.** Source: Instituto  
 323 Geográfico Militar de Bolivia. **C. 2014.** Source: Landsat 8 OLI/TIRS-level 2 courtesy of the U.S. Geological  
 324 Survey. **D. 2019.** Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES / Airbus, DS, USDA,  
 325 USGS, AeroGRID, IGN, and the GIS User Community.



326

327 **Fig. 6: Aerial photographs of the Tiwanaku archaeological site.** The dotted line represent the current

328 situation of the Tiwanaku River. **A. 1930'**. Source: Instituto Geográfico Militar de Bolivia. **B. 1954-55.**

329 Source: Instituto Geográfico Militar de Bolivia. **C. 1972.** Source: Instituto Geográfico Militar de Bolivia.

330 **D.1985.** Source: Instituto Geográfico Militar de Bolivia. **E. 2017.** Source: Guaquira-Tiwanaku project. **F.**

331 **2019.** Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES / Airbus, DS, USDA, USGS,  
332 AeroGRID, IGN, and the GIS User Community.

333

### 334 **3.3 Field acquisition and observation**

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

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

348

## 349 **4 Results**

### 350 **4.1 Remote sensing**

351 We used the NDVI map as a first order approximation to distinguish 3 main classes of vegetation cover  
352 and as an indirect indicator of geomorphological feature (ie. wet grassland (*titora* and *bofedal*); water  
353 and wet area; rock and bare soil areas) (Fig. 4A). In the Tiwanaku valley, during the month of  
354 September, NDVI values ranged from -0.117 to 0.455. Water and wet areas are characterized by  
355 negative NDVI values (D'Allestro and Parente 2015) but no clear features associated to inland water

356 bodies were identified in the Tiwanaku valley. Previous research on the Altiplano (Moreau et al. 2003,  
357 Moreau and Le Toan 2003) demonstrated that NDVI values ranging between 0.508 and 0.143  
358 correspond to areas of wet grassland (*titora* and *bofedal*). They are mainly located along the Tiwanaku  
359 River (*bofedal*) and near the Lake Wiñaymarka (*titora*). These features are related to Pleistocene and  
360 Holocene alluvial plain as well as Holocene lacustrine deposits identified by previous studies (GEOBOL  
361 1994). In particular, two sets of wet grassland (*bofedal*) stand out just on south of the Tiwanaku River  
362 in the middle valley. NDVI values ranging between 0.143 and 0 are located at high and medium  
363 elevation. These features are related to the geological basement, bare soils areas and to large domains  
364 where the vegetation is senescent. They coincide with a large part of lowlands and intermountain area  
365 identified by previous studies (Albarracin-Jordan and Mathews 1990, Calla Maldonado 2011).

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

374 The 15-35% slope range corresponding to high erosion domains (4100 to 4500 m asl), coincide  
375 approximately with the UCZ described by previous studies (Albarracin-Jordan and Mathews 1990, Calla  
376 Maldonado 2011). The >35% range slope corresponds to very high erosion domains (> 4500 m asl) and  
377 are related roughly to intermountain areas described in previous studies (Albarracin-Jordan and  
378 Mathews 1990, Calla Maldonado 2011).

379 The extracted drainage flow roughly mimics the course of the actual Tiwanaku River except in the  
380 downstream part and for several south confluences. This implies that discreet slope changes,

381 undetected by the DEM's resolution using for drainage extraction, have possibly modified the course  
382 of the recent Tiwanaku River.

383 Ancient agricultural systems composed of *sukka kollus* and *kochas* are located in low erosion sectors  
384 (0-5% slope range). These features are associated with wet grassland area (*bofedal*,  
385  $0.143 < NDVI < 0.455$ ) and bare soils area ( $0 < NDVI < 0.143$ ) respectively.

386

## 387 **4.2 Historical geography**

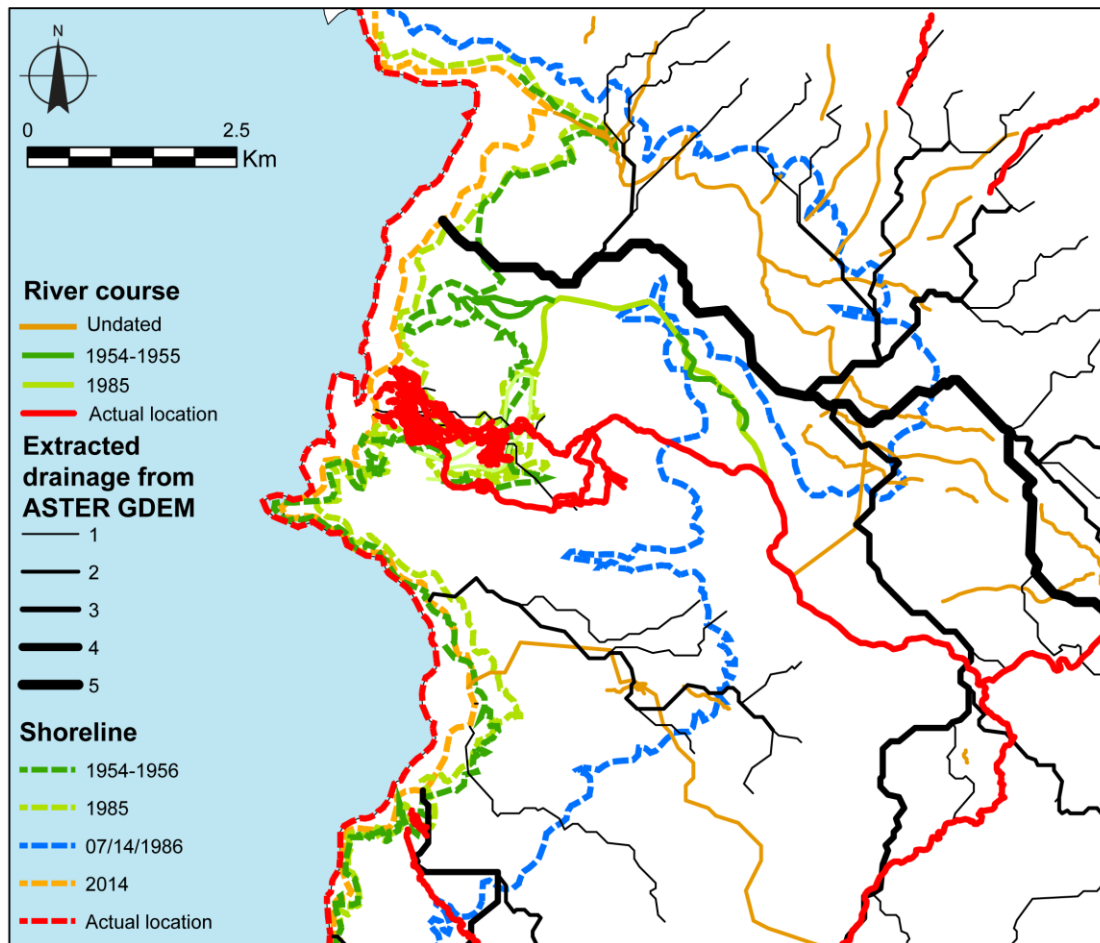
388 The resolution of the historical aerial photographs allows to track the mobility of alluvial and lacustrine  
389 origin landforms since the first half of the 20<sup>th</sup> century. We mainly focus our analysis on Lake  
390 Wiñaymarka (Fig 5 and Fig. 7) and Tiwanaku archaeological areas (Fig.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

393 We have mapped coastline variations of the Lake Wiñaymarka observed between 1954-1955 and 2019  
394 (Fig 5 and Fig. 7). The displacement of the coastline shows a regressive pattern and can be estimated,  
395 on average, at 400 m between 1954-55 and 1985 ( $13.3 \text{ m.yr}^{-1}$ ), and at 100 m between 1985 and 2019  
396 ( $2.9 \text{ m.yr}^{-1}$ ). However, this setback is not linear. A minor transgressive incursion with a fluctuation of  
397 the coastline could be observed between 1985 and 1987 (Gallego Revilla and Pérez González 2018)  
398 and was estimated at 5km inland in comparison to the position of 1985 (SI Fig. 4). We have also mapped  
399 a drainage shift (1.5 km) of the terminal course of the Tiwanaku River and delta toward the south  
400 during the 1954/1955-2019 period. The outlet and delta shifts occurred mainly during the 1954-1985  
401 stage whereas the main stream shift occurred during the 1985-2019 stage. Furthermore, we can  
402 observe that automatic extracted drainage flows of the downstream part of the Tiwanaku River are  
403 more concordant with the 1954-1955 course than the 2019 course.

404 Around the Tiwanaku area (Fig. 6 and Fig. 8), we have observed some clear evidences of channel  
405 evolution since the 1930's. The stream is more meandering between 1930 and 1972 and the loops are  
406 intersected by the 2019 channel. However, some palaeochannels predate the oldest documents used



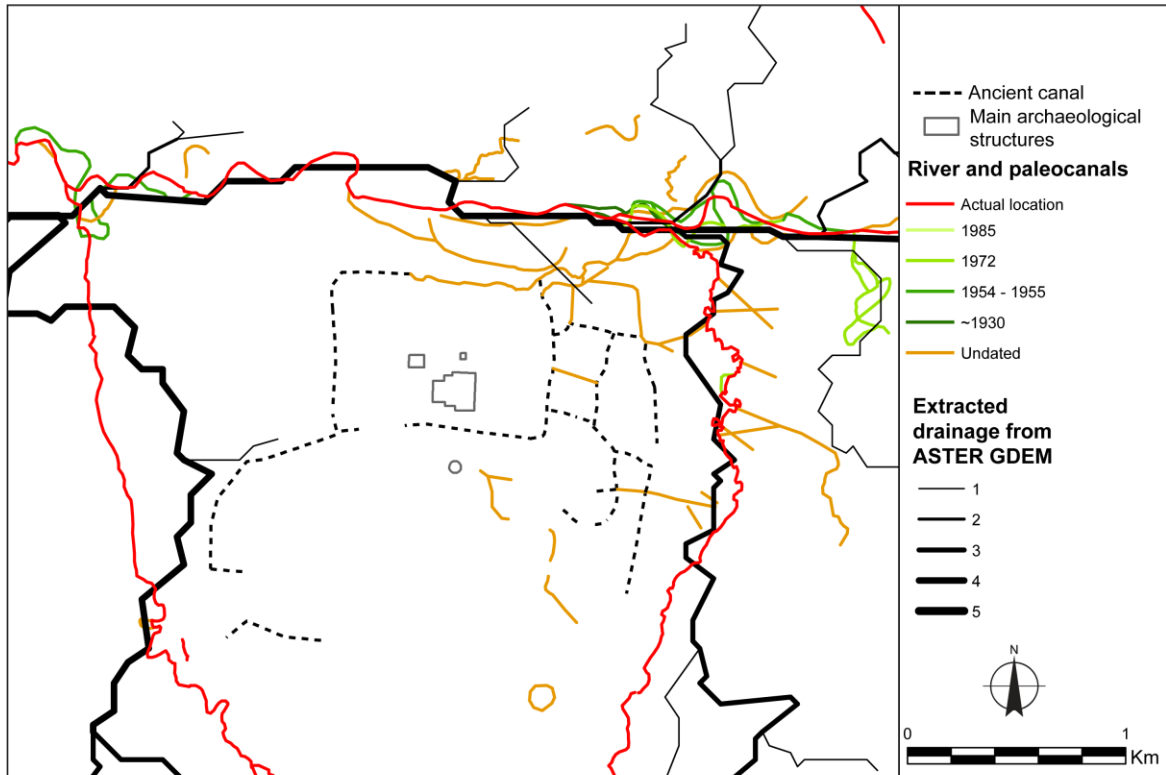
407 in our study (undated paleochannels and/or canals). They are located in the northern part of the lower  
408 valley. They depict an anastomosed morphology which can be linked to a wetter period whose  
409 chronology cannot yet be specified. The historical geography results allow to roughly differentiate the  
410 Pleistocene alluvial deposits from those related to Holocene, but it is necessary to cross combine with  
411 field survey in order to better distinguish these two geomorphological features. Concerning  
412 documented archaeological features, our results are in agreement with previous researches  
413 (Albarracin-Jordan and Mathews 1990, Calla Maldonado 2011, Argollo 2003, Kolata 2003). The  
414 agricultural terraces could not be mapped with actual aerial photography and this still requires a  
415 specific field survey. On the contrary, the *kochas* are still visible and are mainly located on Pleistocene  
416 lacustrine terraces. Ancient canals are mainly associated to Pleistocene alluvial deposits and connect  
417 different part of the Holocene river courses. In the lower valley, some ancient canals correspond to the  
418 extracted drainage from the ASTER GDEM. Around Tiwanaku, they seem to be connected to the  
419 tributary located upstream of the archaeological site (Ojra Jahuirá River). These ancient canals are  
420 located between the wet grassland areas identified on the NDVI map and permanent or intermittent  
421 watercourses in the lower valley and around Tiwanaku. Inside these wet areas, aerial photographs  
422 showed evidences of *sukka kollus* attested by the presence of remnant platforms separated by small  
423 canal.



424

425 **Fig. 7: Evolution of the coastline and of the Tiwanalu River since 1954-55.** Location of Fig. 5 is

426 represented in Fig 4B.



427

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

430

### 431 **4.3 Field acquisition and observation**

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

437 Wet grasslands are characterized by dense hygrophilous vegetation and their location were confirmed  
 438 during field surveys. They can be associated with the area of springs and *bofedales* or seasonal lake  
 439 sectors identified by previous works, (Albarracin-Jordan and Mathews 1990, Argollo et al. 2003, Calla  
 440 Maldonado 2011). However, our cartography provides more accurate details about their location,

441 superficies and characteristics. Wet grasslands (*bofedal*, slope 0-5%,  $0.143 < \text{NDVI} < 0.455$ ) have been  
442 observed in front of the large Holocene sedimentary fans and on the Pleistocene lake terraces on the  
443 southern flank (near Quimsa Chata River and above Tiwanaku archaeological site) and along the river  
444 in the middle and high valley. They are compatible with the agrarian activities of the valley.

445 Slope deposits are related to LCZ, UCZ and intermountain identified by previous studies (Albarracín-  
446 Jordan and Mathews 1990, Calla Maldonado 2011). Our study, based on remote sensing cross  
447 combined with field survey, helps to refine the sedimentary composition and the spatial organization  
448 of slope deposits area. Slopes are composed of structural flats and medium to very high erosion  
449 domains. Structural flats are observed around 4500 m asl in the southern flank of the middle valley.  
450 They are related to bare soils and low vegetation with low erosion potential (slope 0-5%;  $0 < \text{NDVI} <$   
451  $0.143$ ). Medium erosion domains (slope 5-15%) are identified at the bottom of the north and south  
452 slope and are mainly composed of fine colluvium with moderately developed soils. Nowadays, the  
453 most important part of the slopes is related to this geomorphological feature. Sectors of high erosion  
454 (slope 15-35%) are mostly located on the southern flank of the valley between 4100 and 4500 m asl  
455 and present a NDVI related to bare soils, low vegetation or geological basement ( $0 < \text{NDVI} < 0.143$ ).  
456 High erosion sectors are characterized by coarse colluvium, with very little developed soils, with some  
457 scree lanes mostly located on the southern slope. Sectors of very high erosion domains (>35%) are  
458 mostly related to the geological basement ( $0 < \text{NDVI} < 0.143$ ).

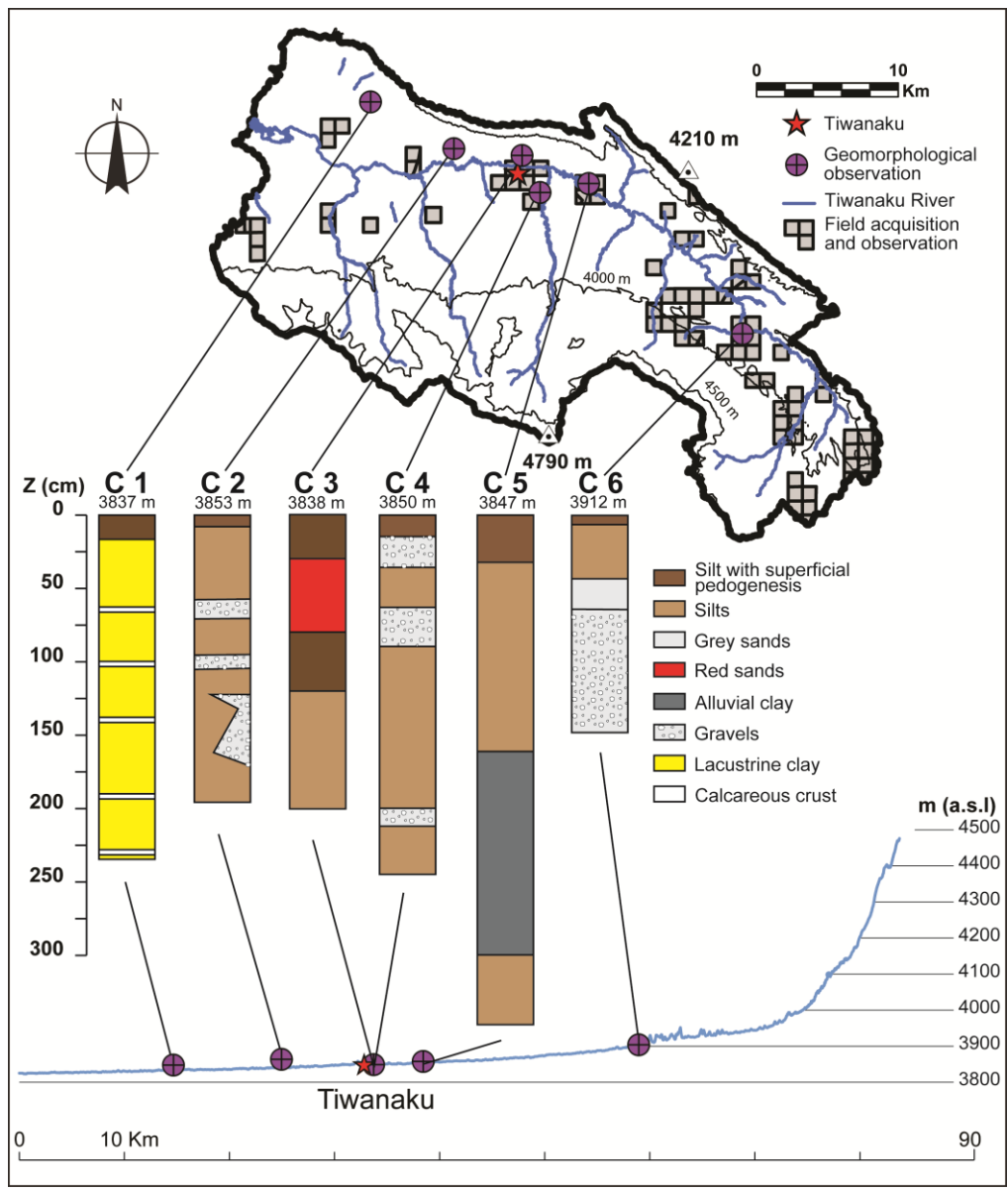
459 Features inherited from Pleistocene and Holocene deposits are outcropping along the valley at low  
460 elevation with little hilly terrain and are sometimes deeply cut by streams. We add 6 geomorphological  
461 sections along the Tiwanaku valley in order to refine the distinction between Pleistocene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

467 0.143 < NDVI < 0.455) mainly along the main river and near the mouth of Lake Wiñaymarka (Figs. 9 and  
468 10). These alluvial plains are composed of non-consolidated gravel, sand and silts, is highly permeable,  
469 and has well developed soils. These areas have currently a high concentration of canals and raised  
470 fields, some of which are still of unspecified age. C3 and C5 sedimentary logs provide valuable  
471 information about stratigraphy deposits (Figs. 9 and 10). C3 stratigraphy is related to recent deposits  
472 likely date from Holocene (maximum depth ~ 2.00 m). From top to bottom, the stratigraphy is  
473 composed of silty formations (0-0.30 m depth), well-sorted red sands (0.30-0.80 m depth) and silt  
474 formation (0.80-1.20 m depth). C5 is related with early Holocene lower alluvial terrace incised by the  
475 current Tiwanaku River (maximum depth ~ 3.50 m). The stratigraphy is composed of silty formations  
476 (0-1.50 m depth) interbedded with clayey and more organic layers (1.50-3.00 m depth). We interpret  
477 this formation as a probable Holocene alluvial fan with low consolidated sediments and coarser  
478 elements (gravels and pebbles) layers.

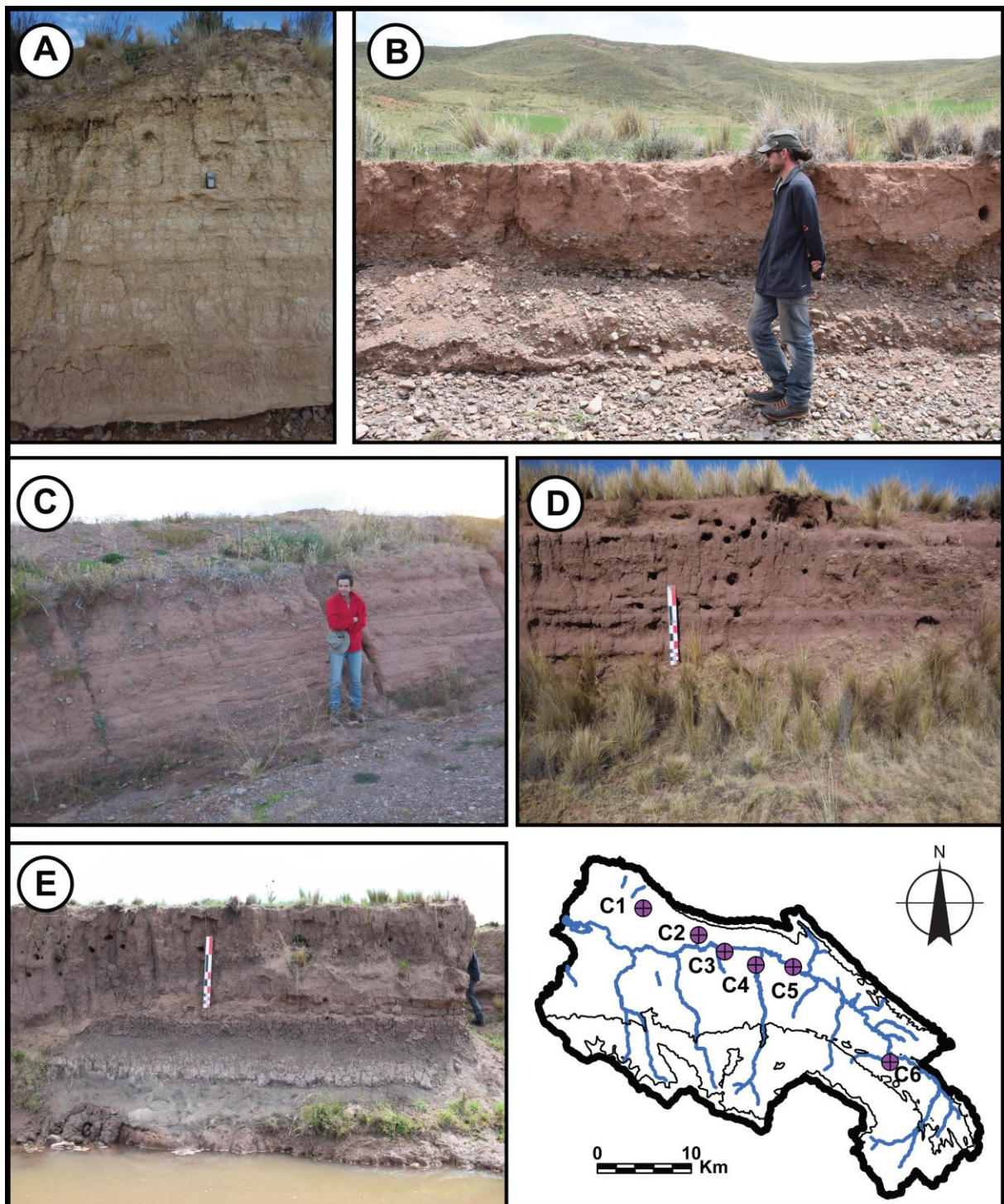
479 Pleistocene lacustrine terraces show a flat relief (slope 0-5%), a NDVI related to bare soils and low  
480 vegetation in general ( $0 < \text{NDVI} < 0.143$ ) and are located between 3810 and 3940 m asl. The Pleistocene  
481 lacustrine terraces (Lake Michin, 3830 m asl, late Pleistocene and Lake Balivian, 3860 m asl, mid-  
482 Pleistocene) have already been distinguished from those associated with early Holocene (Lake Tauca,  
483 3815 m asl) (Argollo et al. 2003, Fritz et al. 2004, Mourguiart et al. 1998). These terrace levels are  
484 composed of an alternation of weak consolidated sand, silts and clays. The low hydraulic permeability  
485 of these formations allows them to constitute a good reservoir of surface water. C1 log show an  
486 alternation of clay formations with calcareous crust intercalations. These formations can be related to  
487 late Pleistocene lacustrine deposits (clay) with lake level variations (emerge land with calcareous  
488 precipitation).

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

493 ~1.50 m) is composed from top to bottom by sandy and silty layers (0-0.70 m depth) and gravels (0.70-  
 494 1.50 m depth). It has been shown in previous studies in the Tiwanaku valley (Argollo et al. 2003,  
 495 GEOBOL 1994) and in other valley in the Lake Titicaca basin (Rigsby et al. 2003) that these sedimentary  
 496 deposits are compatible with Pleistocene and early Holocene alluvial fans mostly located on the  
 497 southern flank of the valley.



498  
 499 **Fig. 9: Geomorphological sections along the Tiwanaku valley.** Location are presented on the  
 500 watershed map and along the topographic profile of the river.



501

502 **Fig. 10: Photo board of geomorphological observation illustrating lacustrine terraces and Quaternary**

503 **alluvial deposits. A: C1, late Pleistocene lacustrine deposits. B: C6, Pleistocene alluvial fans. C: C2,**

504 **Pleistocene alluvial fans. D: C4, Pleistocene alluvial fans. E: C5, early Holocene lower alluvial terrace.**

505

506 **5. Discussion**

## 507 **5.1 Geomorphology of the Tiwanaku valley**

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

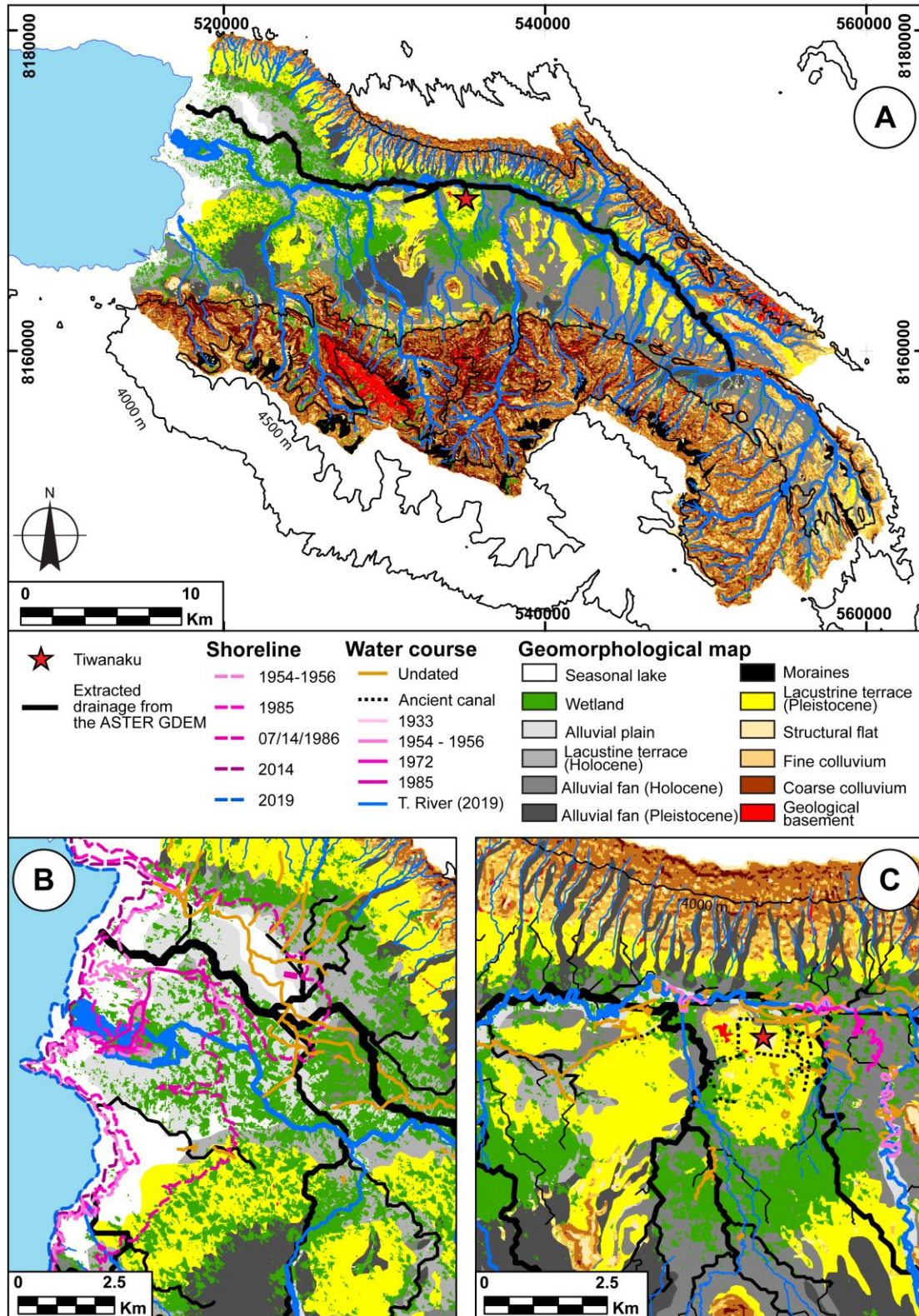
515 The sedimentary composition of the Pleistocene lake terraces previously identified (Argollo et al. 2003)  
516 and observed on the C1 log indicates a high concentration of clay which may be controlled by the  
517 development of the wetlands. Alluvial fan identified on C2, C4 and C6 log is characterized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

529 Our results are therefore roughly in agreement with the major geomorphological features mapped by  
530 previous studies (Albarracin-Jordan and Mathews 1990, Argollo et al. 2003, Calla Maldonado (2011)).  
531 The map produced by Albarracin-Jordan and Mathews (1990) then extended by Calla Maldonado  
532 (2011) contains information on soils and also ecosystems (fauna and flora). However, it is only based



533 on altitudinal parameters and does not completely reflect the diversity of the valley's landform. In our  
534 study we have, for example, shown that the LCZ is not homogeneous; this area is composed of wet  
535 grassland (*bofedal*) separated by Pleistocene to Holocene alluvial fan. The map proposed by Argollo et  
536 al. (2003) takes into account the geology and specifies the chronology of the lake terraces, but does  
537 not distinguish between different categories of slope deposits and therefore the origin of sedimentary  
538 sources. We have clearly shown that we can distinguish structural flat, fine colluvium, coarse colluvium  
539 using slope classification and remote sensing. Our work also shows that the wet grasslands are mainly  
540 located on the south bank of the middle valley. We have shown that they are associated with the  
541 Pleistocene lake terraces. However, the lack of chronological control does not allow us to precise the  
542 landscape evolution during Early to Late Holocene period.

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



549

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

553

## 554 **5.2 Landform evolution over the past 60-70 years**

555 Historical geography results show a significant variation of rivers in the lower (Fig. 11B) and in the  
556 middle valley (Fig. 11C) since the first third of the 20<sup>th</sup> century. Furthermore, the extracted drainage  
557 shows a difference with the actual course of the Tiwanaku River. From 9 km before its mouth into Lake  
558 Wiñaymarka, the calculated flows have a northward shift of 2 km on average. This difference might be  
559 related to an ancient course of the river. The association of the calculated drainage and the maximal  
560 transgressive coastline observed on the satellite image from 1986 (SI) seems to comfort this  
561 hypothesis. At the watershed scale, we note a reduction in the surface of Lake Titicaca since the second  
562 half of the 20<sup>th</sup> century with a shift of the shore in the Tiwanaku valley of 13.3 m.yr<sup>-1</sup> between 1954-55  
563 and 1985 and 2.9 m.yr<sup>-1</sup> between 1985 and 2019. We have detected a delta avulsion of the River that  
564 we have estimated about 2 km towards the South. This shift seems to be associated with an important  
565 sediment progradation of the alluvial plain. This event could not be related to a precise date. However,  
566 considering that the last major flooding of the lake, linked to intense periods of rainfall associated with  
567 the El Niño phenomenon, was recorded in 1985-86 and 1987 (Erickson 1999, Gallego Revilla and Pérez  
568 González 2018, Roche et al 1992), we can assume that the start of this shift dates from this period.  
569 The medium valley shows a significant displacement of alluvial forms upstream of the archaeological  
570 site of Tiwanaku (Fig. 11C). Our work highlights significant avulsion between 1954 and 1972, the  
571 decrease in the number of meander bends and the adoption of a straighter course between 1985 and  
572 2019.

573 Previous climatic conditions inherited from the Medieval Climatic Anomaly (MCA) and Little Ice Age  
574 (LIA) period may have influenced actual landform organization. Andean glaciers can provide valuable  
575 information on precipitation rates. The glaciers have experienced a major recession since the LIA  
576 maximum, losing 89 % of its surface area. The recession was moderate from 1940 to 1963 and  
577 increased in the period 1963-1983. Since 1983, the glacier experienced a major recession rate  
578 (Coudrain et al. 2005, Ramirez et al. 2001). A complete extinction of the glacier would reduce drastically

579 the total runoff of the proglacial stream that feed the Lake Titicaca (Coudrain et al. 2005, Ramirez et  
580 al. 2001). Our observations on the retreat of the shoreline of Lake Wiñaymarka therefore seem to be  
581 consistent with the decrease in precipitation on the Altiplano since the second half of the 20<sup>th</sup> century.  
582 Historical lake-level records document numerous short- and long-term droughts and floods (Dejoux  
583 and Iltis 1992, Kessler and Monheim 1968, Monheim 1963) that can be related to modern glacial  
584 recession. There is some evidence of droughts of 36 continuous years in the 17<sup>th</sup> century and 29  
585 continuous years in the 18<sup>th</sup> century (Stanish 2003). Since the beginning of the 20<sup>th</sup> century, records  
586 show that the lake level (~3810 m asl today) has fluctuated about 6.4 m (Roche et al 1992). Around  
587 1914 the lake level was ~ -1 m; between 1920-1935 the lake level was around 0 m; between 1935-1950  
588 the lake level was located ~-3 m; between 1950- 1970 ~0 m; between 1970-1990 ~+1m. During 1860  
589 and 1959, communities confronted 15 continuous years of droughts (especially 1942 (~-3.5 m) and  
590 1982-83 (~-0.5 m) and a record-breaking flood between 1985 and 87 (+2 m) (Erickson 1999, Kessler  
591 and Monheim 1968, Monheim 1963, Roche et al 1992, Gallego Revilla and Pérez González 2018) (SI  
592 text and SI Fig. 4).

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

601

### 602 **5.3 Implications for ancient and current populations**

603 After about 4000 cal. yr. BP the alluvial terraces present an increased sediment load that may also have  
604 been fed by agricultural runoff as human populations rose in the Lake Titicaca watershed (Farabaugh

605 and Rigsby 2005). The river basin of the Tiwanaku River and Lake Titicaca constituted the main  
606 ecosystems of the Chiripa (3500 to 1900 BP) and Tiwanaku civilization (1500-850 BP) (Janusek and  
607 Kolata 2004, Kolata et al. 2000). Within the Altiplano area, combined land survey, excavation results  
608 and radiocarbon dates demonstrate that the construction and use of raised field systems and  
609 technology began during the late Formative Period (2200-1350 BP, Bruno 2014, Janusek and Kolata  
610 2004). These agricultural structures were then developed on a large scale between 1500-850 BP during  
611 favorable climatic conditions (Erickson 1999, Janusek and Kolata 2004, Kolata et al. 2000). Raised fields,  
612 built in various forms, were concentrated along the lake edge, along rivers, and in the low pampas near  
613 the lake and in the river floodplains (Erickson 1988, 1993, 1994, Kolata 2003, Smith et al. 1968, Stanish  
614 2003). The functions of these canals include channels for reed boat traffic, water management, and  
615 boundary markers for community fields and aquatic resources (Erickson 1999). The final low lake stand  
616 (900-700 cal yr BP) coincides with the decline of raised field agriculture and the collapse of Tiwanaku  
617 culture (Abbott et al. 1997, Janusek and Kolata 2004, Kolata et al. 2000, Ortloff and Kolata 1992). After  
618 this period, local groups continued to cultivate raised fields on a much-reduced scale, as part of a more  
619 diversified subsistence strategy (Stanish 2003, Janusek and Kolata 2004). Other studies assume that  
620 pre-Columbian states and urban centers were ephemeral, rising and falling with some regularity in the  
621 Lake Titicaca Basin (Erickson 1999, Vranich 2013). These studies demonstrated that farming  
622 communities and intensive agriculture did not disappear during the post-Tiwanaku periods (Erickson  
623 1999). It has been also speculated that most of the raised fields in the Katari Valley were built and  
624 managed after Tiwanaku state collapse, as a local adaptation to changing sociopolitical conditions and  
625 the onset of a long-term drought (Graffam 1990). This source (1990) has today been nuanced by other  
626 works that demonstrated that the use of these raised field agriculture continued as relics during post-  
627 Tiwanaku periods (Bruno 2014, Harstorf 2008). The appearance and development of raised field  
628 technology within the circum-lacustre area of the Altiplano supports the long term tradition of  
629 agricultural landscape construction observed at a larger scale from Mesoamerica (Sanders et al. 1979)

630 to South America (Erickson 2003, Kolata 1996, Rostain 2008, Wilson et al. 2002) during pre-Columbian  
631 times.

632 The large number of channels in the lower valley suggest that the alluvial plain morphology has  
633 adopted an anastomosing organization during early Holocene (Argollo et al. 2003), probably at a period  
634 of high lake levels (Fig. 11B). However, without absolute dates, their chronology cannot be verified.

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

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

672 Broader studies realized in the Andean area have demonstrated that long term drought have affected  
673 the Altiplano. The climate-collapse hypothesis (Ortloff and Kolata 1993, Abbott et al. 1997, Binford et  
674 al. 1997) versus anthropogenic environment perspective (Erickson 2000, Williams 2002) is still  
675 vigorously debated. However, the aridity signal is recorded at several location in South America during  
676 the MCA (Stine 1994) from 800 to 1200 AD. Recent studies on Lake Orurillo attest that the driest  
677 climate conditions occur between ca. 915 and 1200 AD, with a more extreme phase between 950 and  
678 1025 AD (Arnold et al. 2021). Records from northern Peruvian coast attested a period of extreme  
679 drought during the MCA 900 to 1250 AD (Rein et al. 2004). In the north-central Andes forest regrowth  
680 was evident between 800 and 1000 AD, but this trend was reversed between 1000 and 1200 AD as  
681 drier conditions coincided with renewed land clearance, (Åkesson et al. 2020). Dry period associated

682 to the MCA has been related to the decline of the Moche civilization in the north coast of Peru at 900  
683 AD (Koons and Alex 2014) and of the Wari state in central Peru at about 1000 CE (Finucane et al. 2007)  
684 suggesting that these Andean states were vulnerable to prolonged drought during the MCA (Arnold et  
685 al. 2021). Drier period associated to low lake level in Lake Wiñaymarka during this period might have  
686 significantly affected raised field agricultural system by limiting the amount of land amenable to  
687 irrigation (Arnold et al. 2021). It is also needed to underline that drastic lake level drop (between 8 and  
688 12 m, Binford et al. 1997, Abbott et al. 1997) certainly induced important erosion in the lower valley,  
689 affecting the general landscape of the Tiwanaku civilization during the MCA.

690 Concerning actual populations, the raised field evidences observed during the study of ancient and  
691 recent aerial photographs reflect more relics than a real operational and integrated system (Fig. 11A,  
692 B and C). However, they bear witness to the persistence of this type of agriculture in the sector to this  
693 day. It has also to be noticed that recent experimental raised fields near Lake Titicaca gave some yield  
694 during the severe 1982-1983 drought and gave excellent yields in 1985-1987, when flooding  
695 devastated other types of farms (Erickson, 1992). This demonstrate that raised field agriculture could  
696 be a rich sources of inspiration for applying ecological engineering in agriculture today (Renard et al.  
697 2012). Our results clearly demonstrate important and rapid landscape transformations during pre-  
698 Columbian times. Current climate changes are associated to glacier recession, drying up of wetland  
699 and of Lake Wiñaymarka and are expected to have important consequences on agricultural activities  
700 of present populations. Increasing population in El Alto (1.5 M ha.) inside the watershed of Lake  
701 Wiñaymarka and the lack of water treatments could also lead to critical environmental situations.

702

## 703 **6. Conclusion**

704 In this paper, we have synthetized and specified the chronology of events of the Tiwanaku valley since  
705 the Recent Holocene thanks to a multi-disciplinary approach (historical geography, geomorphology,



706 geophysical surveys, photogrammetry, remote sensing and cores) crossed with pre-existing  
707 geomorphological data.

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

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

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

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

734

## 735 **Acknowledgments**

736 The author would like to thank first of all the native Indigenous communities, the CIAAAT (Centro de  
737 Investigaciones Antropológicas, Arqueológicas y Administración de Tiwanaku) and the MTyC  
738 (Ministerio de Turismo y Culturas) of the Plurinational State of Bolivia for facilitating the access so the  
739 field survey and the local scientific framework. We also thank the IRD (Institut de Recherche pour le  
740 Développement) and the MEAE (Ministère de L'Europe et des Affaires Etrangères) of France for the  
741 logistical and financial support. Finally, we would like to thank the Bolivian and French students who  
742 participated in the "Rio Tiwanaku Archeology and Environment project". Thanks also go to Danielle  
743 Skuy for polishing the English and the two anonymous peer reviewers who significantly helped to  
744 improve the manuscript.

745

## 746 **Financial support**

747 MEAE-French Ministry of Europe and Foreign Affairs, Embassy of France in Bolivia, IRD.

748

## 749 **Competing Interests**

750 The authors declare no competing interests.

751

## 752 **Author contributions statement**

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

756 **References**

- 757 1. Abbott MB, Wolfe BB, Wolfe AP, Seltzer GO, Aravena R, Mark BG, Polissar PJ, Rodbell DT, Rowe  
758 HD, Vuille M 2003. Holocene paleohydrology and glacial history of the central Andes using  
759 multiproxy lake sediment studies. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 194, pp.  
760 123-138
- 761 2. Abbott MB, Binford MW, Brenner M, Kelts KR 1997. A 3500 <sup>14</sup>C yr high-resolution record of lake  
762 level changes in Lake Titicaca, Bolivia/Peru. *Quaternary Research*, 47, pp. 169-180.
- 763 3. Åkesson CM, Matthews-Bird F, Bitting M, Fennell CJ, Church WB, Peterson LC, Bush MB 2020. 2100  
764 years of human adaptation to climate change in the High Andes. *Nat. Ecol. Evol.* 4 (1), pp. 66-74.
- 765 4. Albarracin-Jordan J and Mathews JE 1990. *Asentamientos Prehispanicos del Valle de Tiwanaku*.  
766 Vol. 1. Producciones CIMA, La Paz, Bolivia.
- 767 5. Apaestegui J, Cruz FW, Sifeddine A, Vuille M, Espinoza JC, Guyot JL, Edwards L 2014. Hydroclimate  
768 variability of the northwestern Amazon Basin near the Andean foothills of Peru related to the South  
769 American Monsoon System during the last 1600 years. *Clim. Past* 10 (6), pp. 1967-1981.
- 770 6. Argollo J, Ticcla L, Kolata AL and Rivera O 2003. Geology, geomorphology, and soils of the Tiwanaku  
771 and Catari river basins. In Kolata A (Ed.): *Tiwanaku and its hinterland: archaeology and*  
772 *paleoecology of an Andean civilization*, 1, pp. 57-88.
- 773 7. Argollo J and Mourguiart P 2000. Late Quaternary Climate History of the Bolivian Altiplano.  
774 *Quaternary International*, 72, pp. 37-51.
- 775 8. Arnold TE, Hillman AL, Abbott MB, Werne JP, McGrath SJ, and Arkush EN 2021. Drought and the  
776 collapse of the Tiwanaku Civilization: New evidence from Lake Orurillo, Peru. *Quaternary Science*  
777 *Reviews*, 251, 106693. <https://doi.org/10.1016/j.quascirev.2020.106693>
- 778 9. Baker PA, Rigsby CA, Seltzer GO, Fritz SC, Lowenstein TK, Bacher NP and Veliz C, 2001a. Tropical  
779 climate changes at millennial and orbital timescales on the Bolivian Altiplano. *Nature*, 409, pp. 698-  
780 701.
- 781 10. Baker PA, Seltzer GO, Fritz SC, Dunbar RB, Grove MJ, Tapia PM, Cross SL, Rowe HD and Broda JP  
782 2001b. The history of South American tropical precipitation for the past 25,000 years. *Science*, 291,  
783 pp. 640-643.
- 784 11. Baker PA and Fritz SC 2015. Nature and causes of Quaternary climate variation of tropical South  
785 America, *Quaternary Science Reviews*, 124, pp. 31-47.
- 786 12. Bandy MS 2006. Early village society in the Formative Period in the southern Lake Titicaca Basin.  
787 In: Isbell WH and Silverman H (Eds.): *Andean Archaeology III: North and South*. Springer, New York,  
788 pp. 210-236.
- 789 13. Bandy MS 2005. Energetic efficiency and political expediency in Titicaca Basin raised field  
790 agriculture. *Journal of Anthropological Archaeology*, 24(3), pp. 271-296.
- 791 14. Baucom PC and Rigsby CA 1999. Climate and lake-level history of the northern Altiplano, Bolivia,  
792 as recorded in Holocene sediments of the Rio Desaguadero. *Journal of Sedimentary Research*,  
793 69(3), pp. 597-611.
- 794 15. Bills BG, de Silva SL, Currey DR, Emenger RS, Lillquist KD, Donnellan A, and Worden B 1994. Hydro-  
795 isostatic Deflections and Tectonic Tilting in the Central Andes: Initial Results of a GPS Survey of  
796 Lake Minchin Shorelines. *Geophysical Research Letters*, 21-4, pp. 293-296.
- 797 16. Binford M, Kolata AL, Brenner M, Janusek JW, Seddon M, Abbott M and Curtis J 1997. Climate  
798 Variation and the Rise and Fall of an Andean Civilization. *Quaternary Research*, 47, pp. 235-248.
- 799 17. Bird BW, Abbott MB, Rodbell DT, Vuille M 2011. Holocene tropical South American hydroclimate  
800 revealed from a decadal resolved lake sediment  $\delta^{18}O$  record *Earth and Planetary Science Letters*,  
801 310, pp. 192-202.

- 802 18. Bharathkumar L, Mohammed-Aslam MA 2015. Crop Pattern Mapping of Tumkur Taluk using NDVI  
803 Technique: A Remote Sensing and GIS Approach. International Conference on Water Resources,  
804 Coastal and Ocean Engineering (ICWRCOE 2015), Aquatic Procedia, 4, pp. 1397-1404.
- 805 19. Boserup E 1965. The Conditions of Agricultural Growth. Earthscan Publications, London (paperback  
806 edition, 1993).
- 807 20. Bruno MC, Capriles JM, Hastorf CA, Fritz SC, Weide DM, Domic AI Baker PA 2021. The Rise and Fall  
808 of Wiñaymarka: Rethinking Cultural and Environmental Interactions in the Southern Basin of Lake  
809 Titicaca. Human Ecology. <https://doi.org/10.1007/s10745-021-00222-3>
- 810 21. Bruno MC 2014. Beyond Raised Fields: Exploring Farming Practices and Processes of Agricultural  
811 Change in the Ancient Lake Titicaca Basin of the Andes. *American Anthropologist*, 116(1), pp. 130-  
812 145. DOI: 10.1111/aman.12066
- 813 22. Calla Maldonado SA 2011. Prospección arqueológica en el valle alto de Tiwanaku, contribuciones  
814 al estudio de la evolución del asentamiento prehispánico en el valle de Tiwanaku, 279 pp.; La Paz:  
815 Universidad Mayor de San Andrés. Tesis de Grado.
- 816 23. Capriles JM, Moore KM, Domic AI and Hastorf CA 2014. Fishing and environmental change during  
817 the emergence of social complexity in the Lake Titicaca Basin. *Journal of Anthropological*  
818 *Archaeology*, 34, pp. 66-77.
- 819 24. Coudrain A, Francou B, Kundzewicz ZW 2005. Glacier shrinkage in the Andes and consequences for  
820 water resources. *Hydrological Sciences Journal*, 50(6), pp. 925-932.  
821 DOI:10.1623/hysj.2005.50.6.925
- 822 25. Craig N, Aldenderfer MS, Baker PA, Rigsby C 2010. Terminal Archaic settlement pattern and land  
823 cover change in the Rio llave, southwestern Lake Titicaca Basin, Peru. In: Dean RM (Ed.): *The*  
824 *Archaeology of Anthropogenic Environments*. Center for Archaeological Investigations, Southern  
825 Illinois University, Carbondale, pp. 35-53.
- 826 26. D'Allestro P and Parente C 2015. GIS application for NDVI calculation using Landsat 8 OLI images  
827 *International Journal of Applied Engineering Research*, 10(21), pp. 42099-42102.
- 828 27. Dejoux C and Iltis A 1992. Lake Titicaca: a synthesis of limnological knowledge. Dordrecht: Kluwer  
829 Academic Publishers.
- 830 28. Delaere C 2017. The location of Lake Titicaca's coastal area during the Tiwanaku and Inca periods:  
831 Methodology and strategies of underwater archaeology. *Journal of Maritime Archaeology*, 12(3),  
832 pp. 223-238.
- 833 29. Dillehay TD, Pino M, Bonzani R, Silva C, Wallner J, Le Quesne C 2007. Cultivated wetlands and  
834 emerging complexity in south-central Chile and long distance effects of climate change. *Antiquity*,  
835 81, pp. 949-960.
- 836 30. Erickson CL 2003. Agricultural landscapes as world heritage: raised field agriculture in Bolivia and  
837 Peru. In: Teutonico, J.-M., Matero, F. (Eds.): *Managing Change: Sustainable Approaches to the*  
838 *Conservation of the Built Environment*. Getty Conservation Institute, Los Angeles, pp. 181-204.
- 839 31. Erickson CL 2000. The Lake Titicaca Basin: A Pre-Columbian built landscape. In Lentz D. (Ed.):  
840 *Imperfect balance: Landscape transformations in the Precolumbian Americas*. New York: Columbia  
841 University Press, pp. 311-356.
- 842 32. Erickson C 1999. Neo environmental determinism and agrarian collapse in Andean prehistory.  
843 *Antiquity*. 73(281), pp. 634-642.
- 844 33. Erickson C 1994 "Methodological Considerations in the Study of Ancient Andean Field Systems." In  
845 Miller N and Gleason K (Eds.): *The Archaeology of Garden and Field*. University of Pennsylvania  
846 Press, Philadelphia. pp. 111-152.
- 847 34. Erickson C 1993 "The Social Organization of Prehispanic Raised Field Agriculture in the Lake Titicaca  
848 Basin." In Scarborough V and Isaac B (Eds.): *Prehispanic Water Management Systems*, Supplement  
849 no. 7, Research in Economic Anthropology, ed.. JAI Press, Greenwich, Conn.
- 850 35. Erickson CL 1992. Prehistoric Landscape Management in the Andean Highlands: Raised Field  
851 Agriculture and its Environmental Impact. *Population and Environment: A Journal of*  
852 *Interdisciplinary Studies*, 13(4), pp. 285-300.

- 853 36. Erickson C 1988. An Archaeological Investigation of Raised Field Agriculture in the Lake Titicaca  
854 Basin of Peru. Ph.D. diss., Department of Anthropology, University of Illinois at Champaign-Urbana.  
855 University Microfilms, Inc., no. 8908674.
- 856 37. Farabaugh RL and Rigsby CA 2005. Climatic influence on sedimentology and geomorphology of the  
857 Rio Ramis valley, Peru. *Journal of sedimentary research*, 75(1), pp. 12-28.
- 858 38. Finucane BC, Valdez JE, Calderon IP, Pomacanchari CV, Valdez LM, O'Connell T 2007. The end of  
859 empire: new radiocarbon dates from the Ayacucho Valley, Peru, and their implications for the  
860 collapse of the Wari state. *Radiocarbon* 49 (2), pp. 579-592.
- 861 39. Fritz SC, Baker PA, Lowenstein TK, Seltzer GO, Rigsby CA, Dwyer GS, Tapia PM, Arnold KK, Ku, Ku TL  
862 and Shangde L 2004. Hydrologic variation during the last 170,000 years in the southern hemisphere  
863 tropics of South America *Papers in the Earth and Atmospheric Sciences*, 29, pp. 95-104.  
864 doi:10.1016/j.yqres.2003.08.007
- 865 40. Gallego Revilla JI and Pérez González ME 2018. Tiwanaku, entre el cielo y la Tierra. The United  
866 Nations Educational, Scientific and Cultural Organization, UNESCO, 178 pp.  
867 <https://unesdoc.unesco.org/ark:/48223/pf0000265365>
- 868 41. Gandhi GM, Parthiban S, Thummalu N and Christy A 2015. NDVI: Vegetation change detection  
869 using remote sensing and GIS: A case study of Vellore District. *Procedia Computer Science*, 57, pp.  
870 1199-1210.
- 871 42. GEOBOL (Geologia de Bolivia) 1994. Mapas geológicas.
- 872 43. Graffam G 1992. Beyond state collapse: rural history, raised fields, and pastoralism in the South  
873 Andes. *American Anthropologist*, 94(4), pp. 882-904.
- 874 44. Graffam GC 1990. Raised fields without bureaucracy: an archaeological examination of intensive  
875 wetland cultivation in the Pampa Koani Zone, Lake Titicaca, Bolivia, unpublished
- 876 45. Guérin R, Desclotres M, Coudrain A, Talbi A, Gallaire R, 2001. Geophysical surveys for identifying  
877 saline groundwater in the semi-arid region of the central Altiplano, Bolivia. *Hydrological Processes*,  
878 15(17), pp. 3287-3301.
- 879 46. Hastorf CA 2005. The Upper (Middle and Late) Formative in the Titicaca Region. In: Stanish C, Cohen  
880 AB and Aldenderfer MS (Eds.): *Advances in Titicaca Basin Archaeology*. Cotsen Institute of  
881 Archaeology, University of California, Los Angeles, pp. 65-94.
- 882 47. Hastorf CA 1999. *Early Settlement at Chiripa, Bolivia*, Contributions of the University of California  
883 Archaeological Research Facility, Berkeley. University of California, Berkeley.
- 884 48. IGM (Instituto Geográfico Militar) 1985. Mapas topográficas.
- 885 49. Isbell WH and Silverman H 2002. *Andean Archaeology II*. Springer.
- 886 50. Janusek JW 2008. *Ancient Tiwanaku*. Cambridge University Press, Cambridge.
- 887 51. Janusek JW 2004. Collapse as cultural revolution: Power and identity in the Tiwanaku to Pacajes  
888 transition. *Archeological Papers of the American Anthropological Association*, 14(1), pp. 175-209.
- 889 52. Janusek JW and Kolata AL 2004. Top-Down or Bottom-Up: Rural Settlement and Raised Field  
890 Agriculture in the Lake Titicaca Basin, Bolivia. *Journal of Anthropological Archaeology*, 23(404), pp.  
891 430-411.
- 892 53. Kessler A and Monheim F 1968. Der Wasserhaushalt des Titicacasees nach neueren  
893 Messergebnissen (The Water Budget of Lake Titicaca, after New Measurements). *Erdkunde*, 22(4),  
894 pp. 275-283.
- 895 54. Kolata AL 2003. The Project Wila Jawira Research Program. In Kolata AL (Ed.): *Tiwanaku and Its*  
896 *Hinterland: Archaeology and Paleoecology of an Andean Civilization*. Vol. 2: Urban and Rural  
897 Archaeology Washington D. C.: Smithsonian Institution Press.
- 898 55. Kolata A 1996. *Tiwanaku and Its Hinterland: Archaeology and Paleoecology of an Andean*  
899 *Civilization*. Volume 1: Agroecology. Smithsonian Institution Press, Washington, DC.
- 900 56. Kolata AL, Binford MW, Brenner M, Janusek JW, Ortloff C 2000. Environmental thresholds and the  
901 empirical reality of state collapse: a response to Ericksson (1999). *Antiquity*, pp. 424-426

- 902 57. Kolata AL, and Ortloff C 1996. Tiwanaku Raised-Field Agriculture in the Lake Titicaca Basin of  
903 Bolivia. In Kolata AL (Ed.): *Tiwanaku and Its Hinterland: Archaeology and Paleoecology of an*  
904 *Andean Civilization*, pp. 109–151. Smithsonian Institution Press, Washington, D.C.
- 905 58. Kolata AL and Ortloff C 1989. Thermal analysis of Tiwanaku raised field systems in the Lake Titicaca  
906 basin of Bolivia. *Journal of Archaeological Science*, 16, pp. 233-263.
- 907 59. Koons ML, Alex BA 2014. Revised Moche chronology based on Bayesian models of reliable  
908 radiocarbon dates. *Radiocarbon* 56 (3), pp. 1039-1055.
- 909 60. Lhomme JP and Vacher JJ 2002. Modelling nocturnal heat dynamics and frost mitigation in Andean  
910 raised field systems. *Agricultural and Forest Meteorology*, 112, pp. 179-193.
- 911 61. Martin L, Fournier M, Mourguiart P, Sifeddine A, Turcq B, Absy ML, Flexor JM 1993. Southern  
912 oscillation signal in South American palaeoclimatic data of the last 7000 years. *Quat. Res.*, 39, pp.  
913 338-346.
- 914 62. Monheim F 1963. Contribución a la climatología e hidrología de la Cuenca del Lago Titicaca. Puno:  
915 Universidad Técnica del Altiplano.
- 916 63. Moreau S, Roland Bosseno R, Gu XF, Baret F 2003. Assessing the biomass dynamics of Andean  
917 bofedal and totora high-protein wetland grasses from NOAA/AVHRR. *Remote Sensing of*  
918 *Environment* 85(4), pp. 516–529.
- 919 64. Moreau S and Le Toan T 2003. Biomass quantification of Andean wetland forages using ERS satellite  
920 SAR data for optimizing livestock management. *Remote Sensing of Environment*, 84(4), pp. 477-  
921 492.
- 922 65. Moseley ME 1983. The good old days were better: Agrarian collapse and tectonics. *American*  
923 *Anthropologist*, 85, pp. 773-799.
- 924 66. Mourguiart P, Corrège T, Wirmann D, Argollo J, Montenegro ME, Pourchet M and Carbonel P 1998.  
925 Holocene palaeohydrology of Lake Titicaca estimated from an ostracod-based transfer function.  
926 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 143(1-3), pp. 51-72.
- 927 67. Ortloff CR 2014. Groundwater Management in the 300 bce-1100ce Pre-Columbian City of  
928 Tiwanaku (Bolivia). *Hydrol Current Res.*, 5(168). DOI:10.4172/2157-7587.1000168
- 929 68. Ortloff CR and Kolata AL 1992. Climate and collapse: Agro Ecological perspectives on the decline of  
930 Tiwanaku state. *Journal of Archaeological Science*, 20, pp. 195-221
- 931 69. Otto M, Scherer D and Richters J 201). Hydrological differentiation and spatial distribution of high  
932 altitude wetlands in a semi-arid Andean region derived from satellite data. *Hydrology and Earth*  
933 *System Sciences*, 15(5), pp. 1713-1727.
- 934 70. Pérez González ME, Gallego Revilla JI 2019. A new environmental and spatial approach to the  
935 Tiwanaku World Heritage site (Bolivia) using remote sensing (UAV and satellite images)  
936 Geoarchaeology. pp. 1-14. DOI: 10.1002/gea.21778
- 937 71. Plazas C and Falchetti AM 1990. *Manejo Hidráulico Zenú. Ingenierías Prehispánicas*. Fondo FEN  
938 Colombia. Instituto Colombiano de Antropología, Bogotá.
- 939 72. Rabatel A, Francou B, Jomelli V, Naveau P, Grancher D 2008. A chronology of the Little Ice Age in  
940 the tropical Andes of Bolivia (16°S) and its implications for climate reconstruction. *Quaternary*  
941 *Research*, 70(2): pp. 198-212.
- 942 73. Ramirez E, Francou B, Ribstein P, Descloitres M, Guerin R, Mendoza J, Gallaire R, Pouycaud B,  
943 Jordan E 2001. Small glaciers disappearing in the tropical Andes: a case-study in Bolivia Glaciar  
944 Chacaltaya (16°S). *Journal of glaciology*, 47(157), pp. 187-194.
- 945 74. Rein B, Lückge A and Sirocko F 2004. A major Holocene ENSO anomaly during the Medieval period.  
946 *Geophys. Res. Lett.* 31 (17). <https://doi.org/10.1029/2004GL020161>
- 947 75. Reichel-Dolmatoff G and Reichel-Dolmatoff A 1974. Un sistema de agricultura prehistorica de los  
948 Llanos Orientales. *Rev. Colomb. Antropol.* 13, pp. 189–200.
- 949 76. Renard D, Iriarte J, Birk JJ, Rostain S, Glaser B and McKey D 2012. Ecological engineers ahead of  
950 their time: The functioning of pre-Columbian raised-field agriculture and its potential contributions  
951 to sustainability today. *Ecological Engineering*, 45, pp. 30-44.
- 952 77. Revollo MM 2001. Management issues in the Lake Titicaca and Lake Poopo system: importance of  
953 developing a water budget. *Lakes Reservoirs Res. Manag.*, 6, pp. 225-229.

- 954 78. Rigsby CA, Baker PA, Aldenderfer MS 2003. Fluvial history of the Rio Ilave valley, Peru, and its  
955 relationship to climate and human history. *Palaeogeography, Palaeoclimatology, Palaeoecology*,  
956 194: pp. 165-185.
- 957 79. Roche MA, Bourges JC, Mattos R 1992. Climatology and hydrology of the Lake Titicaca basin. In:  
958 Dejoux C, Iltis A. (Eds.), *Lake Titicaca: A Synthesis of Limnological Knowledge*. Kluwer Academic,  
959 Boston, MA, pp. 63-83.
- 960 80. Rostain S 2008. Agricultural earthworks on the French Guiana coast. In Silverman H and Isbell W  
961 (Eds.): *Handbook of South American Archaeology*. Springer/Kluwer/Plenum, New York, pp. 217-  
962 233.
- 963 81. Rowe HD and Dunbar RB 2004. Hydrologic-energy balance constraints on the Holocene lake-level  
964 history of Lake Titicaca, South America. *Climate Dynamics*, 23(3-4), pp. 439-454.
- 965 82. Rowe HD, Guilderson TP, Dunbar RB, Southon JR, Seltzer GO, Mucciarone DA, Fritz SC, Baker PA  
966 2003. Late Quaternary lake-level changes constrained by radiocarbon and stable isotope studies  
967 on sediment cores from Lake Titicaca, South America. *Global and Planetary Change*, 38(3-4), pp.  
968 273-290. DOI: 10.1016/S0921-8181(03)00031-6
- 969 83. Rowe HD, Dunbar RB, Mucciarone DA, Seltzer GO, Baker PA and Fritz S 2002. Insolation, moisture  
970 balance and climate change on the South American Altiplano since the Last Glacial Maximum. *Clim.*  
971 *Change*, 52, pp. 175-199.
- 972 84. Sanders WT, Parsons JR and Santley R 1979. *The Basin of Mexico: Ecological Processes in the*  
973 *Evolution of Civilization*. Academic Press, New York.
- 974 85. Seltzer, G.O., Cross, S., Baker, P., Dunbar, R. and Fritz, S., 1998. High-resolution seismic reflection  
975 profiles from Lake Titicaca, Peru/Bolivia. Evidence for Holocene aridity in the tropical Andes.  
976 *Geology*, 26, pp. 167-170.
- 977 86. Senra EO, Schaefer CE, Corrêa GR, Gjorup DF, Reis JS and Francelino MR 2019. Holocene  
978 pedogenesis along a chronotoposequence of soils from the Altiplano to the Cordillera Real, Bolivian  
979 Andes. *Catena*, 178, pp. 141-153.
- 980 87. Servant M. and Fontes J.-C. 1978. Les lacs quaternaires des hauts plateaux des Andes boliviennes;  
981 premières interprétations paléoclimatiques. *Cah. ORSTOM, sér. Géol.*, 10(1), pp. 9-23.
- 982 88. Servant M and Fontes JX 1984. Les basses terrasses fluviatiles du Quaternaire récent des Andes  
983 boliviennes. Interprétation paléoclimatique. *Cah. ORSTOM, ser. Géol.*, 14(I), pp. 15-28.
- 984 89. Servant M and Servant-Vildary S 2003. Holocene precipitation and atmospheric changes inferred  
985 from river paleowetlands in the Bolivian Andes. *Palaeogeography, Palaeoclimatology,*  
986 *Palaeoecology*, 194: pp. 187-206.
- 987 90. Servant M, Fournier M, Argollo J, Servant-Vildary S, Sylvestre F, Wirrmann D and Ybert JP 1995. La  
988 dernière transition glaciaire/interglaciaire des Andes tropicales sud (Bolivie) d'après l'étude des  
989 variations des niveaux lacustres et des fluctuations glaciaires. *Comptes Rendus de l'Académie des*  
990 *Sciences, Paris, Séries II* 320, pp. 729-736.
- 991 91. Silverman H and Isbell W 2008. *Handbook of South American Archaeology*. Springer Science &  
992 Business Media.
- 993 92. Smith C, Denevan W, and Hamilton P 1968. Ancient Ridged Fields in the Region of Lake Titicaca.  
994 *Geographical Journal*, 134(3): pp. 353-366.
- 995 93. Spencer CS, Redmond EM and Rinaldi M 1994. Drained fields at La Tigra, Venezuelan Llanos: a  
996 regional perspective. *Latin American Antiquity*, 5, pp. 95-110.
- 997 94. Stanish C 2003. *Ancient Titicaca. The Evolution of Complex Society in Southern Peru & Northern*  
998 *Bolivia* University of California Press, 338 pages.
- 999 95. Stine S 1994. Extreme and persistent drought in California and Patagonia during mediaeval time,  
1000 *Nature*, 369, pp. 546-549.
- 1001 96. Strahler AN 1957. Quantitative analysis of watershed geomorphology. *Eos, Transactions American*  
1002 *Geophysical Union*, 38(6), pp. 913-920.

- 1003 97. Sylvestre F, Servant M, Servant-Vildary S, Causse C, Fournier M and Yber JP 1999. Lake-level  
1004 chronology on the southern Bolivian Altiplano (18–23°S) during late-Glacial time and the early  
1005 Holocene. *Quaternary Research*, 51, pp. 54-66.
- 1006 98. Talbi A, Coudrain A, Ribstein P and Pouyaud B 1999. Computation of the Rainfall on Lake Titicaca  
1007 Catchment during the Holocene. *Comptes Rendus de l'Académie des Sciences, Série II Fascicule*  
1008 *A—Sciences de la Terre et des Planètes*, 329(3), pp. 197-203.
- 1009 99. Theissen KM, Dunbar RB, Rowe HD and Mucciarone DA 2008. Multidecadal-to century-scale arid  
1010 episodes on the northern Altiplano during the middle Holocene. *Palaeogeography,*  
1011 *Palaeoclimatology, Palaeoecology*, 257(4), pp. 361-376.
- 1012 100. Thompson LG, Mosley-Thompson E, Brecher H, Davis M, León B, Les D, Lin PN, Mashiotta T and  
1013 Mountain K 2006. Abrupt tropical climate change: past and present. *Proc. Natl. Acad. Sci.* 103, pp.  
1014 10536-10543.
- 1015 101. Thompson LG, Mosley-Thompson E and Henderson KA 2000. Ice-core palaeoclimate records in  
1016 tropical South America since the Last Glacial Maximum. *J. Quat. Sci.* 15, pp. 377-394.
- 1017 102. Thompson LG, Davis ME, Mosley-Thompson E, Sowers TA, Henderson KA, Zagorodnov VS and  
1018 Cole-Dai J 1998. A 25,000-year tropical climate history from Bolivian ice cores. *Science*, 282(5395),  
1019 pp. 1858-1864.
- 1020 103. Thompson LG, Mosely-Thompson E, Dansgaard W and Grootes PM 1986. The Little Ice Age as  
1021 Recorded in the stratigraphy of the Tropical Quelccaya Ice Cap. *Science*, 234, pp. 361-364.
- 1022 104. Touahir S, Asri A, Remini B, Saad H 2018. Prédiction de l'érosion hydrique dans le bassin versant  
1023 de l'oued Zeddine et de l'envasement du barrage Ouled Mellouk (Nord-Ouest algérien).  
1024 *Géomorphologie: relief, processus, environnement*, 24(2), pp. 167-182.
- 1025 105. Tucker CJ 1979. Red and photographic infrared linear combinations for monitoring vegetation.  
1026 *Remote sensing of Environment*, 8(2), pp. 127-150.
- 1027 106. USGS (United State Geological Survey) 2015. Landsat 8 (L8) Data Users Handbook, Version 1.  
1028 0, pp. 61-62.
- 1029 107. Vella MA, Sejas S, Lucero Mamani K, Rodriguez LA, Rivera Casanovas C, Guedron S, Brisset E,  
1030 Bievre G, Menacho Cespedes J, Argollo J, Escobar K and Ortuño T 2018. La misión Franco-Boliviana  
1031 Paleambiente y Arqueología del Río Guaquirá-Tiwanaku (Bolivia): un estudio multidisciplinario de  
1032 las interacciones entre las Sociedades Antiguas y el Medioambiente. *Bulletin de l'Institut Français*  
1033 *d'Etudes Andines*, 47(2), pp. 1-25.
- 1034 108. Vining B and Williams PR 2020. Crossing the western Altiplano: The ecological context of  
1035 Tiwanaku migrations. *Journal of Archaeological Science*, 113, 105046.  
1036 <https://doi.org/10.1016/j.jas.2019.105046>
- 1037 109. Vuille M and Werner M 2005. Stable isotopes in precipitation recording South American  
1038 summer monsoon and ENSO variability: observations and model results. *Climate Dynamics*, 25(4),  
1039 pp. 401-413.
- 1040 110. Vranich A, Anderson K, Bandy M, Conklin WJ, Goldstein P, Isbell W, Janusek JW, Knobloch PJ,  
1041 Moseley M, Stanish C, Seddon MT, Williams PR 2013. *Visions of Tiwanaku*. Cotsen Institute of  
1042 Archaeology Press.
- 1043 111. Walker JH 2004. *Agricultural Change in the Bolivian Amazon*. University of Pittsburgh, Latin  
1044 American Archaeology Publications, 13. University of Pittsburgh.
- 1045 112. Weide DM, Fritz SC, Hastorf CA, Bruno MC, Baker PA, Guedron S and Salenbien W 2017. A  
1046 6000 yr diatom record of mid-to late Holocene fluctuations in the level of Lago Wiñaymarca, Lake  
1047 Titicaca (Peru/Bolivia). *Quaternary Research*, 88(2), pp. 179-192.
- 1048 113. Williams PR 2002. Rethinking disaster-induced collapse in the demise of the Andean highland  
1049 states: Wari and Tiwanaku. *World Archaeol.* 33 (3), pp. 361-374.
- 1050 114. Wirthman D 1992. Morphology and bathymetry. In: Dejoux C and Iltis A (Eds.): *Lake Titicaca. A*  
1051 *synthesis of limnological knowledge*. Kluwer Academic, Dordrecht, MOBI, 68, pp. 16-22.
- 1052 115. Williams PR 2002. Rethinking disaster-induced collapse in the demise of the Andean highland  
1053 states: Wari and Tiwanaku. *World Archaeology*, 33(3), pp. 361-374.



1054 116. Wilson C, Simpson IA and Currie EJ 2002. Soil management in pre-Hispanic raised field systems:  
1055 micromorphological evidence from Hacienda Zuleta, Ecuador. *Geoarchaeology*, 17(3), pp. 261-283.  
1056 117. Wirrmann D. 1988. Paleohidrología del lago Titicaca durante el Holoceno, Memoria de la  
1057 Sociedad de Ciencias Naturales La Salle, XLVII, Supl. 2, pp. 57-67.  
1058 118. Wirrmann D. and Mourguiart P. 1995. Late Quaternary spatiotemporal limnological variations  
1059 in the Altipiano of Bolivia and Peru. *Quaternary Research*, 43, pp. 344-354.  
1060

1061

1062

1063

1064

1065

1066

1067

1068

1069

1070

1071

1072

1073

1074

1075

1076

1077

1078

1079

1080

## 1081 Supplementary information

### 1082 1. Remote sensing

#### 1083 1.1. NDVI

1084 NDVI has been the most widely used spectral vegetation indices (Moreau et al. 2003). NDVI is sensitive  
1085 to relative differences in absorbed/reflected light in the red and NIR spectra. Soils and senescent  
1086 vegetation converge in this region, particularly where vegetation cover is not complete (Vining and  
1087 Williams 2020). Taking this into account many of studies performed on semi-arid environments  
1088 involved the development of spectral indices taking into account the influence of bare, unsaturated  
1089 soil backgrounds to minimize soil noise like the Soil adjusted vegetation index (SAVI) developed by  
1090 Baret, Guyot, and Major (1989). However Purevdorj and Tateishi (1998) indicated the superiority of  
1091 NDVI and SAVI for the estimation of the green vegetation cover, with a better performance of NDVI.  
1092 Bork, West, and Price (1999) demonstrated that SAVI often resulted in either no improvement or a  
1093 minimal improvement relative to NDVI.

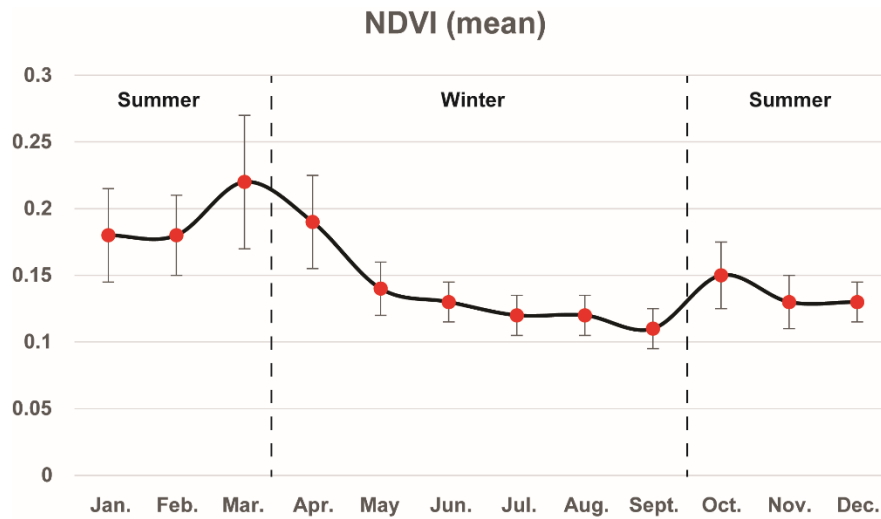
1094 Landsat 8 OLI/TIRS-level 2 images have been chosen with regards to the less cloud cover. 10 images  
1095 were selected in order to cover all the vegetation phases during one year (SI Tab. 1). As the cloud cover  
1096 was too important (>10%) from October to March 2020 and 2019 (summer in the southern  
1097 hemisphere), we choose to select best images for each month during the last decade (2014-2020). The  
1098 evolution of the mean NDVI highlight the division in two distinct season (SI Fig. 1). For the purpose of  
1099 our study, we selected the image of the month of September (SI Fig. 2). This map is related to the  
1100 Austral winter period were most of the vegetation is senescent. It has already be noted that the  
1101 continued growth and low senescence of Andean wet grasslands during the Austral dry winter is  
1102 highlighted by the small variation of the green tissue cover in *bofedales* between summer and winter  
1103 (Buttolph, 1998). The cultivated plant are then less represented and only the minimal distribution of  
1104 wet grassland (*titora* and *bofedal*) are highlighted (Vining and Williams 2020).

1105  
1106  
1107

1108 **SI Tab. 1. Characteristics and statistics of the Landsat 8 OLI/TIRS -level 2 images selected for the NDVI**  
1109 (source: U.S. Geological Survey)

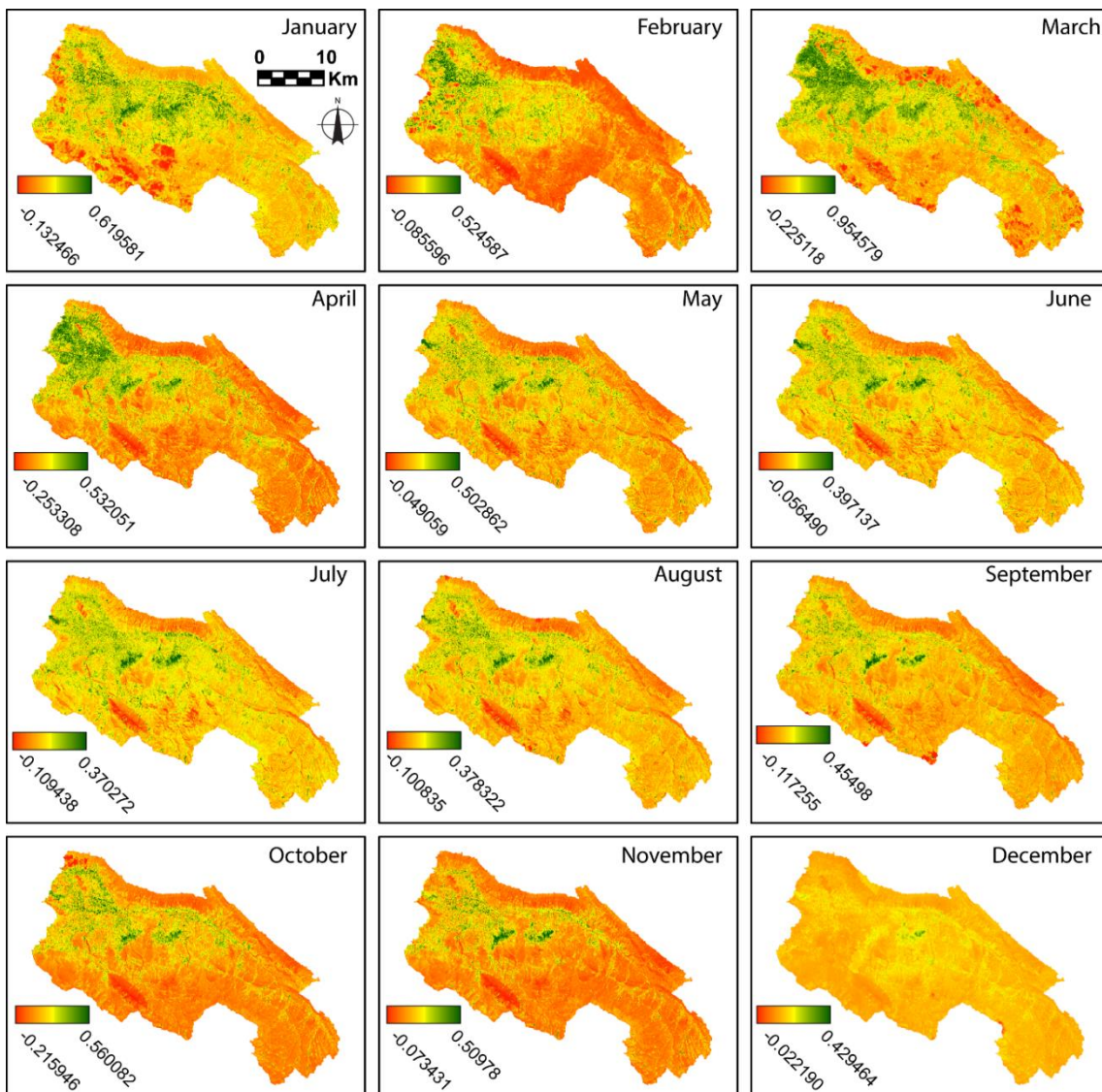
Date (year-month-day)	Cloud cover	NDVI
2016-01-22	2-10%	-0.132466<NDVI<0.619581
2017-02-09	2-10%	-0.085596<NDVI<0.524587
2016-03-26	2-10%	-0.225118<NDVI<0.954579
2016-04-27	0-2%	-0.253308<NDVI<0.532051
2020-05-24	0-2%	-0.049059<NDVI<0.502862
2020-06-25	0-2%	-0.056490<NDVI<0.397137
2020-07-27	0-2%	-0.109438<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

1110  
1111  
1112



1113  
1114  
1115  
1116

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



1117  
1118  
1119

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

1120

## 1121 **1.2. Slope and drainage extraction**

1122 National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission Version 3.0  
1123 Global 1 arc second (SRTM 3) and Advanced Spaceborne Thermal Emission and Reflection Radiometer  
1124 (ASTER) Global Digital Elevation Model Version 3 (GDEM 003) datasets were imported in an ARCGIS  
1125 10.3 environment in order to compare the influence of their respective resolution (90m and 30m) on  
1126 the slope and drainage extraction.

1127 - The Slope tool from Arcgis 10.3 environment is performed on a projected flat plane using a 2D  
1128 Cartesian coordinate system. The slope value is calculated using the average maximum technique  
1129 (Arcgis Pro documentation Slope, Burrough 1998).

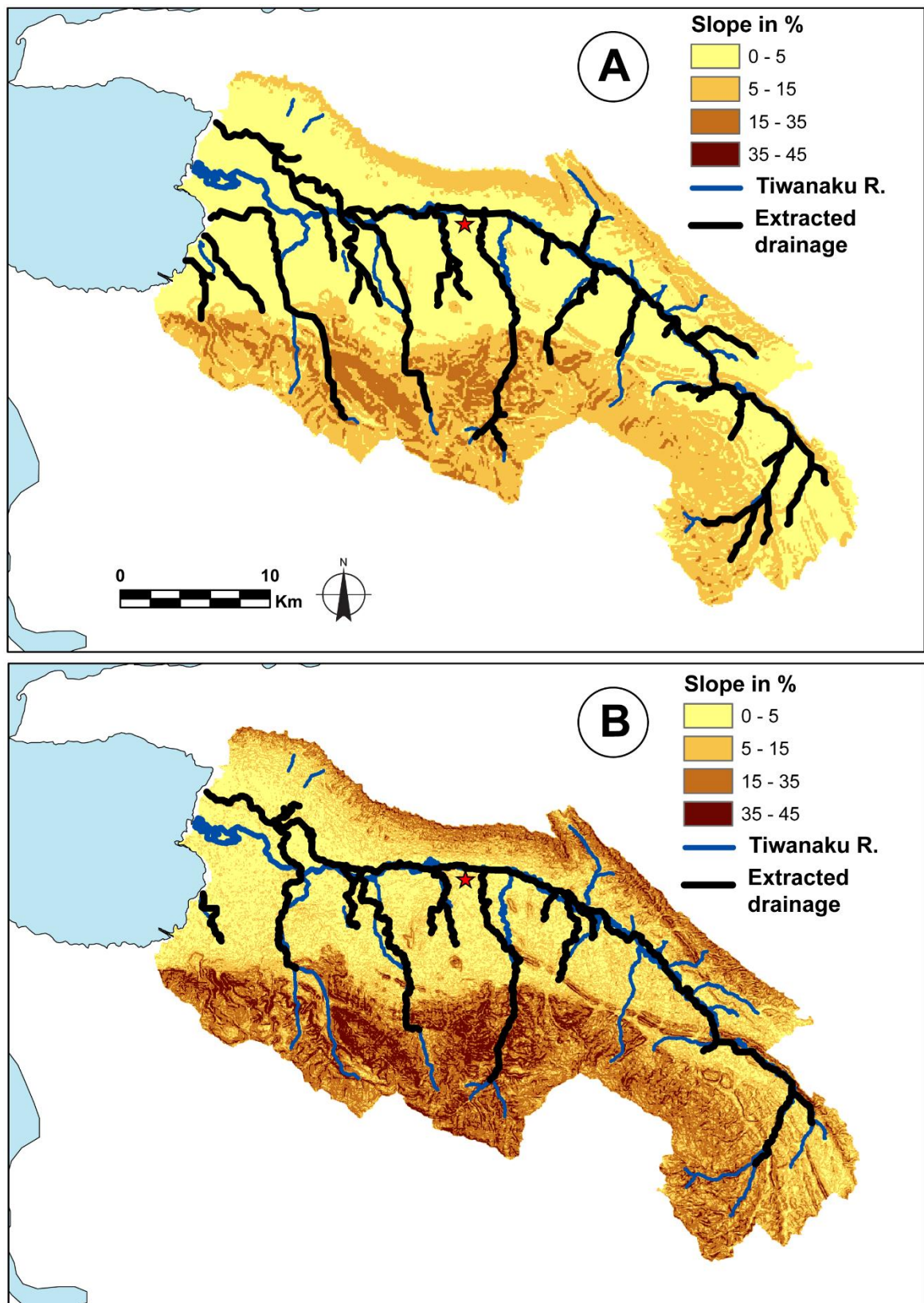
1130 Same procedure was used for the extraction of the slope from NASA SRTM 3 and ASTER GDEM. The  
1131 slope map from both datasets show some same general tendencies. Lower values represent the main  
1132 part of the valley and are located in the center of the map; medium values are located at the foot of  
1133 both mountain flanks (northern and southern); higher values are observed in the southern flank of the  
1134 valley. However, some differences could be identified between both dataset. First of all, the DEM from  
1135 ASTER shows higher values (SRTM 3, mean slope ~6.1% and ASTER, mean slope ~14.7%). Then on the  
1136 ASTER slope map, the values above 35% are more represented on the southern flank of the valley and  
1137 thus highlight more the shapes of the relief in comparison with the SRTM slope map. These differences  
1138 do not change the general tendencies of both datasets and might be related to the presence of noisier  
1139 values on the ASTER GDEM

1140 - The flow direction can be obtained from a D8 method or MFD algorithms extracted from an initial  
1141 DEM. Here we adopt the D8 method implemented in the Arcgis 10.3 software (Arcgis Pro  
1142 documentation Stream Order, Tarboton 1991). The calculated flow direction is then included as an  
1143 input to deduce a flow accumulation map that calculates the number of upstream cells flowing in every  
1144 pixel. Thanks to a threshold value, this flow accumulation map allows to reproduce a drainage network  
1145 starting from any initial DEM.

1146 Same procedure was used for the extraction of the drainage system from the SRTM and ASTER GDEM.  
1147 Flow accumulation map has been classified selecting values  $\geq 1000$ . Major differences from the current  
1148 situation concern the drainage extracted from the SRTM 3 GDEM: the Tiwanaku River is located closer  
1149 to the northern flank of the valley; the closest tributary to Lake Wiñaymarka does not join the course  
1150 of the Tiwanaku River but has a mouth in the lake; the watercourse of the tributary located upstream  
1151 of the archaeological site is located closer to the pre-Columbian city. However the extracted drainage  
1152 from the ASTER GDEM present also some differences with current situation. Even if the Tiwanaku River  
1153 is nearer to the actual watercourse, the extracted drainage is still located closer to the northern flank  
1154 of the valley; the tributary associated to the archaeological site present a similar watercourse as the  
1155 one observed with the SRTM 3 map. The medium vertical sensitivity and spatial resolution of the SRTM  
1156 DEM clearly induced some artifacts in the extracted drainage. Although the one extracted from the  
1157 ASTER GDEM seems more reliable, some differences with the current situation are still observed. These  
1158 differences might still be related to the resolution of the GDEM but these discreet slope changes could  
1159 also indicate some inherited topography from previous erosion phases and low lake level stands. These  
1160 palaeo-flows, well developed and preserved in the topography, are indirectly found by the flow  
1161 algorithm of the SIG (which fills the depressions linked to discrete divides to find an outlet).

1162 In conclusion, because of its greater resolution, ASTER GDEM and its by-products (slope and drainage)  
1163 were retained for our study.

1164



1165  
 1166  
 1167  
 1168  
 1169  
 1170

**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.

1171  
1172  
1173  
1174  
1175  
1176  
1177  
1178  
1179  
1180  
1181  
1182  
1183  
1184  
1185  
1186  
1187  
1188  
1189  
1190  
1191  
1192  
1193

## 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  $11.4 \text{ km}^2$  in 65 years ( $0.17 \text{ km}^2 \cdot \text{yr}^{-1}$ ). 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.



1194  
1195  
1196  
1197  
1198

**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.

## References

- 1199 1. Arcgis Pro documentation Slope. [https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-](https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-slope-works.htm)  
1200 analyst-toolbox/how-slope-works.htm
- 1201 2. Arcgis Pro documentation Stream Ordering. [https://pro.arcgis.com/en/pro-app/latest/tool-](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-stream-order-works.htm#GUID-7981F8C1-C714-41A9-871E-F9EDA687E1DC)  
1202 reference/spatial-analyst/how-stream-order-works.htm#GUID-7981F8C1-C714-41A9-871E-  
1203 F9EDA687E1DC
- 1204 3. Baret F, Guyot G and Major DJ 1989. TSAVI: a vegetation index which minimizes soil brightness  
1205 effects on LAI and APAR estimation. Proceedings of the 12th Canadian Symposium on Remote  
1206 Sensing, Vancouver, Canada, July 10– 14, pp. 1355-1358.
- 1207 4. Bork EW, West NE and Price KP 1999. Calibration of broad- and narrow-band spectral variables for  
1208 rangeland cover component quantification. International Journal of Remote Sensing, 20(18), pp.  
1209 3641-3662.
- 1210 5. Burrough PA, and McDonell RA 1998. Principles of Geographical Information Systems (Oxford  
1211 University Press, New York), 190 pp.
- 1212 6. Buttolph L 1998. Rangeland dynamics and pastoral development in the High Andes: the camelids  
1213 herders of Cosapa, Bolivia. PhD dissertation, Utah State University, 286 pp.
- 1214 7. Erickson C 1999. Neo environmental determinism and agrarian collapse in Andean prehistory.  
1215 Antiquity. 73(281), pp. 634-642.
- 1216 8. Gallego Revilla JI and Pérez González ME 2018. Tiwanaku, entre el cielo y la Tierra. The United  
1217 Nations Educational, Scientific and Cultural Organization, UNESCO, 178 pp.  
1218 <https://unesdoc.unesco.org/ark:/48223/pf0000265365>
- 1219 9. Kolata AL 2003. The Project Wila Jawira Research Program. In Kolata AL (Ed.): *Tiwanaku and Its*  
1220 *Hinterland: Archaeology and Paleoecology of an Andean Civilization*. Vol. 2: Urban and Rural  
1221 Archaeology Washington D. C.: Smithsonian Institution Press.
- 1222 10. Moreau S, Roland Bosseno R, Gu XF, Baret F 2003. Assessing the biomass dynamics of Andean  
1223 bofedal and totora high-protein wetland grasses from NOAA/AVHRR. Remote Sensing of  
1224 Environment 85(4), pp. 516–529.
- 1225 11. Pérez González ME, Gallego Revilla JI 2019. A new environmental and spatial approach to the  
1226 Tiwanaku World Heritage site (Bolivia) using remote sensing (UAV and satellite images)  
1227 Geoarchaeology. pp. 1-14. DOI: 10.1002/gea.21778
- 1228 12. Roche MA, Bourges JC, Mattos R 1992. Climatology and hydrology of the Lake Titicaca basin. In:  
1229 Dejoux C, Iltis A. (Eds.), Lake Titicaca: A Synthesis of Limnological Knowledge. Kluwer Academic,  
1230 Boston, MA, pp. 63–83.
- 1231 13. Strahler AN 1957. Quantitative analysis of watershed geomorphology. Eos, Transactions American  
1232 Geophysical Union, 38(6), pp. 913-920.
- 1233 14. Tarboton DG, Bras RL and Rodriguez-Iturbe I 1991. On the Extraction of Channel Networks from  
1234 Digital Elevation Data. Hydrological Processes. 5, pp. 81-100.
- 1235 15. Vining B and Williams PR 2020. Crossing the western Altiplano: The ecological context of Tiwanaku  
1236 migrations. *Journal of Archaeological Science*, 113, 105046.